Evolutionary algorithms for sustainable building design

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Evolutionary Algorithms For Sustainable Building Design

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Abstract

This approach to sustainable design explores the possibility of creating an architectural design process which can iteratively produce optimised and sustainable design solutions. Driven by an evolution process based on genetic algorithms, the system allows the designer to “design the building design generator” rather than to “designs the building”. The design concept is abstracted into a digital design schema, which allows transfer of the human creative vision into the rational language of a computer. The schema is then elaborated into the use of genetic algorithms to evolve innovative, performative and sustainable design solutions. The prioritisation of the project’s constraints and the subsequent design solutions synthesised during design generation are expected to resolve most of the major conflicts in the evaluation and optimisation phases. Mosques are used as the example building typology to ground the research activity. The spatial organisations of various mosque typologies are graphically represented by adjacency constraints between spaces. Each configuration is represented by a planar graph which is then translated into a non-orthogonal dual graph and fed into the genetic algorithm system with fixed constraints and expected performance criteria set to govern evolution. The resultant *Hierarchical Evolutionary Algorithmic Design System* is developed by linking the evaluation process with environmental assessment tools to rank the candidate designs. The proposed system generates the concept, the seed, and the schema, and has environmental performance as one of the main criteria in driving optimisation.

***Keywords**: sustainable design, CAAD, conceptual design, generative design, evolutionary algorithm, genetic algorithm.*

1 A computational architectural design method for generating parameterised sustainable design models

Sustainable designs produced using existing CAD systems might not represent the most sustainable design outcome. This is due to the lack of capacity of current software packages to evaluate any great number of design iterations in a reasonable amount of time.

While Computer Aided Design (CAD) systems have been successfully utilised in architectural design for many years, they have by no means reached their full potential (Boddy, Rezgui, Cooper & Wetherill, 2007). Some scholars refer to the obstacles faced by designers in switching between the conscious thought required to operate a computer and the unconscious flow of creative thought, as the reason that CAD systems are not readily able to adapt to conventional design methods (Liddament, 1999). From this perspective, although computers are being more widely used in the design process itself, it is noticeable that when they are utilised in architectural design, they are most frequently used for drafting and visualisation (Holness, 2006).

Despite the fact that architectural CAD systems have not reached their full potential, there have been promising developments in the field. The three most notable, in terms of their potential to produce sustainable designs, are used as foundation for the proposed design methodology. They are generative design systems, performance based design, and Building Information Modelling (BIM).

The generative design systems considered in this paper generate design alternatives from a simple "seed", according to a set of rules governing the growth process (Frazer, 1974) (Frazer & Connor, 1979). Working in a similar way, but using environmental factors as their basis, are the evolutionary design systems, which evolve designs from a “genetic code” of an architectural concept in response to the environment, through natural selection (Frazer, 1995, p. 65).

Evolutionary systems seek design solutions which have the “symbiotic behaviour” and “metabolic balance” found in the natural environment (Frazer, 1995, p. 9). Essentially, evolutionary systems aim to produce sustainable built environments through a responsive design process. The design itself takes shape as a result of the natural environment, as opposed to conventional design processes where designs are adapted in order for them to respond to the natural environment.

Performance based design, which has come to the forefront of research to a great extent due to the need for sustainability (Kolarevic & Malkawi, 2005, p. 195), is a comprehensive design approach which utilises the computer’s capabilities of simulation of targeted performance to generate building forms in response to its simulated environment (Kolarevic & Malkawi, 2005, p. 197). Although qualitative simulation capabilities are still being researched, computers can aid human qualitative assessments through their quantitative capabilities (graphic output, visualisation etc).

Building Information Modelling (BIM) is “a digital representation of the physical and functional characteristics of a facility”, (NBIMS, 2007) which can be used as a means for collaboration between all stakeholders throughout the lifecycle of the project. BIM provides an all-encompassing approach to the design of the building, taking into account all aspects of the building’s performance simultaneously, which establishes the base from which sustainable designs can be produced.

Project Services, the building procurement arm of the Queensland State Government in Australia, is testing various methods of procurement that exploit the use of BIM (Building Information Model) technology (Holness, 2006). One experiment they conducted involved the thorough analysis of the thermal performance of a range of building forms at the early sketch design stage by mechanical engineers (GBCA, 2009). The architects then developed the optimal design through to contract document stage and construction.

The “standard” process, where normally the architects design the building and only discuss the design with the mechanical engineers once the design has developed was turned around. This enabled the building to achieve the high Green Star rating without relying on unusual techniques to score extra Green Star points. However, this process had a significant cost in human effort to run over 200 analyses using the BIM and thermal analysis software to iterate towards an appropriate solution.

The research being carried out is based on the proposition that the developments in evolutionary systems, performance base design and BIM can be adapted and integrated with each other to create an architectural design process that supports and fosters human creativity in a digital scripted form. This paper presents a method to automate much of this process. This would eventually allow the exhaustive analysis of options to be more widely used.

It is expected that a generative formation design model can be developed that simulates the project’s environments and also simulates its desired performance to generate sustainable design solutions in response to the selected environmental parameters. Thus, the conceivable possibilities will be assessed and the outcomes will be objective measurements of the best choices made through optimisation.

The proposed design system operates during the pre-design and schematic design phases of the design process. Here, the designer is able to make informed and objective decisions which will have a higher impact on the quality of the design and a lower impact on cost. “To produce smart sustainable designs within [man hour and time constraints] designers need to be disciplined and focus efforts more at the early schematic design stage, and to test options while there are fewer constraints on the process.” (Kolarevic & Malkawi, 2005, p. 45).

The proposed system, illustrated in Figure 1, seeks sustainable design solutions during the earliest and most critical phases of the design process.

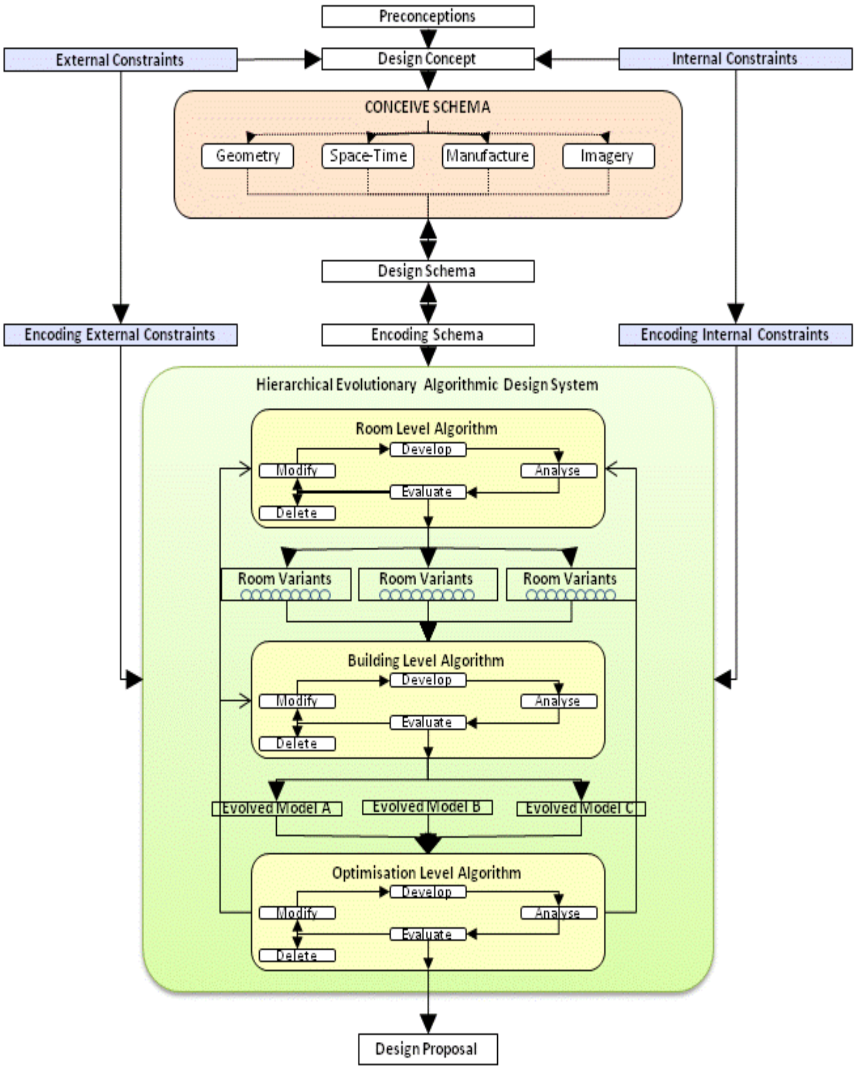

Figure 1 An illustration of the proposed design method.

The results presented in this paper have been fully specified as a process and worked through as "paper studies" to ensure that the algorithms and design factors are appropriate. The system is currently being implemented in computer software.

1.1 Design Context

The design context incorporates every aspect of the design problem, which is very often not immediately obvious but comes to light through the problem solving process (Lawson 2006). As most design problems seek to satisfy multiple functions which are both overlapping and interacting, design solutions need to respond to a multitude of requirements. The generators (client, user, designer and legislator) of the design constraints, both internal and external, seek to respond to four types of functions; formal, symbolic, radical and practical (Lawson, 2006).

Bertel, Freksa and Vrachliotis (2004) and Lawson (2006), describe constraints as the "result from required or desired relationships between two or more elements" of the design problem (Bertel et al., 2004, p. 267).

1.1.1 Design constraints

Two types of constraints were recognised; 'External Constraints' and 'Internal Constraints'. The external constraints are the unchangeable part of the design problem which are not affected by the design method and cannot be changed without creating a further problem. For instance, site (location, orientation and neighbouring built environment), weather, building regulations and the laws of physics are all prime examples. The internal constraints such as functional expression or modes of fabrication, on the other hand, have some level of flexibility and can be changed without creating problems. These values vary through the design process and are determined by the designer.

The external constraints simulate the site's external physical environment with its unchangeable (within the scope of the project) facts. The internal constraints animate the hosted activities in ideal and extreme conditions to virtualise the targeted internal environment of the building.

Bertel et al. (2004, p. 267) cited Carrara, Yehunda and Novembri (1994) to suggest that "a prioritisation of goals, reflecting a descending order of preferences, may be imposed by the designer or by the client, [indicating] which combination of performance criteria the designer should attempt to accomplish first". The prioritisation of the project's constraints to meet with the project's goals is highly influenced by the designer's preconceptions.

1.1.2 Designers' preconceptions

A number of researchers argue that architects have preconceptions as they design. Broadbent modified the 1960s design process by including 'preconceptions' in the synthesis stage of the process (Broadbent, 1988). These preconceptions play an essential role in the creative aspects of the design process (Janssen, 2004). Two types of preconceptions can be identified;

<u>Guiding Principles</u> - Variously called the designer's 'paradigmatic stance' (Broadbent, 1988), 'guiding principles' (Lawson, 2006) and 'theoretical position' (Rowe, 1998). The guiding principles reflect the philosophical beliefs,

cultural values and background of the designer. This stance is evolved and developed all the way through the designer's practicing career (Janssen, 2004). The guiding principles contribute to the designer's preconceptions by influencing the capture of the design concept.

Primary Generators - Various scholars attribute the formation of these initial ideas to a variety of sources; the 'primary generators' (Drake, 1979), 'enabling prejudices' (Rowe, 1998), 'concept or parti' (Lawson, 2006) and 'Generative Concept' (Frazer, 1974) (Frazer & Connor, 1979) (Frazer, 1995). The primary generator influences the conception of the design schema.

The guiding principles of the designer's preconceptions influence the prioritisation of the design constraints according to the project's goals and objectives. The subjectivity in the prioritisation of the design constraints influences the capture of the design concept based again on the designer's guiding principles (Frazer, 2002). Abstracting the captured design concept, the designer's primary generator influences conceiving the design schema in reflection to the third type of constraint in Lawson's (2006) observations, which is derived from the designer's stance and is thus a 'self-imposed' constraint (Janssen, 2004).

1.2 Design Schema

A design schema is a highly customisable but generic working method. As an adaptable design model inserted into the design process, the design schema characterises the designer's style as an abstract conception of common features of their designs (Janssen, Frazer & Tang, 2002). The design schema is also employed to maintain the designer's creative expression as a central part of the design process. The design schema, allows transfer of the human creative vision into the rational language of a computer. The design schema leaves the door open for the continuance of human creativity to invent new design tools.

The design schema translates the design concept with a digitally parameterised representation and a set of defined transformation rules. The design schema is then elaborated into the use of genetic algorithms to evolve innovative and performative design solutions.

1.2.1 Conceiving the design schema

Several scholars have studied design principles, from the conventional paper based architectural design practice and its descended digital version through to the digital architectural design practice.

Rowe (1998) presented five forms of heuristics that a designer may use in the search for a design solution; (i) 'Anthropometric Analogies' – which use the human form as an inspiration, (ii) 'Literal Analogies' – which use established and readily recognised shapes and forms, (iii) 'Environmental Relations' – which relate to the building's performance within its environment, (iv) 'Typologies' – using established design solutions and (v) 'Formal Language' – which uses the formal, accepted solution as a guide. Kolarevic (2003) introduced six methods of digital morphogenesis, (i) Parametric Design (ii) Dynamic and Field of Force (iii) Datascape (iv) Metamorphosis (v) Genetics (vi) Performative. Flanagan (2005) presented four generative methods in digital design, (i) 'Generative Geometry' (ii) 'Generative Imagery' (iii) 'Generative Manufacture' (iv) 'Generative Space-time'.

Without having to make an in-depth comparison of the above three approaches, it can be seen that they share some common elements. Which of these fundamentals is used is based on the designer's preconceptions but any one of them can nevertheless be used to interpret the design concept in a digital representation.

1.2.2 Encoding the design schema

The design schema can be encoded (Janssen, 2004) in one of three ways. The highly-generic approach applies standard rules and representations using binary strings which do not rely on any domain or task-specific knowledge. Performance of an evolutionary algorithm in generating designs, based on broad generalisations, is not necessarily highly efficient. However the lack of performance is compensated by re-usability. The domain-specific approach incorporates domain-specific knowledge in the rules and representations to improve the performance of the system, however there is a corresponding loss in re-usability. Finally, the task-specific approach can be used when the type of task in the domain is complex and a high level of performance is required. The task-specific approach is at the opposite end of the spectrum to the generic approach. While it offers the highest levels of performance, re-usability is very low.

In the domain of building designs, when the task-specific rules and representations of a specific designer are encoded, the system will reflect the designer's preconceptions and style. Therefore, the domain-specific approach is found to evolve more generic designs and it is also more flexible for re-use by other designers. In addition, the domain-specific approach evolves designs with high variability but with poor efficiency. On the other hand, the task-specific approach compensates the re-usability and style issues by evolving more surprising and challenging designs with high efficiency.

1.3 Generation and Formation

Nature, ever changing and evolving, serves as a rich source of inspiration for designers and researchers attempting to optimise the performance of their designs. This is not a new concept, John Frazer coined the phrase 'Evolutionary Architecture' (1974) (1979) (1995), referring to the investigation of, and search for form-generating processes in architecture, based on the notion of morphogenesis in the natural world. Frazer's conceptualisation of architecture goes beyond the idea of shapes and forms to encompass a set of rules that generate spaces and forms. The built environment is thus produced through a series of evolutionary steps based on the selection of solutions that best respond to the fitness function criteria.

Genetic algorithms are used to simulate the concept of evolution with computer logic. Genetic Algorithms were first presented in the 1960s by John Holland in his investigation of the process of natural selection systems. As described by Holland (1992), the structure of genetics consists of a population of chromosomes which represent possible solutions to a problem. Genetic operators, such as crossover and mutation between two or more genotypes produce a new generation phenotypes. The genetic make-up of the next generation is dependent on the process of selection which decides on what part of the population will pass to the next generation. Every solution in the population is evaluated and selection is made on the basis of fitness. As genetic algorithms deal with a huge number of possible solutions, as opposed to just one solution at a time, it is much more likely that an acceptable solution will be found (Kalay, 2004, p. 283).

1.3.1 A responsive generative formation design model

The concept of the designer as a tool maker (Janssen et al., 2002) is introduced here as the simulation of the project's environments are employed as a tool to aid in the generation of design solutions.

Simulated External and Internal Environments; The Evolutionary Design Systems, on the one hand, using a repeated cycle of genetic scripted code, are able to produce designs adapted to the environment. Performance Based design on the other hand, applies modifications to the produced design, based on its performance in an analytical simulation. The proposed design method develops a generative formation design system with two environments encoded into the system. The project's external constraints simulate the external environment of the project. The project's internal constraints simulate the internal environment and animate the desired performance of the project. Thus, the design would be generated in response to the simulated external and internal environments and also to the animated desired performance.

Prioritisation of constraints; all the project's identified constraints are encoded according to the relative priority assigned to them by the designer. The generative formation system will act in favour of the constraint which is assigned the highest priority. For example, if the building orientation is determined to be more important than environment, the environmental solution will be applied on the best orientation solution. On the other hand, if the environmental constraint is set with a priority over that of orientation, the best environmental setting determines orientation. Thus, each prioritisation produces a different generation of solutions with a set of different characteristics.

The prioritisation of the project's constraints and the subsequent design solutions synthesised in accordance with the simulation of the project environment during design generation is expected to resolve most of the major conflicts, in the evaluation and optimisation phases. The system produces a responsive design solution, optimised and developed through its creation process in simulated and animated environments, thus responsive to its living environment, responsive to the captured performance and responsive to the designer's creativity which is reflected in the design schema.

1.3.2 Hierarchical Evolutionary Algorithmic Design System

The system is designed to incorporate the notion that the design problem cannot be “comprehensively stated”, “require[s] subjective interpretation” and “tend[s] to be organised hierarchically” (Lawson, 2006, p. 120). The system is divided into three levels to respond to the hierarchical decomposition of the design problem into further levels of sub-problems. Each level of the HEAD system is thus able to tackle issues of sustainability sequentially.

The first level, *the room level algorithm*, generates successful variants of possible solutions for each required space based on assigned fitness functions. The fitness functions include the project’s design criteria, design standards, building codes and functional requirements applicable to individual rooms. The evolved successful generations are available for the second level of the system.

The second level, *the building level algorithm*, combines one variant of each generated space from the first level according to the adjacency requirements, mode of fabrication and a grid system. The successful configurations of the space lay-out are then fed into the third level.

The third level, *the optimisation level algorithm*, optimises the successfully evolved building configurations based on over-all thermal, light, acoustics and cost performance.

There are no optimal solutions to any design problem but rather an infinite number of possible solutions (Lawson, 2006). The design process is never-ending and designers work in the context of a need for action (Lawson, 2006). Thus the system loops back to earlier levels allowing the system itself or the designer to make modifications on the successful selected solution.

1.4 Optimisations

Performance analysis on the chosen model can be conducted by *the optimisation level algorithm* to verify different performance aspects of the produced design. Although available performance analysis applications are valuable tools, they do not normally come with modification capabilities. To overcome this issue when modifications are required or even to test the impact of design decisions, alternative design solutions can be fed back into an earlier phase by varying chosen parameters.

Unlike the performance-based design case where modifications are done after synthesis by evaluating the performance of the produced design based on analytical simulation, in our case, the generation and formation of the design happens in response to the synthesis simulation of the project’s environments. This means that the system will only produce solutions from the design space of viable designs for the design situation without having to generate all design situations that could possibly be produced by every combination.

Thus, the system will have fewer design solutions to produce and to run through the optimisation cycle in order to identify the successful model(s). This also means that the modification capability could be added to the optimisation cycle within the generative system to enable automatic adjustments and development.

2 Research Framework

2.1 Plan

To test the proposed hypothetical proposition the intention is to build a system specifically to design a particular building typology. It is not intended to build the responsive generative formation design system in its full capacity. At this stage a test system will be built around the specific pilot project.

A mosque is selected as a pilot project. Mosques have more defined design problems due to the fact that specific planning and design criteria arise from a set of explicit religious requirements. These distinguishing features would give greater control over design variants and thus a more controlled design space and generation of solutions. On top of that, these features provide a reference to the functional evaluation of the produced design solution.

The system will be set up to simulate the selected pilot project’s environments and its desired performance based on the prioritised external and internal constraints of a selected existing mosque project.

2.2 Action

A retrospective BIM performance analysis will be carried out on the selected mosque to establish a base against which the design solutions produced by the proposed model can be compared. The intuition of selecting a mosque design as the pilot project arises from the need to maintain control over design variants while regenerating different design solutions for different site conditions. Two scenarios are proposed:

- Design a new schema for the conventionally designed selected mosque and process it through the Hierarchical Evolutionary Algorithmic Design System to generate a responsive design solution. The design solution will capture the codified concept abstracted into the design schema in response to its environment.
- Run the design schema from above through the Hierarchical Evolutionary Algorithmic Design System, but at a different geographical location, to generate a responsive design solution to the new environment.

2.3 Evaluate

The design solutions produced by both of the scenarios discussed above, as well as the conventionally produced design solution of the pilot project, will be evaluated according to environmental performance analysis, functional performance analysis, cost estimates and all other associated fitness functions.

The interoperable nature of the produced design models will allow immediate performance analysis to be carried out to verify various performance aspects of the design.

3 Pilot project: Mosques

3.1 Mosque Architecture

Mosque architecture has been a controversial issue for as long as mosques have existed. One school of thought abandons the charged ornaments all over the building and seeks simplicity in design based on religious functionality, much like those built during early Islam. The other school of thought gives higher aesthetic and social value to the place, acknowledging the Muslim architectural heritage and emphasizing symbolic features that have become the stereotypical image of the mosque.

Mosque typologies have developed over the centuries, benefiting from the diverse and dispersed cultures all over the world while maintaining their identity (Frishman, Khan & Al-Asad, 1994). Each of the Muslim ecological cultural regions has contributed to mosque architecture. With defined spatial organization principles and a set of generic forms, historic mosques reflected the ‘eclectic and integrative’ nature of Islamic architecture (Ardalan, 1980).

Nader Ardalan (1980) presented a preliminary survey covering 113 mosques around the world in which he identified a typology of spatial organization and distinguishing generic Islamic forms. The Islamic world was categorized into six regions based on ecological and cultural backgrounds. Each zone is presented with a dominant typology; The Arabian Peninsula and North Africa; dominated by the Hypostyle with Dome Accent typology. Turkey; dominated by the Central Dome typology. Central Asia; dominated by the Four Iwans typology. India; dominated by the Hypostyle with Domical Vaulting typology. East and West Africa; dominated by the Hypostyle typology. Far east; dominated by the Complex typology.

Although a dominant typology found in each zone is clearly noticeable, other typologies are also found in the same region. For example, in the zone of the Arabian Peninsula and North Africa all typologies were found. Despite the fact that the 113 samples were not equally divided between the six zones, eight generic forms were found in each zone and typology; the niche *‘Mihrab’*, the courtyard, the dome, the Minaret, the gateway, the portico, the ablution place and the plinth.

Looking at the spatial categories of the historic Mosques in Ardalan’s research, we find that most mosques consist of two main parts; the prayer hall and the courtyard. The prayer hall includes the Mihrab, gateways and a portico. The courtyard also includes gateways, minaret(s), an ablution place and a portico. Additional spaces for required functions are added to either part accordingly. All the other spaces and generic forms are hosted and represented within these two parts.

Ardalan (1980) noted some spatial organization principles; direction, introversion, centrality, symmetry and symbolic. The main spatial organization principle is the orientation to Makkah. The Mihrab in the centre of the Qiblah wall is the architectural organic form found in each and every mosque since the first mosque in Madinah was built 1430 years ago to orientate the prayers toward the direction of the Kaabah in Makkah. Introversion, which comes from the prayer ritual itself, is served with the courtyard and central dome planning. The gateway and the portico, as transitional spaces, buffer the prayers from distractions. Centrality and symmetry, which also come from the prayer rituals during the formation of the rows behind the Imam on both sides equally, are reflected in the domical and the pyramidal forms highlighting the main sacred space. The principle of symbolic spatial organisation is seen in the use of the plinth, especially in a single plan courtyard, which adds the value of a raised space to the mosque.

Environment has a great influence on mosque planning and architecture. For example, the courtyard is designed to provide, among other functions, natural lighting and fresh air to the prayer hall. The courtyard of the mosques found in Arabia, Persia and India are spacious, where as those found in Turkey and central Asia are smaller, and in some extremely cold regions have completely disappeared. The porticos are designed to provide shaded areas surround the courtyard of most of the mosques built in Egypt and the eastern Muslim countries. In the western Muslims countries and Andalusia, the porticos where covered for protection against heavy rain.

Modern mosques follow the spatial organization principles of historic mosques and keep the essential generic forms, developing in response to economical, cultural and environmental issues. Mosque typologies which emerged from the ecological cultural regions have, over time, become symbolic. Emphasis of some generic forms such as the dome and the Iwans are noticeably vanishing in modern mosques. Advancements in technology, building systems and building materials are greatly influencing modern mosque design.

However, Aksamija (2007) cites Rafael Moneo as stating that, “the work of Architecture is irreducible to any classification”, suggesting that typology is based on the continuous development of shared characteristics (Aksamija, 2007), which always result in a fitter generation of types. Looking at mosques from a genetic development perspective and based on Moneo’s concept of developing types, we can note that mosque typology has indeed developed from a gene pool of generic forms which follows a typology specific to ecological regions. For instance the first mosques were built as simple hypostyle prayer halls. The Mihrab, the pulpit *'Minbar'*, the minaret and the courtyard were introduced later, followed by other generic forms which were influenced by the various ecological Muslim regions. The emphasis of a certain generic form within the combination of generic forms, with respect to the principles of spatial organisation, came about in answer to the specific needs and architectural language of a particular region. Mosque architectural development can thus be looked at from a genetic perspective where certain generic forms are introduced by an ecological region as chromosomes, resulting in a distinguishable typology; for example the dome, the Iwans and the pyramidal roof were all introduced as genotypes which resulted in a phenotype typology. Regional genes or generic forms are adopted by other regions, fusing into another generation of typologies.

Looking at the mosque from the perspective of developing typologies, we can identify six regions with six dominant typologies. These typologies are all influenced by their environment and culture, resulting in a set of guidelines or a set of shared characteristics specific to each typology. The characteristics of each typology can be formalised by different schemas, where each schema produces several successful permutations.

3.2 Mosque design schema

The design schema for the pilot project is inspired by a combination of selected elements from Rowe, Kolarevic and Flanagan's approaches. The schema applies Rowe's *lateral analogies*, *environmental relations*, *typology* and *formal language*, with Kolarevic's *parametric design*, *genetics* and *performative morphogeneses*, as well as Flanagan's *generative geometry* and *generative manufacture*. The design schema is conceived on a task-specific basis, that is to say, it is specifically designed for a mosque design project

Through observation and with reference to Rowe's *lateral analogies*, *typology* and *formal language*, we note that all the generic forms are included within two main parts of the mosque; the prayer hall and the courtyard. As a result we can distinguish mosques that have only a prayer hall, hosting the generic forms associated with it and mosques that combine the prayer hall with a courtyard, which include the generic forms associated with both.

Each generic form and space is parameterised according to the *room level algorithm's* assigned fitness functions. The genetic algorithm explores all variants and evolves successful permutations.

A Prolog programme using definite clause grammar (DCG) is developed to build seeds from high level descriptions of various mosques, resulting in a symbolic representation of sequence strings out of the different configurations, to govern *the building level algorithm.*

The spatial organisations are graphically represented according to the adjacency constraints between spaces. This form of representation is not new (Levin, 1964) but is still being proposed to support analysis (Wu, Lee, Koh, Aouad & Fu, 2004). Each configuration is represented by a graph where nodes are placed to represent spaces which are linked by relationship lines analogous with graph and circuit theories. The adjacency data in the graph is processed as either true or false, which does not allow the priority to be defined. The use of weighted adjacency matrices could generate different graphs.

Each graph is then translated into non orthogonal duals (Grason, 1970) and fed into the genetic algorithm system and expected performance criteria are set to govern evolution in the *optimisation level algorithm*. Each generic form and room is parameterised with functional and performance criteria such as lighting, thermal and acoustic performance used as fitness functions during assessment and selection.

Within the context of mosque design, the orientation towards Makkah for the prayer hall, and the module of the prayer mat within the prayer hall, are the two overriding design constraints. The courtyard and ancillary spaces can be oriented in whichever direction is appropriate. The fitness functions that are used to select the "best" members of the population generated by the system are heat flow for the four solstice and equinox dates, cost as a function of the sizes of the various building components and CO_2 equivalent emissions of the building materials.

4 Conclusion

Performance evaluation systems available today are not equipped to evaluate the large number of design iterations which need to be assessed in order to find the most sustainable design solutions. In addition, these systems do not have modification capabilities. Using performance-based design, modifications are done after synthesis by evaluating the performance of the produced design based on analytical simulation.

Bringing together the evolutionary systems, performance based design and BIM system, the proposed HEAD system aims to produce sustainable designs through a responsive design process. Sustainable performance targets, whether environmental, economic or social, can be set for any or all aspect of the design, and design solutions are generated in response to these simulated targets. The generated design solutions can then be tested using BIM, allowing for sustainable choices to be made early in the design process.

The research explores the level of human interventions during the early design process in a guided evolutionary environment, aiming for a design system that facilitates multidisciplinary integration in the early stages of the design process. Environmental performance is one of the main criteria to drive optimization by linking the evaluation process of evolutionary algorithms with environmental assessment applications to rank the candidate designs. In the case of the proposed HEAD system, the generation and formation of the design happens during the synthesis stage, in response to the simulation of the project's targeted environments.

As Mahadev Raman points out “professionals tout definitions of sustainability but the practical application of these concepts presents major challenges” (Kolarevic & Malkawi, 2005, p. 43). If sustainability is taken to be “about finding the right balance between environmental, economic and social concerns” (Kolarevic & Malkawi, 2005, p. 43) then the proposed system holds the potential of producing sustainable design solutions.

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