PhD dissertation

Programming and Computation in Architectural Design

{Mukta V. Deshpande}

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Ahmedabad, India

Undertaking

I, **Mukta Vishwakumar Deshpande**, the author of the dissertation titled **Programming and Computation in Architectural Design**, hereby declare that this is an independent work of mine carried out towards partial fulfilment of the requirements for the award of the PhD degree by CEPT University, Ahmedabad, India. This work has not been submitted to any other institution for the award of any Degree/Diploma. All views and opinions expressed in this dissertation report are mine, and do not necessarily represent those of the institute.

Name of student	: Mukta V. Deshpande
DP №:	: 2012
Date	: 28 October 2015
Place	: Pune

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This is to certify that the dissertation titled **Programming and Computation in Architecture** has been submitted by **Mukta V. Deshpande** (DP№.2012) towards partial fulfilment of the requirements for the award of PhD degree at CEPT University and has been carried out under my supervision.

Guide : Prof. Dr. Nilesh Uke
(Minor dissertation)
Date : 28 October 2015

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Abstract

The research study aims at an enhanced understanding of Programming and Computation in Architectural design. It also signifies the application of artificial intelligence in architectural design. The research gap is identified through literature review and supported with the experiments conducted in a specific set up. A relation was established between computable aspects of the theory of architectural design and Bio-inspired artificial intelligence from the theory of computation. The logic was progressively exploited to develop a hypothetical computational design model as an *autonomous mediator*. The autonomous mediator may assist the designer in making precise and optimal design decisions. The application of this model of designing can further be extended into automated construction and CNC manufacturing processes and mass customization of architectural design.

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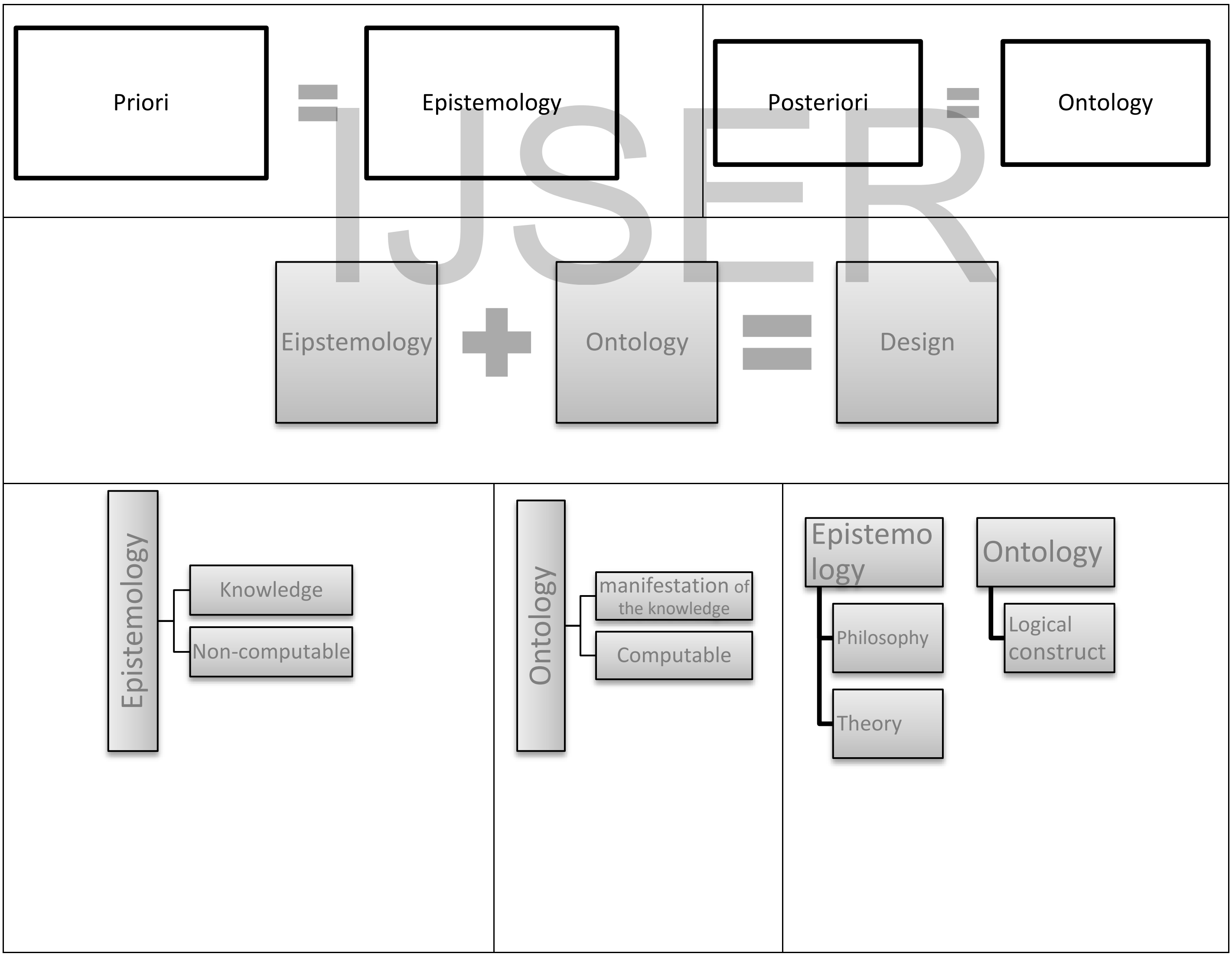
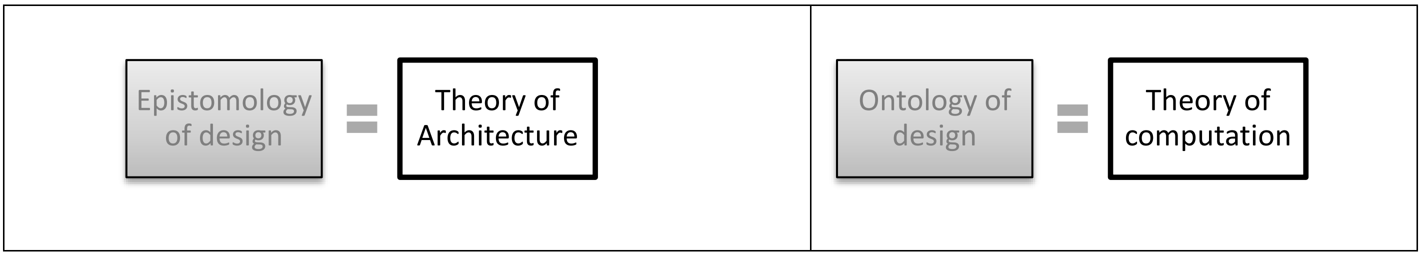
1 Introduction to the dissertation

Designing is an expression of the human intellect, its origin being *formless*. Cognition is the basis of this form of the formless. The formless can be manifested with the help of several tools such as; words, a piece of Art, sound. A designer can express his design cognition through his sketch or model. Thus, we understand that transcendence of the formless form of the cognition requires a medium for expression. The path of the transcendence can be described as; the origin of thought to the priori, to its posteriori, and, to the designer's sketch or a model. This concept is understood as a transcendence of the formless expression to its physical manifestation. The concept of transcendence is scientifically explained in terms of epistemology and ontology. Moreover, it can be *interpreted into the computational design* as follows;

Table 1: Interpretation of design in terms of its epistemology and that of ontology





1.1.1 Background of the study

Designing with computers (for architecture); is based on interdisciplinary theory; i.e. theory of computation and theory of architecture as the foundational theories. The first ever known model of designing with computers was based on 'Schön and Wiggins' model of designing, known as 'seeing-moving-seeing' (SCHON, 1992). It argues that "design is an interaction of the designer with his sketch". Schon argued that "Research should focus on computer environments that enhance the designer's capacity to capture, store, manipulate, manage and reflect on what he sees" (SCHON, 1992). Thus the studies in this domain focused on the development of the *models* or the *machines* for designing (KELLY & GERO, 2012). These models help the designer as a tool; so that the design decision remains the designer's domain. (PROTZEN, HARRIS, & CAVALLIN, 2000). In this particular study, the primary objective of the research is to identify these environments of the architectural designing. TABLE 1 explains these environments as, the epistemology of design and the ontology of design. TABLE 2 explains their interpretation in terms of the computable parameters and non-computable parameters of architectural designing.

Table 2: The computable and non-computable parameters of architectural design

List of the *computable* parameters		**List of the *non-computable* parameters**
Visual parameters	Colour, light, texture, contrast, value, space, form (CHING, 1979)	Design cognition **(RIITAHUHTA & ASKO, 2004)**
Graphical parameters	Scale, proportion, pattern(order, rhythm, hierarchy) (CHING, 1979)	Socio-cultural sensitivity and variables (SALVAN)
Geometrical parameters	Point, line, plane, shape, size, position(coordinates) (CHING, 1979), anthropometry, grammars	Aesthetic sensitivity

	(Mitchell, 1990), smart geometry (Burger, et al., 2015), **(6th ASCAAD Conference 2012 CAAD | INNOVATION | PRACTICE)**, (Asish, 2008), **(Hesselgren, et al., 2013)**	
Mathematical parameters	Matrices, vectors **(Issa & Robert McNeel & Associates, 2010)**, series, rules, range, equations, relations	Perceptual quality of space (Salvan)
Building performance parameters **(Djordje, 2013)**	Climate, Sustainability, energy efficiency	Psychological space (Salvan)
Economic parameters **(Djordje, 2013)**	Cost, time	Character (3 types; Functional, Associative, and personality or Emotional appeal) (Salvan)
Safety parameters **(Djordje, 2013)**	Fire protection, accessible buildings, barrier-free structures	

It can be understood from the background study that the computable parameters (ontology) should be utilised *to achieve that of the non-computable (epistemology)*.The mechanical tools such as measuring devices and calculators, statistical tools such as sun path diagrams, and climatic data or digital tools such as the computers. Various models of designing have been established based on the above requirements (e.g. modular design (Corbusier, 2005)). Similarly, the paradigm of programming and architecture has its foundation based on the theory of computation. The theory of computation has its own, classified foundation into the theory of architecture that stands out from the other domains of that of architecture. The theory of computation has an extensive and progressively growing capacity to encompass all of these domains. All the tools, as listed above (mechanical, statistical and so on), can be replaced by computers and programming. The evolution and genesis of the theory of programming and computation in architecture are explained in the next chapter, i.e. LITERATURE REVIEW. The literature review unfolds parallel paradigms of systems developed in this domain of programming and computation in architecture. The *parallel* development falls in the era of working in collaborative environments. It has majorly caused interdisciplinary influence. Similarly, this study follows the same approach of interdisciplinary nature.

1.2 Definitions

Programming in architecture refers to the generation or adoption of a computer algorithm or a program to achieve graphical, virtual output in the form of 2-D drawing or 3-D model. *Computation in Architecture* refers to the literal meaning of computation i.e. calculation in a broad sense. The computations for ratio, proportions, repetition, progression, grammars can be considered as the basis of computation to develop programs and algorithms. These programs and algorithms will help to interpret data based on the input data. Thereby, saving time and reducing human efforts for complex calculations and computations.

Programming and Computation for architecture is generation of computer program/s in relation to the computable functions of architecture that will help the designer as a tool (primarily, to save time and reduce human efforts for complex calculations and computations).

1.3 Research Plan

The approach of this study is based on the foundational theories of computation and that of architecture. The non-computable (i.e. qualitative) aspect is followed by the theory of architecture, and computable (i.e. quantitative) aspect is followed by the theory of computation. So, a programming and computation method of designing is developed to help as a tool for the designer. The advance research studies state that, *the design is a problem-solving exercise* and, it involves parallel thinking in multiple directions. Managing the parallel issues makes *design* a multi-criteria problem-solving exercise. **(GERO, 1996)**.It leads to the introduction of *artificial intelligence* (AI) into architectural design process/es. The process of evolution of programming and computation in architectural design till the introduction of AI is thoroughly explained in this research. This research is based on its theoretical fundamentals and also includes analysis of *experiments carried out practically*. The experiments are *practical solutions* to the architectural design projects. These experiments and their observations are documented as **PRIMARY SOURCE OF DATA COLLECTION: EXPERIMENTS AND OBSERVATIONS4.2**. Research gap is identified based on both; the theory; i.e. the secondary data source, and, the observations of the experiments i.e. the primary data source. This study aims at developing a theoretical framework in the form of *a hypothetical model of design viz; the autonomous mediator*. **(DJORDJE, 2013) (MORGAN & MORRISON, 1999)**

1.3.1 Research Plan

i. To establish the significance of programming and computation into architectural design: Discussed in Section **2 LITERATURE REVIEW**
ii. To establish need for AI into architectural design based on literature review and experimentation: Discussed in section **2 LITERATURE REVIEW** and **SECTION 4 AUTONOMOUS MEDIATOR MODEL OF DESIGN**
iii. To establish significance of Bio-inspired AI into architectural design: **SECTION 3**
iv. To develop a theoretical framework for autonomous mediator: **SECTION 4**
v. To develop and detail the autonomous mediator: **SECTION 5**

1.3.2 Scope of the study

The focus of this study is limited to the development and detailing of the autonomous mediator, the evaluation and testing of the model of design becomes out of it's scope.

1.3.3 Significance of the study

The autonomous mediator will benefit;

a. The researchers who may develop models of design.
b. Software developers who generate software or plugins for architects and designers.
c. Architects and designers who practice computational design methodology.

1.4 Achievements

This study develops an *autonomous mediator* **(Morgan & Morrison, 1999)** with the following as its derivatives

a. Introduction of Artificial Intelligence, specifically Bio-inspired AI into architectural design
b. Establishing the relationship between Evolutionary systems of Bio-inspired AI and Systems of architectural design

This autonomous mediator further allows *simulation* **(Axelrod , 1997)**and *optimization as a value addition* to its original derivative nature. A *strategy* of computational design **Figure 14** is the basis of the autonomous mediator.

1.5 Overview of dissertation

The first chapter explains the initial concept of the research and its background study. The second chapter is the literature review where, the history of programming and computation in architecture is explained. Moreover, based on the analysis of history, research questions are formulated. Review of the literature includes two categories; literature from the primary research studies and literature from the applied research studies, represented with a history timeline and, analytical models of digital design (Oxman, 2006). This study is of 'interdisciplinary' nature and comprises of the theory of architecture and theory of programming and computation. Precisely, it focuses on the theory of bio-inspired artificial intelligence. The *aim* of this study that is, to *develop a theoretical framework* in the form of an *autonomous mediator* as an *alternative method of design*. *The objective* of the study is to *identify significant foundational theory attributed to the theory of architecture and bio-inspired AI and derive parameters* for the formulation of the theoretical framework. The alternative method is inspired by the theory of bio-inspired AI. The research methodology (similar to that explained by Stojanovic, Đorđe (Stojanovic, 2013)) is based on that of *exploratory research to derive the theoretical framework and concludes with a hypothetical model of designing.*

The methodology of data collection;

a. Secondary data sources for the derivatives of the autonomous mediator

b. Primary data includes qualitative analysis of the experiments conducted for their practical significance

The experiments were conducted within a time span of three years in the city of Pune, Maharashtra, India.

2 Literature review

2.1.1 Brief history of programming and computation in architectural design

History of programming and computation is understood as the evolution of the computational design models. The literature review explains the history of programming and computation in a combined format of slides of timeline and analytical models of design such that;

i. Timeline to mark the milestones

The timeline indicates the remarkable incidents in the history of programming and computation in architecture. The timeline is explained in association with the models of digital design. It is understood from the timeline that these developments happened simultaneously. The parallel development is explained in association with the analytical models of digital design.

ii. Analytical models of the prevailing theoretical framework along with illustrations of its translation into architectural design and practice.

The initial model of design with computers based on Schon and Wiggins' model of designing, is known as 'seeing-moving-seeing'. This back and forth interaction between the designer and his representation is expressed in the analytical models of design by Oxman. These analytical models of design represented by Rivka Oxman, explain the interaction of the designer with his design representations and this interaction is a fundamental factor in the design. (OXMAN, 2006). The importance of these models of design is that they mark the *developmental stages* in the theory of digital (programming and computation) design.

In each section below, the interaction of designer and his representation is discussed. The figure to the left indicates the model of design and figure to the right indicates its output.

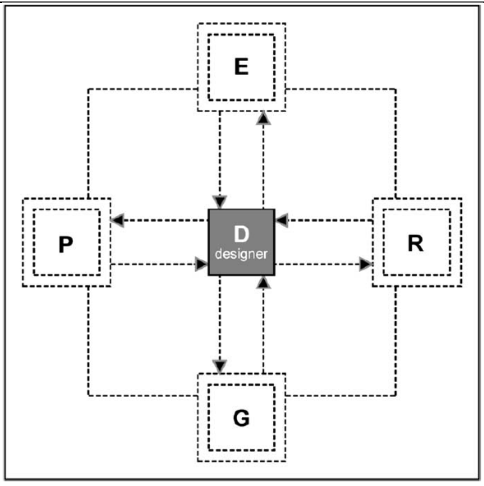


Figure 1:Generic schema represents interactions, relations and properties

The graphical models include four components of digital design; R, E, P and G. R indicates the representation i.e. the output, E indicates the evaluation, P indicates the performance, G indicates the Generation

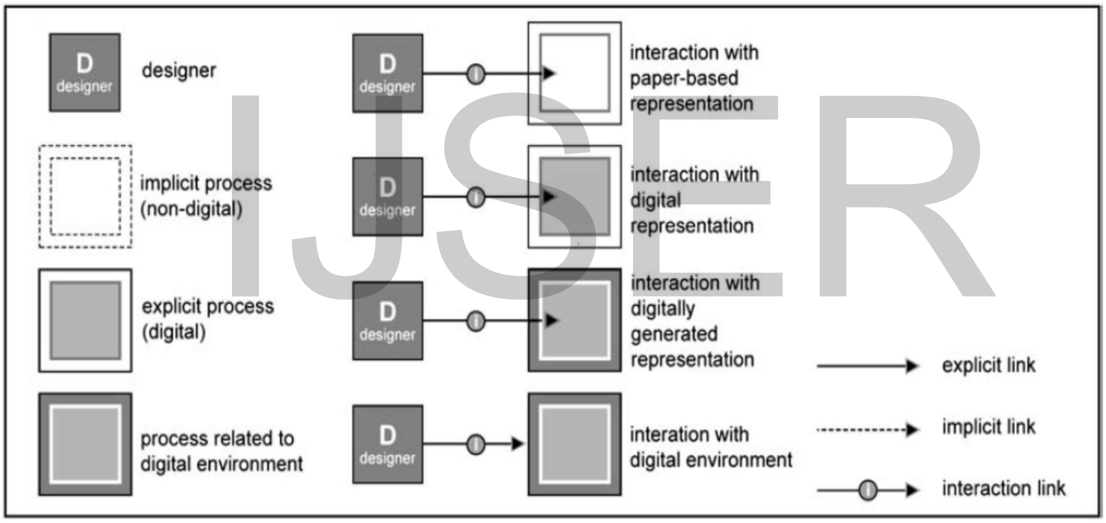
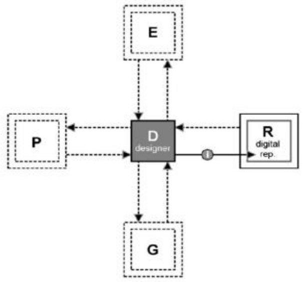
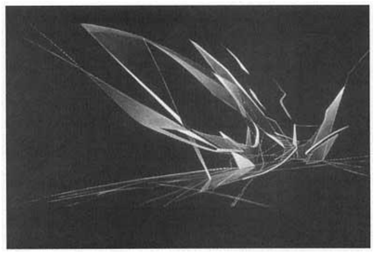


Figure 2:Generic schema of digital design (OXMAN, 2006)

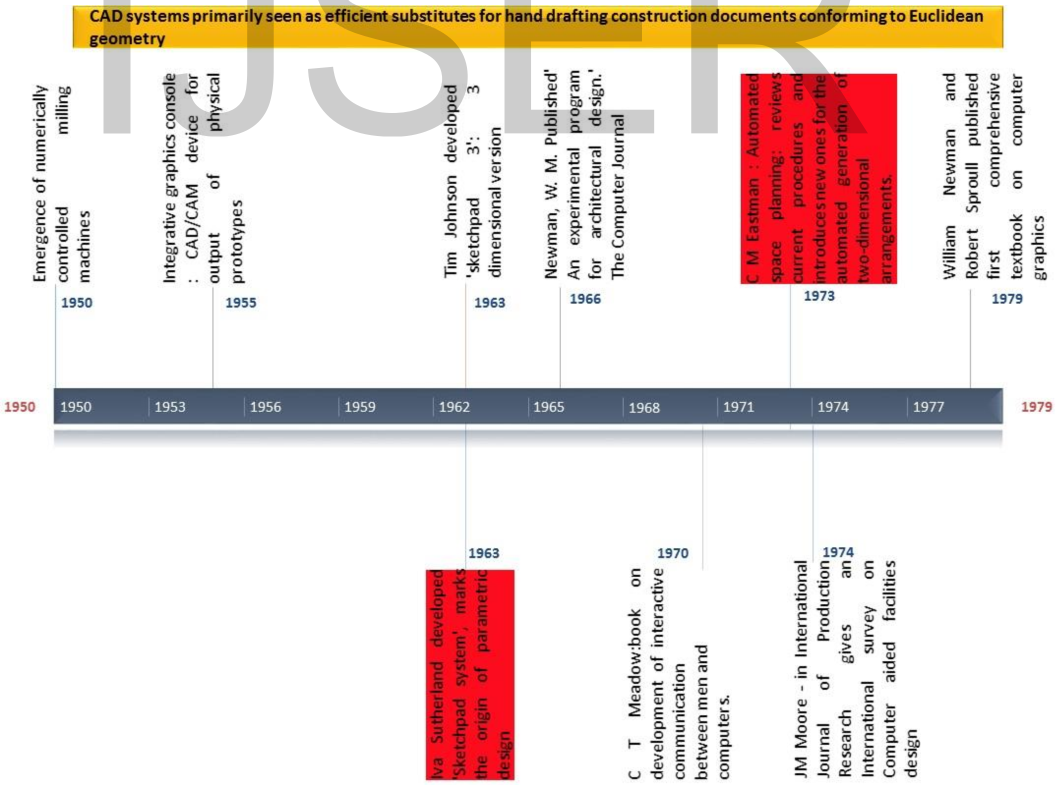
2.1.2 Paper-based (non-digital) interaction

A designer interacts directly with a representation of the design object through a sketch, drawing or a physical model to create his design. It represents the non-digital interaction that is paper based.

 (OXMAN, 2006, P. 245)	 (SCHALLER, 1997, P. 43)
Figure 3:Paper based non-digital model of design	**Figure 4a:Paper based non-digital model of design**

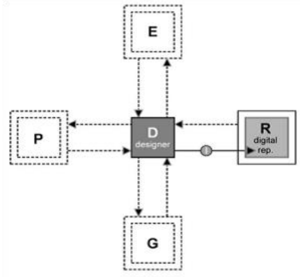
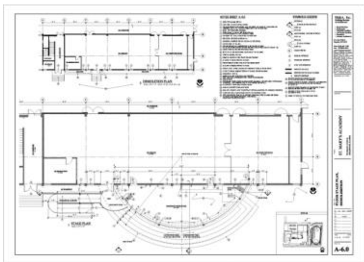
2.1.2.1 **Interaction with digital constructs**

The timeline represents the emergence of CAD systems in architecture its development. The highlights indicate the emergence of automation in the CAD systems. The emergence of numerically controlled milling machines, in the 1950s first motivated interest in the possibility of computer-aided design systems. Origins of parametricism have been expressed by Ivan Sutherland while the development of his system called *Sketchpad*. (SUTHERLAND, 1963)



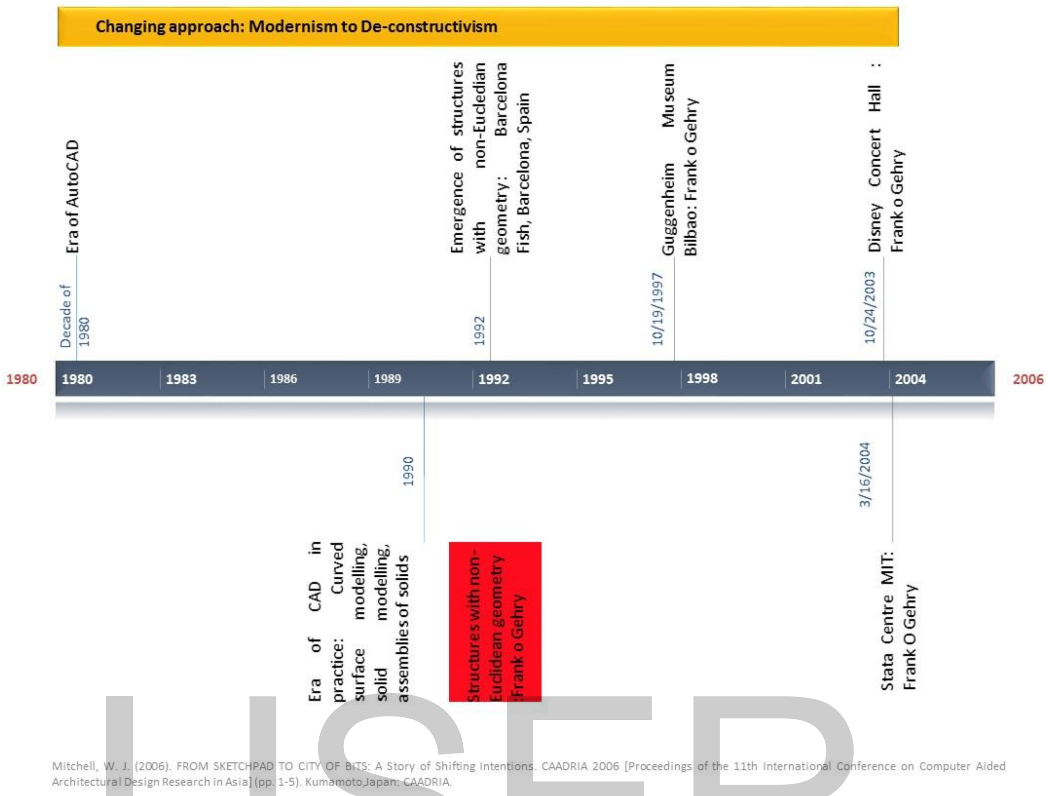
Mitchell, W. J. (2006). FROM SKETCHPAD TO CITY OF BITS: A Story of Shifting Intentions. CAADRIA 2006 [Proceedings of the 11th International Conference on Computer Aided Architectural Design Research in Asia] (pp. 1-5). Kumamoto,Japan: CAADRIA.

This type of interaction as shown in the digital model below is typical of a CAD-based design. In this case, the designer interacts with a digital sketch, digital drawing or the digital model. For example, various geometrical modelling/rendering software. In these models, the designer deals with the geometric structure of priori design objects. These models show a little qualitative effect on design in comparison to conventional models.

	
(OXMAN, 2006, P. 247) **Figure 2a: Traditional CAD models**	(ALEX CANTU:: CD DRAFT, 2014) **Figure 2b: Example of Architectural representation of the model as seen in figure 2a**

2.1.2.2 The era of deconstructivism

The CAD systems of mid-century were based on modernism and had established a characteristic strategy of standardisation and repetition. This development was influenced by the effect of the world war that is to build large scale, inexpensive structures in comparatively less time. William Newman implemented a pioneering system that shifted the focus of CAD from the design of parts to the design of large complex assemblies. (MITCHELL W. J., 2006). CAD systems could develop a long-term connection with the practice as they were perceived as more efficient substitutes for hand drafting. This conception brought in its commercialisation in the form of the software, e.g. AutoCAD. These software had systems based on the Euclidean geometry. Technologies tried to develop beyond the two-dimensional representations i.e. the three-dimensional geometric modelling. It made the systems develop into computer graphics. A close observation of this development suggests that the development was about the representation of the designer's idea. Research studies from outside architecture showed a development into tools for modelling the non-linear, non-Euclidean geometry. Frank Gehry and his team started exploring these systems (e.g. software CATIA) and implemented them in their pathbreaking structures such as Guggenheim Museum Bilbao. This timeline represents the developmental stages of this journey from modernism to deconstructivism.



(MITCHELL W. J., 2006)

Figure 5: Era of CAD

These systems support the efficient design of buildings with curved surfaces and complex, non-repetitive forms. The cost of the building increased right from its design stage and expected more responsibility and entailed more liability on the designers. This eventually led to the emergence of parametric or rule-based design systems and can be explained as;

2.1.2.2.1 Interaction with a digital representation generated by a mechanism

This type of interaction is typical of interacting with *generative design mechanisms*. In this case, the designer interacts with a digital structure that was generated by a mechanism according to a set of predefined rules or relations.

2.1.2.2.2 Interaction with digital environment that generates a digital representation

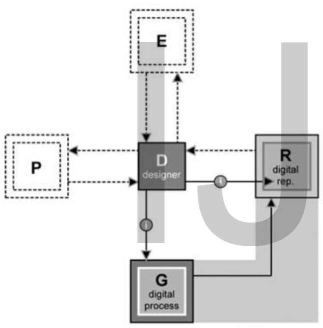
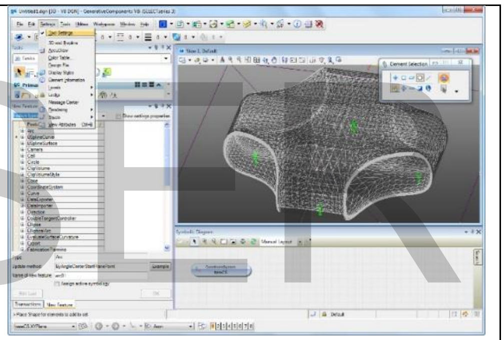
This type of interaction is typical of interacting with the *operative part of a generative design mechanism*. In this case, the designer can interact with the computational mechanism that generates the digital representation.

2.1.2.2.3 A practical generative design method: generation models

These models are characterised by the provision of computational mechanisms for formalised generation processes. The designer interacts with a generative mechanism. Shapes and forms of the design are considered to be a result of pre-formulated generative processes. In this model, the interaction of the designer has a priority.

Interactive module is required to employ generative mechanisms into design

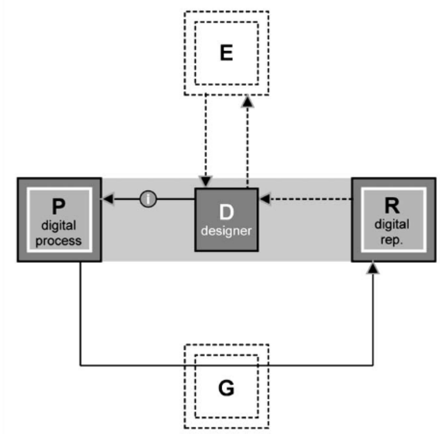
The interactive tool provides the designer the control and choices to guide the selection of desired solutions.

	
(Oxman, 2006, p. 255)	(Google , 2014)
Figure 6:Generation model of design	**Figure 7: Example of its architectural translation**

These systems further developed to address the performance of the built form. The systems when linked to the regional context; interacts, gives feedback, and generates solutions. This development marks the era of online collaboration i.e. the internet. These systems are called as information modelling systems.

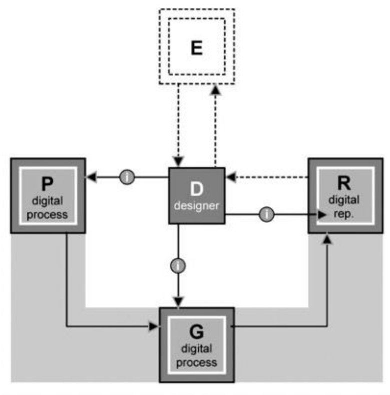
2.1.2.2.4 Performance based models

These design models propose that the object is generated by simulating its performance: e.g. Use of environmental performance techniques to reduce energy consumption: Swiss RE building (2004) by Foster and Partners. Forces in a given context are the design determinants.



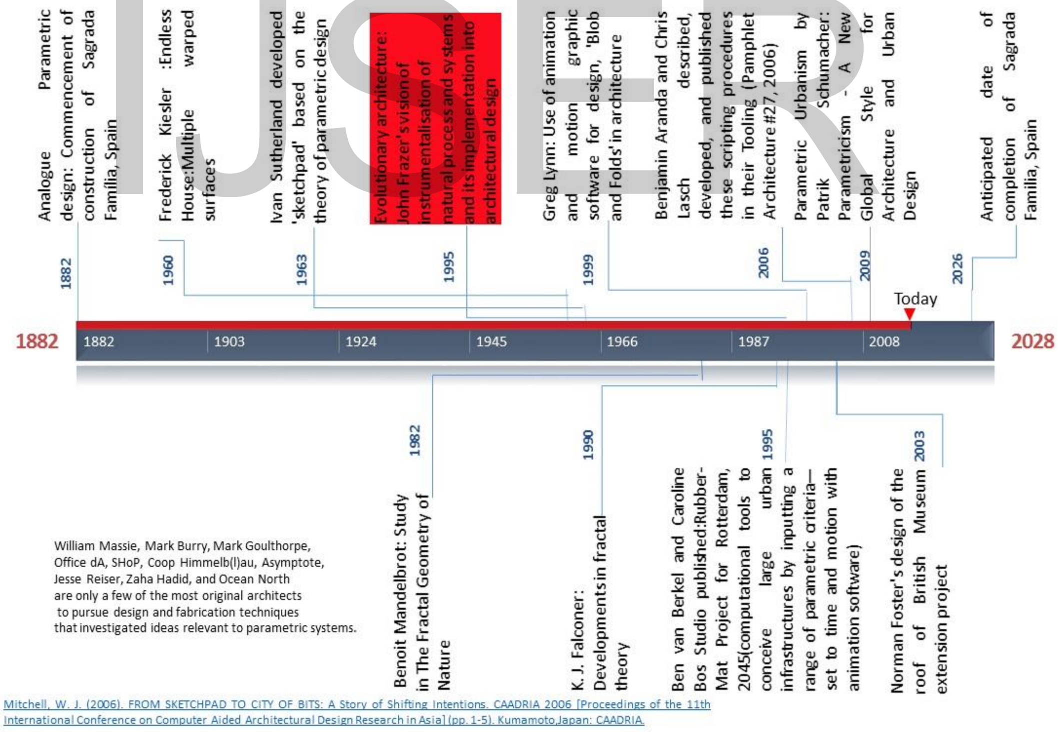
(OXMAN, 2006, P. 258)

Figure 8: Preformance based formation model



(OXMAN, 2006, p. 259)

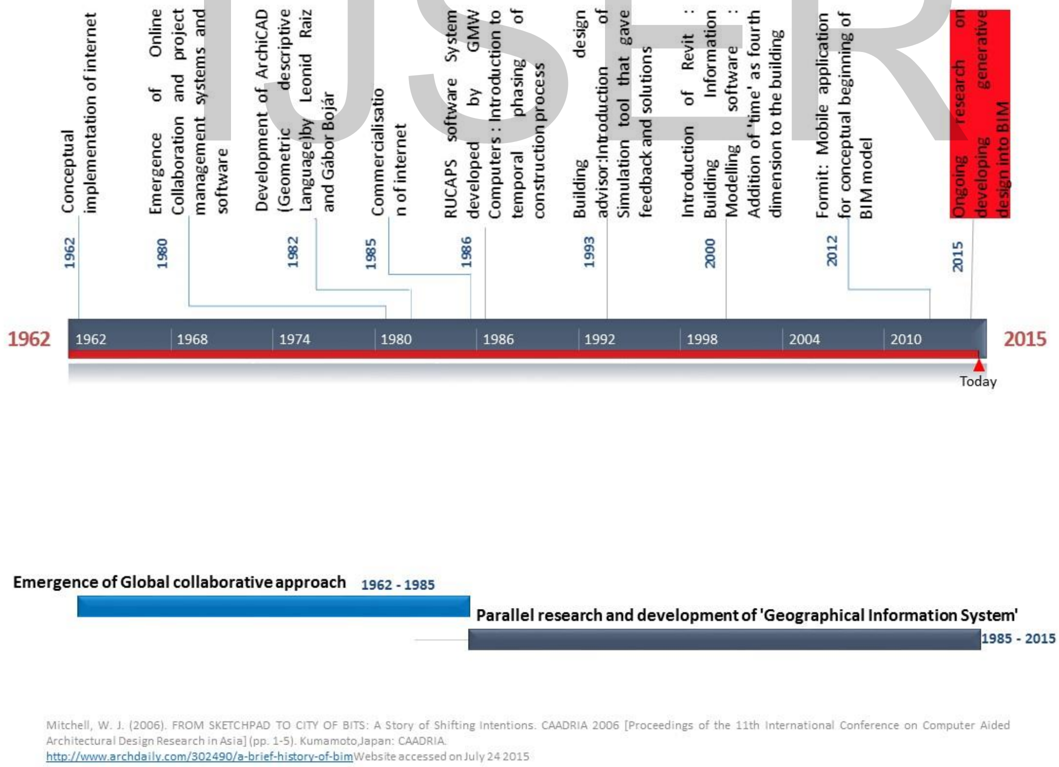
Figure 9: Performance based generation model



(MITCHELL W. J., 2006)

Figure 10: Era of Parametricism

The internet era has contributed majorly to the collaborative culture of business even into architecture. It influenced the architectural design and motivated to develop designs that carry information. The designs and drawings proved to be technically precise and *linked* with all the necessary information. It started percolating even into the structures and termed as *intelligent buildings*. Meaning, they bear automated structural features. The information linked to the drawings included its three-dimensional virtual model along with its structural properties and its two-dimensional representations, developed with the help of skilled architects and designers and termed as Building Information Modelling. The intelligent buildings include automated features e.g. automated artificial lighting for its energy saving. The structures started becoming more dynamic, responsive and interactive. The intelligence of the drawings, designs and built spaces is not limited to its representation, formation or generation. It extends into the *processes of the design* of buildings (*Artificial Intelligence*) and urban design (Geographic Information System) as well.

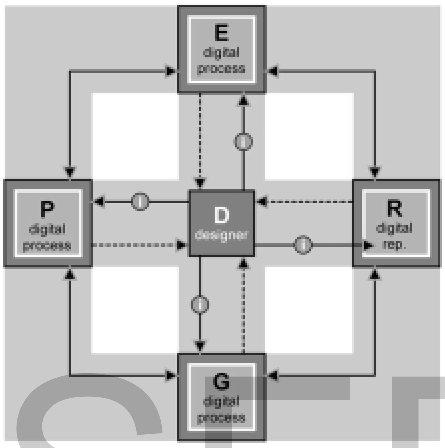


(MITCHELL W. J., 2006) (QUIRK, 2012)

Figure 11: Era of CAD, Communication and Collaboration

2.1.2.3 Compound model of design

This model is a representation of the future implementation of the idea of digital design. This model is based on integrated processes, including; the formation, generation, evaluation and performance. In this model of design, the external influence of forces can be applied for formation; examples of external forces are; structural loads, acoustics, transportation, site, program and information. The major influential characteristic of this model of design is that the digital design *processes* are responsive in character.

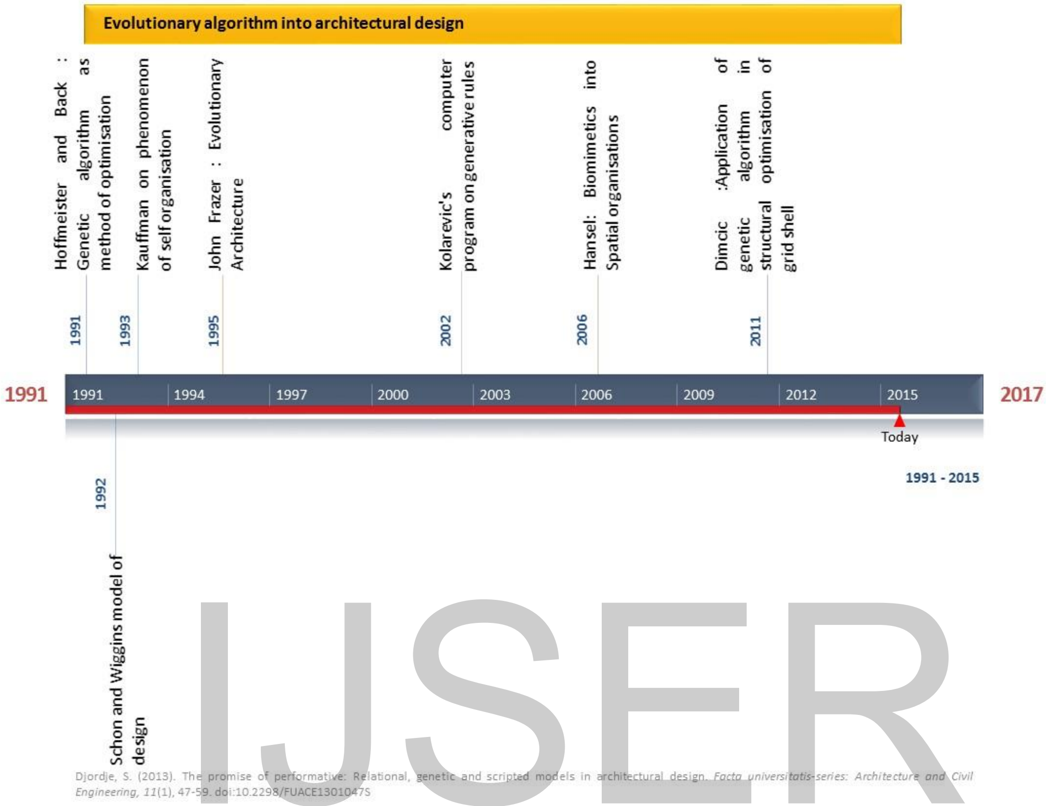


(Oxman, 2006, p. 261)

Figure 12: Compound model

2.1.2.4 AI into architectural design

The above model of digital design proposes a comprehensive approach to optimise or simulate the design at design process level. Another approach to modeling the digital design is to consider design as a problem-solving exercise. Where, all these layers that are labelled as processes are considered as *design problems*. The expected outcome is a logical construct for the design problems. This perspective makes the designer build a mathematical relation between the design concept and the expected outcome of the design. This approach leads the designer to *compute* the mathematical relations in terms of *computable functions*. Development of application of genetic algorithms, primarily in technical problem solving started in the mid-twentieth century. John Frazer explains the concept of possibilities of instrumentalisation of natural processes and systems organisation within the field of architectural design, by applying computer-aided modeling techniques **(Djordje, 2013)**. The timeline below represents the brief history of AI into architectural design.



(DJORDJE, 2013)

Figure 13: Evolutionary algorithm into architectural design

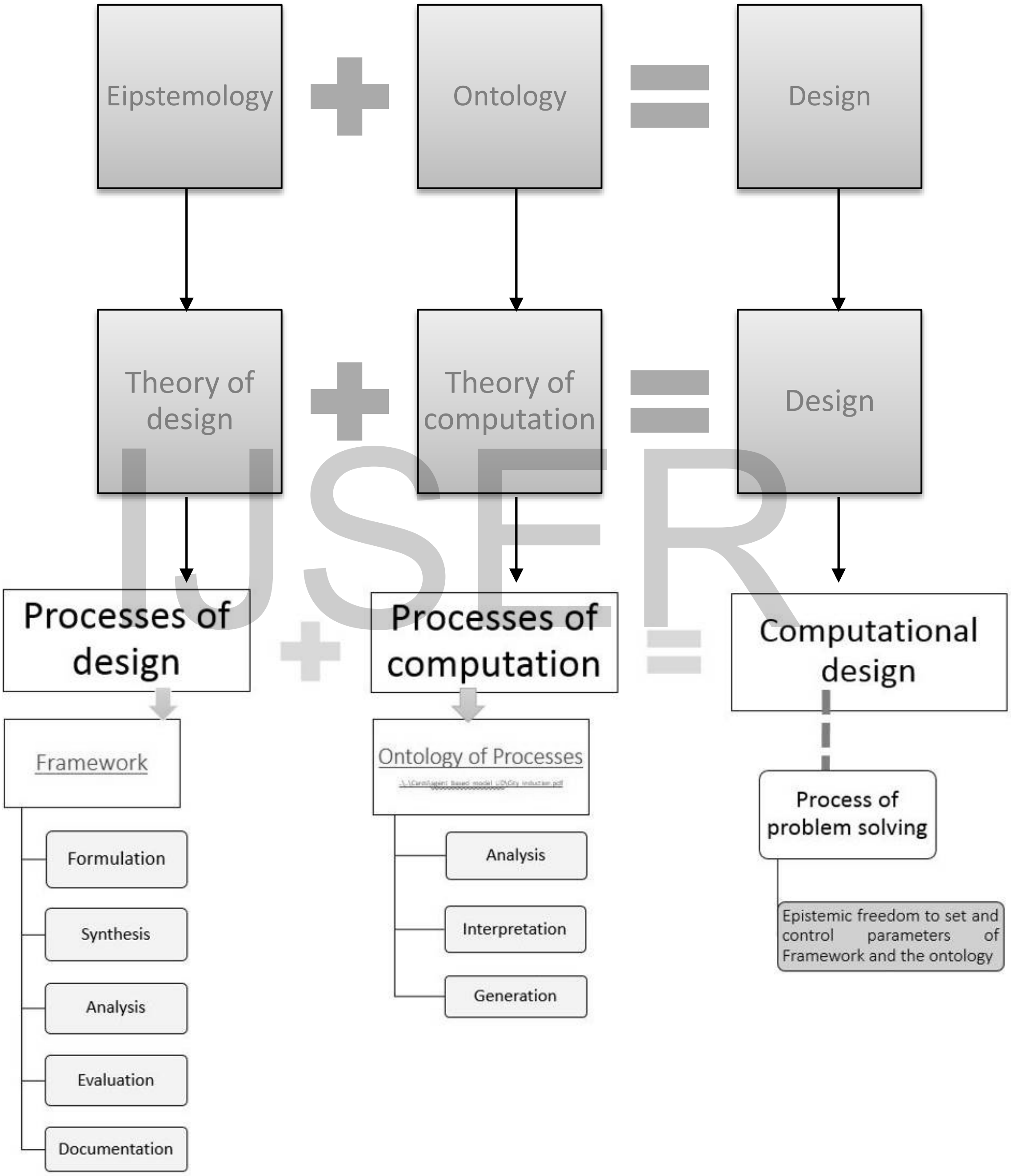
2.1.2.5 **Theory of computation: AI into architectural design: Design as process of problem-solving**

The above study poses a *question* that,

What are the comparable theories of computational intelligence applicable to architectural design?

As an address to the question, the theory of computation is studied in detail and further related to the theory of architectural design.

Design, as a process of problem-solving, is expected to generate visual as well as graphical output. The process includes both methodologies viz; qualitative and quantitative. Qualitative aspect is defined by the designer and it is the epistemological construct. The quantitative aspect is defined by the logical construct, and that is a computable function, controlled by the designer and processed by the computer. The role of the designer is to control the ontology and define the epistemology. Theory of AI is introduced to handle this complexity. As shown in the figure below, this study *defines* the strategy for the proposal of the model of computational design (DESHPANDE, KULKARNI, & UKE, 2014).



(DESHPANDE, KULKARNI, & UKE, 2014) (GERO & KANNENGIESSER, 2004) (LUGER, 2005)

Figure 14: Design as a process of problem-solving

It comprises of the above-listed processes such as; the formulation, synthesis, analysis, evaluation and documentation. The analysis, interpretation and generation will be generated with programming and computation, i.e. with AI. For example, the architectural design includes 3D visualization (with parametric modelling tools) will give generation and interpretation. The drawings are in the form of information, and this information can be translated for optimization (structural analysis, energy analysis and so on).

2.1.2.6 **Identified methodologies (with Literature survey) to solve the design problem**

- Parametric design Methodology: Comprises of algorithms
- Compound model of digital design process: comprises of building information modelling.
- Artificial Intelligence into architectural design

Out of several disciplines of AI, this study focuses on the theory of bio-inspired artificial intelligence (AI) for its application to the architectural design (FRAZER, 1995) (SIMON, 1996). The theory of bio-inspired AI is described in detail in section 3.3 of this report.

As explained in TABLE 1: , epistemology of design is inspired from the theory of architecture. Ontology of design is inspired from the theory of bio-inspired AI to generate three-dimensional and two-dimensional graphics for the architects and designers.

2.1.3 Research Questions

The literature review identifies the remarkable episodes in the history of programming and computation into architectural design. The history comprises of various developments happening simultaneously in the purview of programming and computation into architectural design, thereby, provides an overview of its evolution and Genesis. The analytical models are included in this literature review to co-relate the episodes and their theories. The review of evolution and Genesis poses a question,

1. To identify *comparable theories* of AI to be used significantly in architectural design.
2. What should be the structure of the model of designing?

Architectural design is *stated* as a process of problem-solving, a *strategy* is applied to its model of design. The strategy *is based* on the relation as explained in **TABLE 1**. Similarly, it states the logical construct of non-computable and computable parameters of design and its expected outcome FIGURE 14. This model is intended to be of autonomous mediator type **(MORGAN & MORRISON, 1999)** and will include simulation into its framework. Focus of this study is on Bio-inspired AI to derive its theoretical framework. Bio-inspired AI allows computation with population, mutation, reconfiguration and selection as its fundamental characteristics. As established by Frazer **(FRAZER, 1995)**and Simon **(SIMON, 1996)**, these proved to be effective for architectural design.

3 Building a theoretical framework for the development of AI agent

3.1 Analysis of the case study from the secondary data collection source

The table below explains the analysis of the *case studies* from the secondary data collection sources.

Parameters	*Case study 1* (ALFARIS & RASHAD)	*Case study 2* (SCHUMACHER, 2009)
Formulation of a design problem	a. To achieve design solutions of the massing of the built form b. To achieve a performance-based design solution	a. To constitute a sub-centre on Istanbul's Asian side to release the pressure on the historic centre. i. The site is being reclaimed from industrial estates and is flanked with the small grain fabric of suburban towns. ii. The adjacent context - in particular, the incoming lines of circulation – is an important input for the generation of the urban geometry
Analysis model of computation	Generate and analyse virtual model in virtual environment	Marek Kolodziejczyk, Wool-thread model for optimized detour network
Synthesis of theory of architecture and theory of computation	a. Developing a generative system of loop b. Analysing the generations for qualitative and quantitative aspects. c. Develop Computational model and simulation	Developing Road network using MEL script of Maya

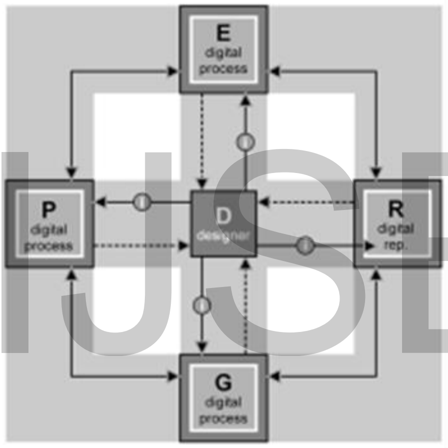
<table>
<tr>
<td>Qualitative Analysis: The epistemological construct</td>
<td>a. Analysis for the massing of the built form
b. Analysis for the thermal comfort of the built form</td>
<td>Frei Otto’s theory of minimising detour network</td>
</tr>
<tr>
<td>Quantitative analysis: Testing on the parameters of Fundamental theory of Architecture</td>
<td>a. Real estate requirement as a parameter of testing
b. Thermal comfort scale as a parameter of testing</td>
<td>a. Global height regulation
b. Correlation of the built-up of height with the lateral width of the overall field</td>
</tr>
<tr>
<td>Model of design : The ontological construct</td>
<td>

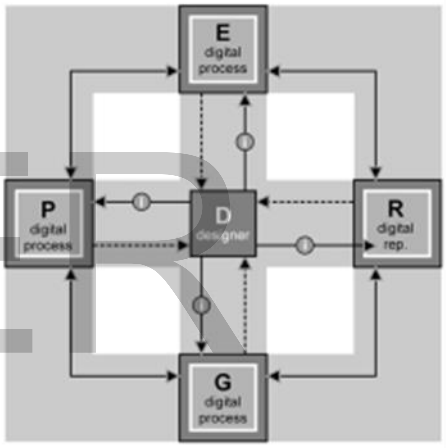
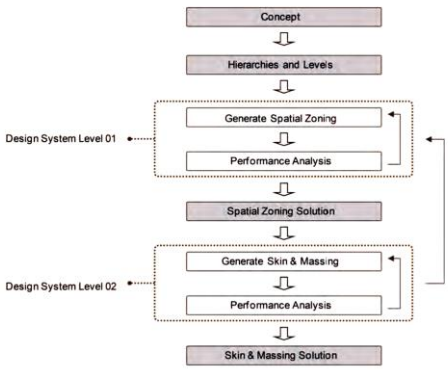
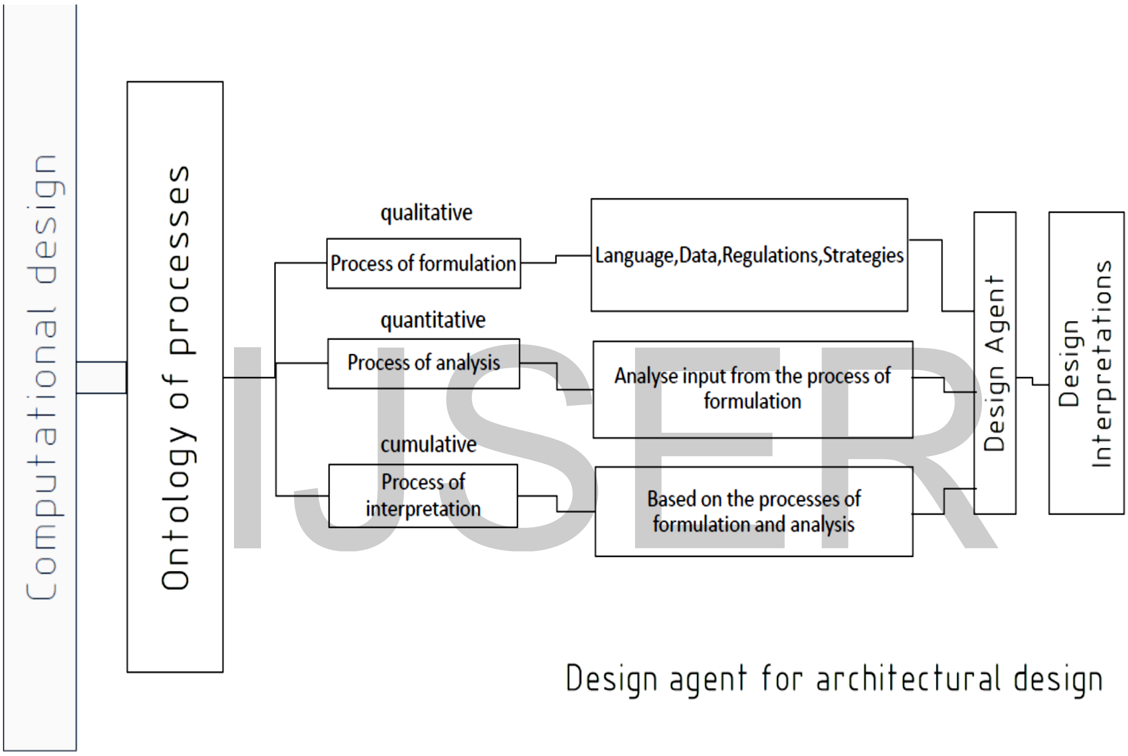
FIGURE 12: COMPOUND MODEL</td>
<td>

FIGURE 12: COMPOUND MODEL</td>
</tr>
<tr>
<td>Process model of computational design</td>
<td>
</td>
<td>a. Developing typologies with parametric design methods
b. Hybrid detour net & deformed grid for developing optimized detour length
c. Global Maya Model: Split block variation model for built form typologies
d. Urban peak indices</td>
</tr>
</table>

Theory of computation	The generative system includes parameters, constraints, rule sets, and algorithms.	Generative component, i.e. genotypes that allows for wide range of pheno-typical variation
Optimisation model	Automation of the process of design for better breeding capabilities and use of more sophisticated analysis tools would offer more robust solutions. (Alfaris & Merello, 2008)	a. Wool-thread model to compute optimised detour path networks b. Morphing :Courtyards morph into internal atria as sites get smaller, and blocks get taller c. Split block variation model for height optimisation based on the relative width
Evaluation model:	*Outputs of generative and analysis system* • The massing analysis evaluates balance proportion and aesthetics. • The real estate analysis re-evaluates the rentable area of the building to gauge the effect and change that occurred due to surface deformations. • The thermal analysis calculates the surface solar intensity and the effect of deformation on it. Finally, the structural system is evaluated based on an estimate of construction cost and complexity generated by surface deformations	a. Maya's (MEL script) hair dynamic tool achieved a parametrically tuned bundling of the incoming paths into larger roads enclosing larger sites. b. Depending on the adjustable parameter of the thread's sur-length, the apparatus – through the fusion of threads – computes a solution that significantly reduces the overall length of the path system while maintaining a low average detour factor c. Scripting for calligraphy block patterns that configure the perimeter blocks depending on parcel size, proportion and orientation

3.2 Identification of existing fundamental theory of AI into architectural designing based on secondary source of data collection

As mentioned earlier this study *aims* at developing a theoretical framework for the design of an AI agent, and this model of designing is derived from the theory of architecture and theory of computation. This way it is an *autonomous mediator model based on interdisciplinary theoretical foundation*. The conceptual framework is explained as follows.



(DESHPANDE, KULKARNI, & UKE, 2014)

Figure 15: Conceptual Framework for an AI agent

As discussed above **RESEARCH QUESTIONS**, this study *proposes* that the cumulative aspect of interpretation **FIGURE 15**, to be based on the theory of bio-inspired AI. Bio-inspired AI has its scope spread out to a great extent. To develop the theoretical foundation, this study describes properties and characteristics of all the identified theories, and co-relation of their respective natural models of computation and artificial models of computation.

3.3 Theory of Bio-inspired artificial intelligence

There are seven systems of bio-inspired artificial intelligence studied so far, (FLOREANO & MATTIUSSI, 2008)

i. Evolutionary systems
ii. Cellular Systems
iii. Neural systems
iv. Developmental systems
v. Immune Systems
vi. Behavioural Systems
vii. Collective systems

This section focuses on the first four systems for their extensive applications into architectural designing and relates them to the computational models of intelligence. Each section states their respective architectural applications to provide an overview.

3.3.1 Comparative study of biological systems of computation

This comparison gives an overview of the theories mentioned above and understanding their relation to computation. The discussion is followed by a descriptive explanation of these theories. Further, each theory is related to its respective computational algorithms and their architectural applications.

Table 3: Overview of Biological systems of computation

Parameters of comparison	Biological systems of computation (FLOREANO & MATTIUSSI, 2008)			
	Evolutionary systems	Neural Networks	Cellular systems	Developmental systems
Fundamental characteristics	No pre-defined goal	System of neurons develops a *network of communication*	Single cell considered as a component	Study of multi-cellular organism= assemblies of cells organised in very complex structures.

	Essentially an *open-ended adaptation process*	*Receive signal* from the environment and *respond to the signals*	In a multicellular system, even though the cells contain the same genetic material, the morphology and function of two cells show significant difference	Complex assemblies of cells require very efficient co-ordination and functionality
	Its *reproductive* success defines fitness of an individual	Neurons *learn* when exposed to various environments	Although composed of many copies of a cell, it produces a global behaviour and pattern	Cells form patterns of organised activity in space and time using a variety of mechanism.
	Shows *diversity and creativity*	Show *Self-organisation* as their characteristic	Global behaviour and pattern emerge through the non-linear communication of the unit cells	Zygote, i.e. the fertilised egg contains genome. The genome has a set of instructions to steer the process of self-organised construction of the organism.
Translated Computable processes	Processes of natural evolution are robust,	Processes show characteristics i. of *adaptation(learning)* on	Processes of evolution constitute the complex rules and	Zygote and genome constitute a *developmental*

	complex and adaptive.	evolution i. *Transmission* of adapted characteristics to offspring	interactions of the biological cells of the biological cellular tissues. For example *Cellular Automata*	*representation* of the organism
	The processes are based on the pillars of evolution, namely, *population, diversity, heredity and selection e.g. Evolutionary Algorithm* (HOLLAND J. , 1975)			Show property of *scalability*[1]
Models of computation	i. Phenotype (DARWIN, 1964) i. Genetic representation	Neural networks	Cellular Automaton (SAKODA, 1971)	i. Model of rewriting system i. Model of *Evolutionary developmental system*

3.4 Evolutionary systems

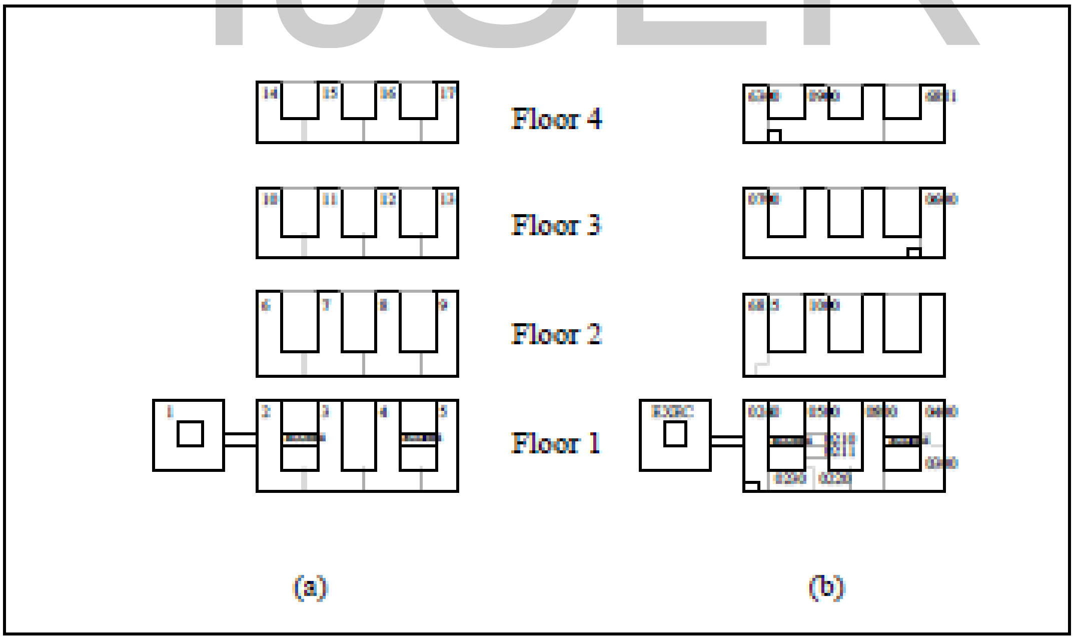
All biological systems result from an evolutionary process. More than 40 years ago, computer scientists and engineers began developing algorithms inspired by natural evolution (Rechenberg, 1965) (Fogel, Owens, & Walsh, 1966) (Holland J. H., 1975). The algorithms were developed to generate solutions to the problems that were tough

[1] Scalability is related to the fact that developmental process is a self-organised and distributed process whose activity is decentralised and characterised by parallel operation of its constitution.

to handle with any other analytical methods. Evolutionary systems apply to a wide spectrum namely; machine learning, system optimisation, computer assisted manufacturing, hardware design, material production technologies and robotics.

3.4.1 Application of Evolutionary digital design

One of the studies (Jo & Gero, 1998)show the construction of a genetic/evolutionary *model of designing* is based on the natural genetics. This study could find two major issues that, how to represent design knowledge for the evolutionary design model and usefulness of the model for design problems. For the representation of design knowledge in the model, similar to the theory of computation, a schema concept was introduced. The utility of the model is based on its computational efficiency and its capability of producing satisfactory solutions for the given set of problem requirements. Thus, using a combined approach of open-ended evolution (Viability evolution) (Mattiussi & Floreano, 2005) and SAGA (Harvey, 1992)(species adaptation genetic algorithm). This design model was demonstrated for office layout planning problem with the associated topological and geometrical arrangements of space elements.



(JO & GERO, 1998)

Figure 16(a): The data defining zones for the office layout problem (b) The solution produced by Liggett's system

3.5 Cellular systems

In the natural cellular systems, simplest kind of systems that we can consider as living are biological cells (Harold, 2001)even though they are quite complex. The most complex forms of life are multicellular organisms, that is, structured assemblies of cells. In a multicellular system, even though the cells contain the same genetic material, the morphology and function of two cells show a significant difference. These systems show properties such as the system is composed of many simple units that interact non-linearly and unexpected global behaviours, and patterns can emerge from the interaction of many such systems that communicate only locally. In a multicellular organism, almost all cells contain the same genetic material, and yet the morphology and function of two cells can be strikingly different. The difference can be scientifically explained as, the state of each cell depends not only on its genetic material but also on the state of the cell when it was generated and on the influences that acted on the cell from the moment onward. So, a multicellular system, even though composed of many copies of a fundamental unit-the cell- produces a global behaviour. (Floreano & Mattiussi, 2008)

3.5.1 The abstract cellular system

To capture the essence of the properties that the multicellular systems show one should focus only on those models whose fundamental units are very simple, much simpler than the biological cells. *(Floreano & Mattiussi, 2008)* The basic constituents that are required to define such models are;

i. Cell and cellular space

The collection of cells in the system is called the cellular space. In the abstraction of a cellular tissue, the collection of cells become a discrete cellular space.

ii. Neighbourhood(local space)

Neighbourhood is a set of cells (including the cell itself) whose state can directly influence the future state of the cell.

iii. Cell state

The state of a cell represents the information specifying the current condition of the cell and it is the memory of what happened to the cell in the past.

iv. Transition rule

This/these is defined by following guidelines;

a. State transition function
b. Boundary conditions
c. Initial conditions
d. Stopping conditions

3.5.2 Cellular Automata

The simplest and most popular kind of cellular system containing all the constituents is the cellular automaton (CA). The name CA is derived from the mathematical concept of automaton.It is a discrete system with a finite set of inputs I, a finite set of states S, a finite set of outputs O, a state transition function φ and output function η which gives current output as a function of the current state. This way, each automaton that issues its state as output and input for it is the output of the neighbourhood cell. Modelling with a cellular system is expressed as the following sequence;

a. Assign the cellular space
b. Assign the time variable
c. Assign the neighbourhood
d. Assign the state set
e. Assign the transition rule
f. Assign the boundary conditions
g. Assign the initial condition
h. Assign a stopping condition
i. Proceed to update the state of the cells until the stopping condition is met.

The activity of a CA is observed with the help of a space-time diagram (or space-time plot).

3.5.2.1 Application of Cellular models: Agent-based models

Classic work of Sakoda (Sakoda, 1971) formulated a model where a population of agents belonging to two distinct classes of society are distributed on a two-dimensional cellular space. Another application of the agent-based model of CA is used to understand the social dynamics. (Hegselmann & Flache, 1998).Another Application of Agent-based modelling includes understanding the residential behaviour of humans. (Benenson, 2004).Another remarkable example can be the agent-based model to understand the computational sociology, based on *sugarscape system*. (EPSTEIN & AXTELL, 1996).Development of Agent-based models (ABM) to achieve a comprehensive view of urban dynamics is seen in *Batty's work*. Batty begins with models based on cellular automata (CA), simulating urban dynamics through the local actions of automata. He then introduces agent-based models (ABM), in which agents are mobile and move between locations. (BATTY, 2007)

3.6 Neural Systems

This study is an overview of the salient principles and mechanisms of biological neural systems and how are those elements modelled with artificial neural networks. (FLOREANO & MATTIUSSI, 2008, P. 166)

3.6.1 Biological neural system

To understand the potential advantage of a neural system for an animal or machine, we can compare with some of the single cellular animals e.g. Paramecium, who do not have neurons. They can perform many functions necessary for their existence, by means of chemical processes and electric potential across their membrane. Even a multicellular organism e.g. sponge can regulate their behaviour with the help of chemical processes. If we try to understand the advantages of the neural system, we can find the following features;

a. Selective transmission of signals across distant areas
b. Complex adaptations give survival in changing environments

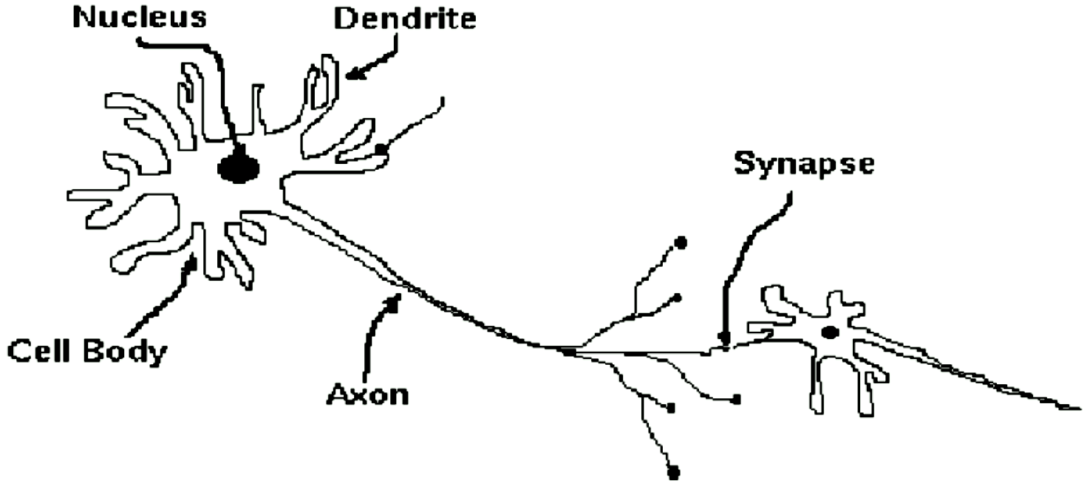
The basic building blocks of biological neural systems are nerve cells, called neurons. A neuron is made up of cell body – dendrite and an axon. The interconnection of the axon of one neuron and dendrite of another neuron is called a *synapse*. Signals propagate from dendrites, through cell body to the axon; from where the signals propagate to all connected dendrites. A cell *fires* means a signal is transmitted to the axon of a neuron. The function of a neuron is to inhibit or excite a signal. (ENGELBRECHT, 2007, P. 6)

3.6.1.1 Neural communication

There are hypothetical theories on neural communications (FLOREANO & MATTIUSSI, 2008, PP. 170-171), such as,

a. Firing rate

b. Firing time
c. Direct connections



d. Long-range neuro-transmitters

(ENGELBRECHT, 2007, P. 6)

Figure 17: A Biological Neuron

3.6.1.2 Neural Typology

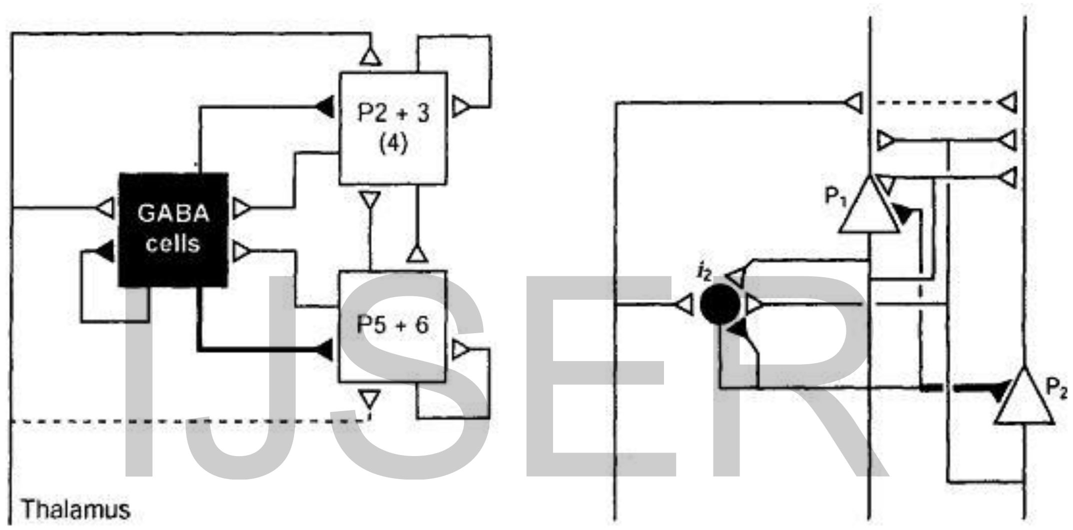
Neurons are classified based on their functions as follows; (FLOREANO & MATTIUSSI, 2008, PP. 169-170)

a. Excitatory: Establish synaptic connections that tend to increase the activation of postsynaptic neurons.
b. Inhibitory: Establish synaptic connections that tend to decrease or block the activation of postsynaptic neurons.
c. Sensory: Peripheral cells that have an input detector- exposed to environment and output connection – to diverge to make contact with several other neurons or effectors (muscle cells).
d. Motor: Peripheral cells –send signals directly to other neighbouring motor neurons.
e. Interneurons: Neural cells that establish connections with other neurons, but, not directly connected to the environment.

3.6.1.3 Neural topology

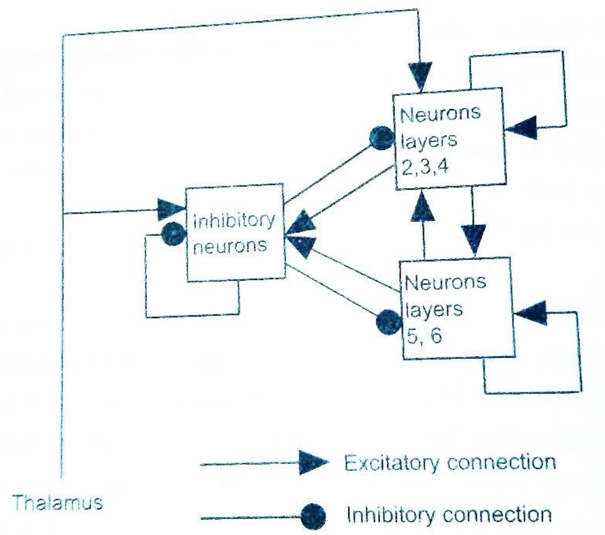
Neural systems display regular architectural patterns generated during the process of cellular growth. Most of the neurons receive connections from, and project to, neighbouring neurons. (FLOREANO & MATTIUSSI, 2008, P. 171) This architectural feature has three consequences;

a. Neighbouring neurons respond to neighbouring sensors
b. Neighbouring neurons respond to similar patterns of simulation
c. Nervous systems are organised in local circuits of specific patterns of connectivity.



(DOUGLAS & MARTIN, 1990)

Figure 18: The canonical cortical circuit: characterises essential organisation of a brain region



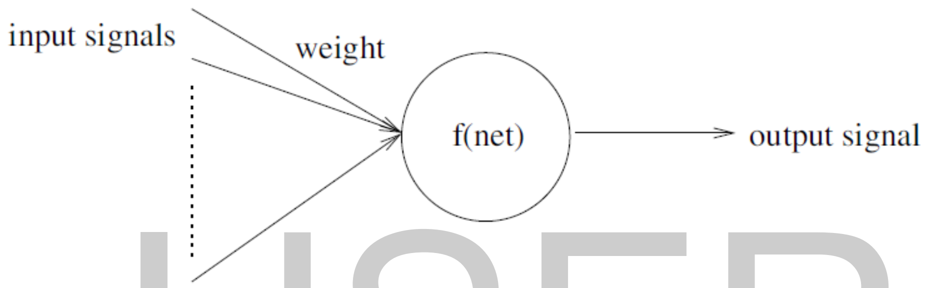
(FLOREANO & MATTIUSSI, 2008, P. 172)

Figure 19: Interpretation of the canonical cortical circuit. Numbers within the blocks are the layers of cortex: 2, 3, 4 are closer to the skull and layers 5, 6 are closer to the centre of brain

3.6.1.4 Artificial Neural Networks

Researchers from many scientific disciplines are designing artificial neural networks (ANNs) to solve a variety of problems in pattern recognition, prediction, optimization, associative memory, and control.

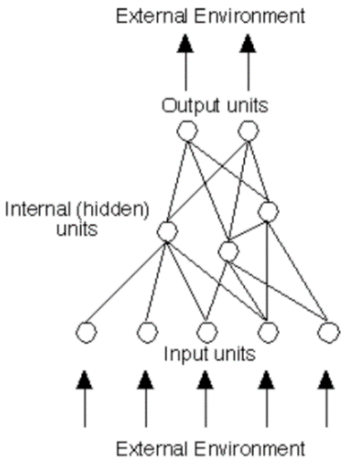
An artificial neuron is a model of a biological neuron. Its function is to receive a signal from the environment, or other neurons, gather these signals and when fired, transmit a signal to all connected artificial neuron.



(ENGELBRECHT, 2007, P. 6)

Figure 20: Representation of an artificial neuron

The input signals are inhibited or excited through negative and positive numerical weights associated with each connection to the neuron. The firing of an artificial neuron and the strength of the exiting signal are controlled by a function called as activation function. The neuron collects all the incoming signals and computed a net signal as a function of the respective weights. The net input signal serves as input to the activation function that calculates the output of the artificial neuron.

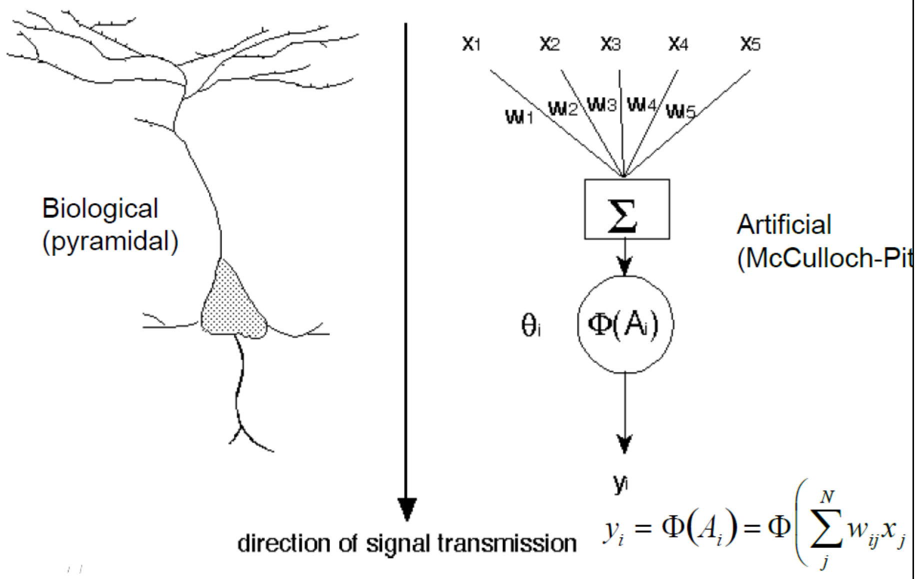


(FLOREANO & MATTIUSSI, 2008, P. 176)

Figure 21: Artificial neural network architecture

Table 2: Comparison of biological neural network and artificial neural network

Function based on sending signals	Biological neurons are either inhibitory or excitatory and have the same effect on all neurons that they send signals to	Artificial neurons can emit both negative and positive signals, and thus the same neuron can establish both negative and positive synaptic connections, because a. AN are mathematical objects that are not constrained by the physiological properties biological neurons for the same functionality. b. Artificial neuron often models the average response of a population of biological neurons, which may include both excitatory and inhibitory neurons.

<table>
<tr><td>Diagrammatic representation</td><td colspan="2">

(Floreano & Mattiussi, 2008, p. 178)

Figure 22Biological and artificial neural networks</td></tr>
<tr><td>Learning</td><td>Learn by modification of synaptic strengths when presented with simulation from the environment</td><td>Learning consists of adjusting weights values and threshold values until a certain criterion (or several criteria) is (are) satisfied. There are three main types of learning
a. Supervised learning
b. Unsupervised learning
c. Reinforcement learning</td></tr>
<tr><td>Self organisation</td><td>Kohonen model (Kohonen, 1989) and Hebbian (Hebb, 1949, p. 62)learning model can develop topological maps of the sensory space, like those found in the cortex of mammals.</td><td>The phenomenon, when adapted into the computation model, is called as self-organising maps.</td></tr>
</table>

Table 3: Comparison of neural networks and symbolic AI

The comparison (Barnden, 1995) based on the work done by Barnden.

Advantages	Neural Networks	AI
Graceful degradation	Degrade gracefully when it can tolerate significant corruption of its inputs or internal working.	Tend not to degrade gracefully. A small corruption of an input data structure is likely to make it fail to match the precise form expected by the rules.Finally, they fail totally to be enabled. Alternatively, other rules might erroneously be enabled. Minor damage to a rule can have a vast effects on the system operation.
Pattern completion	An incomplete pattern is filled out to become a complete pattern somewhere in the network	
Similarity-based generalisation	The similarity of representations induces similarity of processing more readily than AI. It is called as automatic similarity-based generalisation.	There is a higher degree of naturally achievable continuity in the mapping of inputs to outputs. Previously unseen blends of different representations will naturally tend to lead to processing
	More sensitive to subtle contextual effects	
	Can have more emergent rule-like behaviour	
	Facilitates soft constraint satisfaction. i.e.	Symbolic framework of AI provides no special support for soft constraint satisfaction
Symbolic		Better than NN at encoding

Framework		and manipulating the complex, dynamic structures of information that cognition requires.
Support to the degree of confidence	Supports confidence levels in a natural way	The computations have to be specially and explicitly designed

3.6.1.5 Artificial neural networks in architecture

Research studies into applications of artificial neural networks into architecture and design show a wide range, few of them are as below; (GERO, 2014)

a. Constraint-based reasoning
b. Case-based reasoning
c. Learning
d. Data representation
e. Non-monotonic reasoning
f. AI into design
g. Computational models of creative design processes (GERO, 1994)
h. Application of PDP (parallel distributed processing) to simple spatial reasoning in computer-aided design (COYNE & POSTMUS, 1990)

3.7 Developmental Systems

The natural/biological developmental systems is a study of multicellular organisms. Multicellular organisms are assemblies of cells organised in very complex structures that require very efficient coordination and functionality. The assembly is constructed with the process of development. The developmental process starts from a single cell and builds progressively to form a complete organism. All the details are not explored in this area of Developmental process that builds biological organisms, but many aspects have been already elucidated. (TICKLE, 2011)

To build the final structure, cells form patterns of organised activity in both, space and time, using a variety of mechanisms. These mechanisms include the exchange of signals between cells, the reactivity of cells to environmental conditions, and the ability of cells to grow, divide, die, and migrate and differentiate.

All these activities are influenced by a genome and by the initial state of the zygote (the fertilised egg). The concentration and distribution of chemicals determine the initial steps of the developmental process. The zygote does not contain a blueprint of the developed organism but the instructions that, in a suitable environment, steer the process of self-organised construction of the organism.

The zygote and its genome constitute a developmental representation of the organism.

3.7.1 Advantages of a developmental representation

A developmental representation provides the possibility of defining a compact description of potentially very complex structures.

The biological evidence shows that a developmental representation permits the definition of structures possessing a certain degree of modularity and symmetry. Developmental representations can have good properties of scalability. A Developmental process is a self-organised and distributed process whose activity is decentralised and characterised by parallel operation of its constituents. The biological evidence suggests that significant changes in the size and structure of the outcome of the developmental process can be achieved with minimal changes in the developmental description.

Summary: A developmental representation for a system has favourable properties such as compactness, scalability, self-organisation, robustness, adaptability, evolvability, fault tolerance, and self-repair.

3.7.2 Genetically instructed developmental process

These systems bear greater evolvability with respect to more rigid genetic descriptions.

The processes that structure a multicellular organism are most apparent in the first stages of the organism’s life, this phase is called its ‘embryonic phase’. It should be noted that these processes are not completely and suddenly disabled once the overall structure of an organism is in place but, rather, continue to some extent during the whole life of the organism. The developmental processes observed in biological organisms are self-limiting, that they subside as soon as the required structure is built, with the possibility of reactivation if the need arises.

3.7.3 Advantages and challenges

This section includes explanation of advantages and challenges of the developmental processes

Advantages

- The Developmental processes are a powerful tool for the description and synthesis of complex artificial systems
- Scalability is achieved with the help of possibility of reuse of substructures and modules
- More complex structures do not require a correspondingly complex developmental description
- In case of absence of some clue (information) concerning basic developmental mechanism, can be obtained, from a recursive definition of a geometric object.
- Important source of inspiration for the definition of artificial developmental systems
- Artificial evolution can provide a powerful tool for the exploration of the space of the combinations of these building blocks

Challenges

- The indirect and less transparent relation between the description and the resulting system can create difficulty in the definition of a developmental system producing a given result.
- Multiplicity of mechanisms at work poses a significant difficulty in the choice and combination of the basic elements
- A better understanding of the role of elements and the integration of the elements and some of the guiding principles are required beforehand for this system to develop as building blocks.

The challenges of this system can be answered by combining the phenomenon of evolution and development.

3.7.4 Artificial developmental system

It is the combination of developmental representation and the rules that specify how the representation must be interpreted to build the artificial system.

Examples of these systems can be; artificial developmental systems inspired by the processes of lifetime adaptation, learning and regeneration of biological organisms.

This theory includes following tasks:

a. Rewriting the systems: e.g. L-systems

b. Evolutionary developmental system: Studies about the role of development in the generation of the selectable variation of the organisms, through the action of natural selection, to the generation of evolutionary changes in phenotypes (MDE, 2008) (WAGNER, 2001) (WAGNER & LARSON , 2003) (COYNE & POSTMUS, 1990)

3.8 Contribution to the research

i. Identification of comparable theories of Bio-inspired AI for the autonomous mediator.

ii. Relation of a compound model of digital design FIGURE 12: Compound model and the computational design process FIGURE 14.

iii. Three experiments based on various models of designing with respect to programming and computation.

iv. A conceptual framework of AI FIGURE 15: CONCEPTUAL FRAMEWORK FOR AN AI agent and its relation to the Evolutionary-developmental model of computation 3.7.4.

v. Development of the autonomous mediator model of designing.

4 Autonomous mediator model of design

4.1 Identification of the research gap based on the analyses explained in SECTION 3.1 AND 3.2 THROUGH 3.7.4

Based on the visionary concept of John Frazer **(FRAZER, 1995)**, this study proposes an *analogy of bio-inspired artificial intelligence and architectural design.* The fundamental consideration here is that *design is a process of problem-solving* where, it *integrates* the fundamental processes of designing and computation. Setting up a *framework for design* provides the *epistemological construct* and *design ontology* will provide the *quantitative aspect*.

This section primarily explains the theoretical framework and stepwise development of a generic model of design.

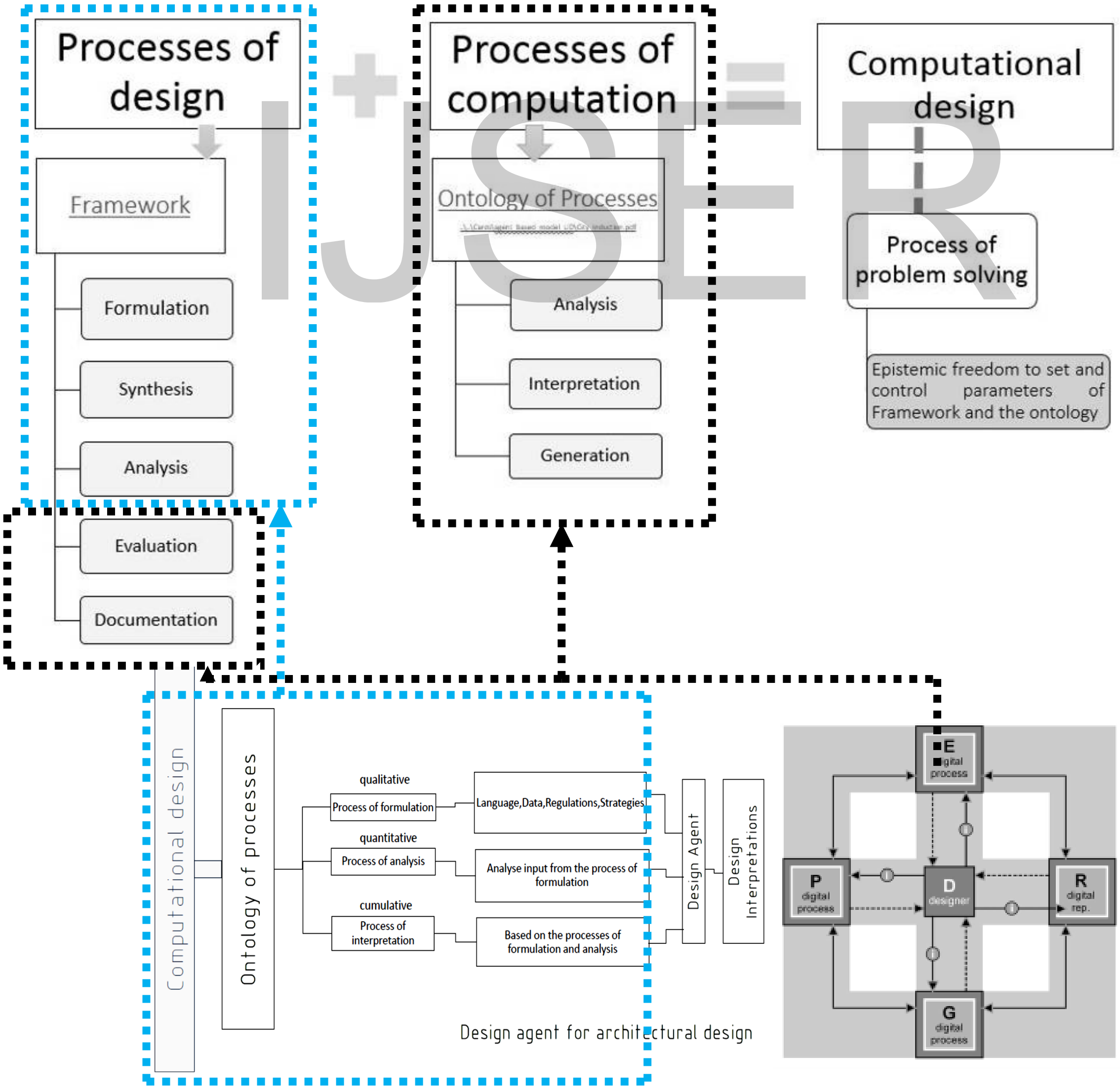


Figure 23: Research Gap

The proposed autonomous mediator will simplify all these processes. Based on the above-identified theories, this study formulates the autonomous mediator as *the combination of AI agent of the Evolutionary-developmental system to the process of computation and AI agent of learning to the design framework.*

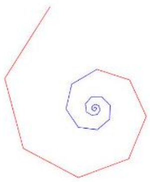
4.2 Primary source of data collection: Experiments and observations

Several experiments were carried out to observe *applicability of design framework and compound model in the regional context.* Out of which, results and observations of three experiments are explained here.

4.2.1 Experiment 1: Master layout of a residential township

Processes of design, i.e., epistemology is a designer's sketch. Ontology using an algorithm is developed to translate the sketch into a digital expression. Evaluated by a group of professionals and regenerated with digital tools for its execution. The process is represented as follows and the entire study can be referred from

APPENDIX 2

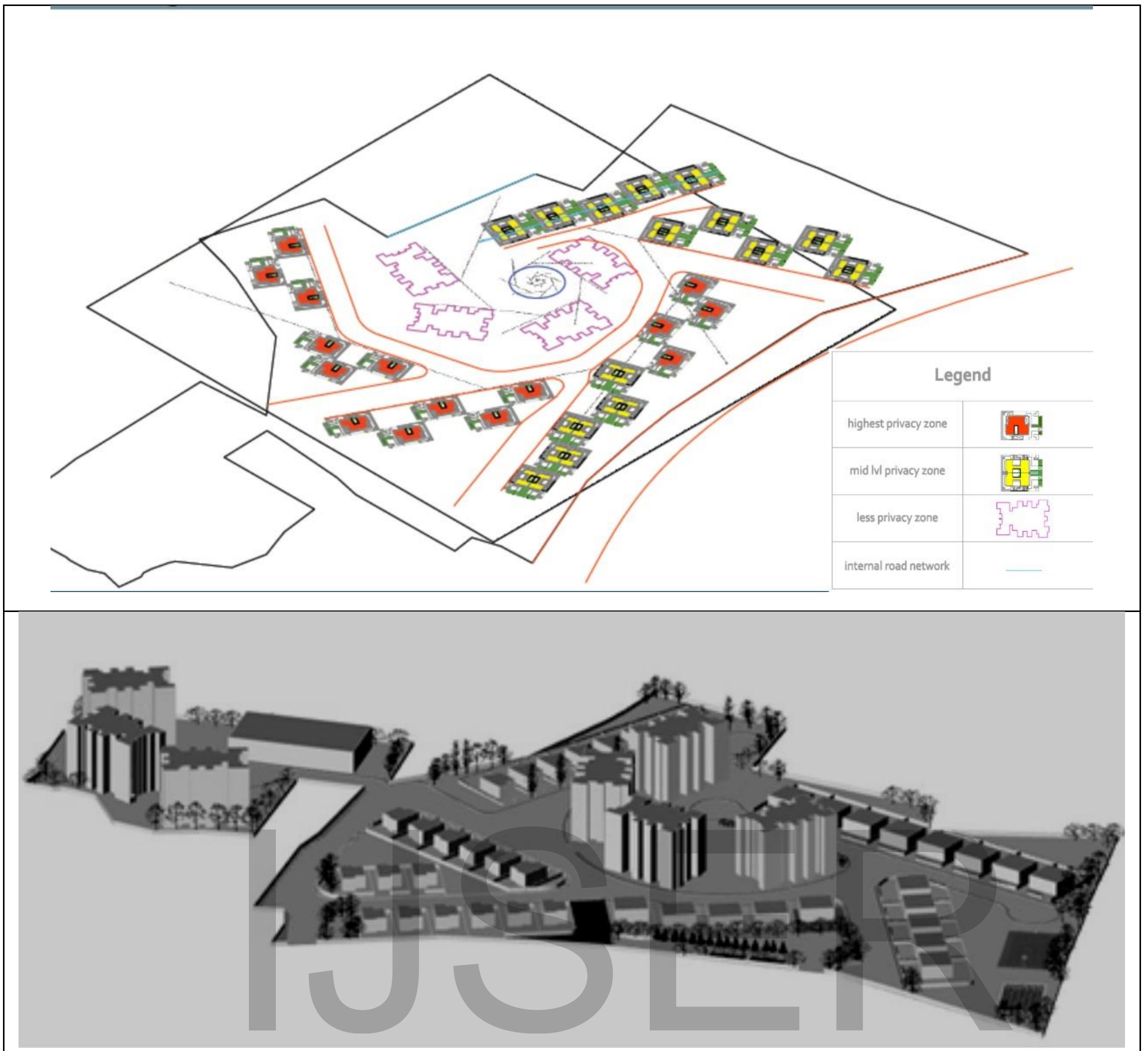


```
float theta;
int j;

void setup() {
  size(800, 600);
  smooth();
}

void draw() {
  background(255);
  frameRate(30);
  stroke(100);
  // Let's pick an angle 0 to 90 degrees based on the mouse position
  float a = 47.5;
  // Convert it to radians
  theta = radians(a);
  // Start the tree from the centre of the screen
  translate(width/2,height/2);
  // Start the recursive branching!
  branch(2);
//start with value of 2, this value will be incremented based on fibonacci ratic
}

void branch(float h) {
  j=0;
  // counter to keep count of pushes to stack
  color bung = color(#FF0000);  //color for bungalow
  color apt = color(#0000FF);  //color for apartment
  //here, ours is when the length of the branch is 200 pixels or less
  while (h<200)  //setting 200 as the exit condition
```



Ontological construct

Use of mathematical proportions of mollusc structure to generate algorithm
Use of algorithm to remodel the form to develop pattern
Consider three major planning requirements: Circulation, Privacy zones and Green Spaces
Design proposes application for one such iteration of Algorithm , the process will go on for infinite number of iterations

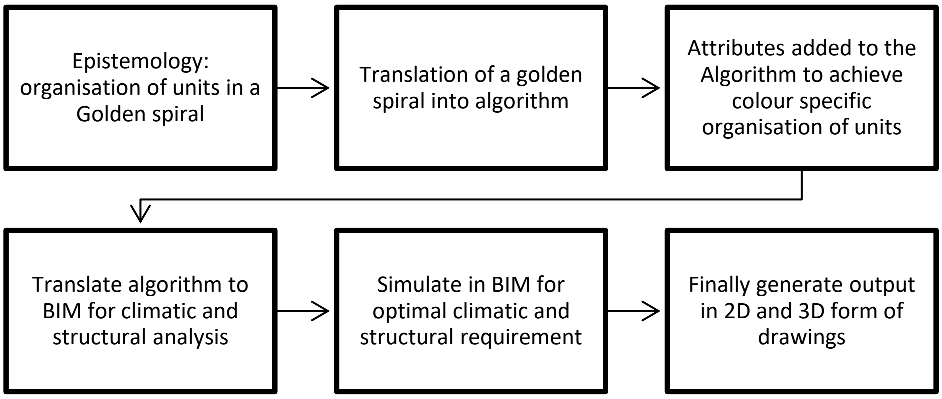


Figure 24: Experiment 1: Flowchart

4.2.1.1 **Observations in the form of Advantages and limitations Advantages**

The designer defines the non-computable parameters of design, i.e. its epistemology in terms of his sketch and then it is represented in terms of an algorithm, i.e. its ontology.

Advantages

a. The algorithm for translation gives various alternatives thereby reduces time and reworking.
b. The expected outcome is achieved through modifications in just the algorithm.
c. Any number of design alternatives is achievable
d. The designer has a freedom to select the best suitable alternative
e. The output of this algorithm, when linked to BIM environment, will provide a platform for its structural and climatic optimization.
f. Simultaneously, it will provide a platform for its information exchange. For example collaborating with other consulting organisations such as structural design, HVAC design, and so on.
g. The expected outcome is two and three-dimensional drawings.
h. This result can be linked to CAM (Computer Aided Manufacturing) and CNC and 3D printing wherever required.
i. *The designer's focus is more on the process, so the form is generated and not pre-defined.*

Limitations

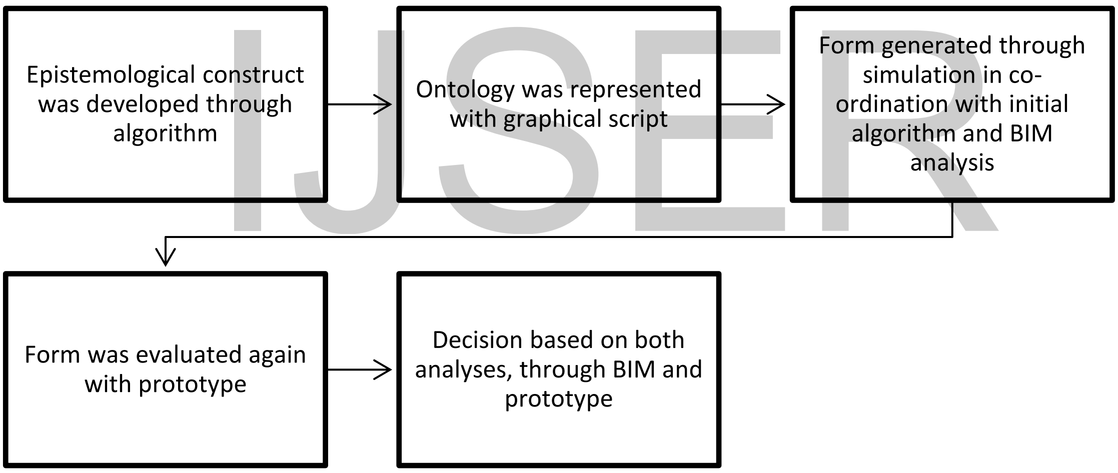
a. Designer's major role is the design of the algorithm, means the translation of human intelligence to artificial intelligence within the parameters.
b. The linkage of algorithm and BIM environment requires compatible programming platform.
c. The technical detailing in programming the algorithm and handling the software require advanced skills.
d. The responsibility of the designer is much more; as a programmer, as a controller and as a decision maker.
e. The generated form of the design requires expertise and precision for its materialisation.

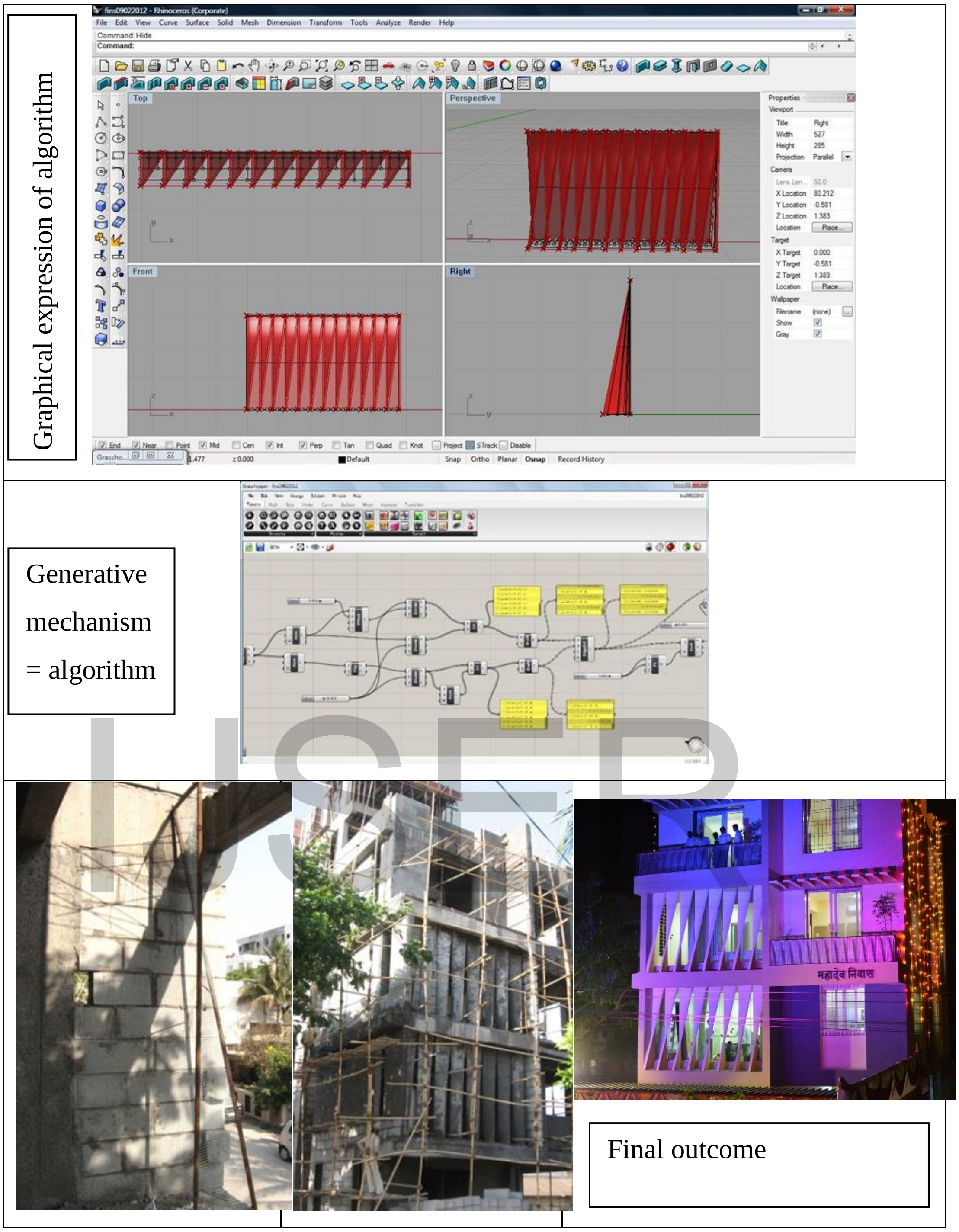
4.2.2 Experiment 2: Design of a residential building

This experiment was carried out on modifications to the previous experiment.

The modifications were;

a. Graphical scripting tool (Grasshopper 3D) was used to develop the programming based on the algorithm
b. In addition to the structural analysis with the BIM environment, its prototype was built at 1:1 scale
c. The decision of the structural material was considered on the basis of findings of the BIM structural analysis and the prototype.
d. Availability of structural material and skilled labour was taken into consideration as an additional parameter to the designer's decision.
e. The labour was specially trained to fabricate the prototype.





(DESHPANDE, KNOWLEDGE BASED FORM FOR ARCHITECTURAL DESIGN, 2012)

Figure 25: Experiment 2: Flowchart

4.2.2.1 Observations of experiment 2 in the form of advantages and limitations

The epistemology of the design is formulated as a graphical script, and synthesis and analysis are the ontology builders, with BIM as a tool.

Advantages

a. The designer has a freedom to simulate at the process level, *which is not possible without programming and computation.*
b. The designer has a great benefit moving to and fro throughout the entire process of design. It allows the formulation-synthesis-analysis and simulate based on all the set parameters (computable and non-computable) such as structural stability, building performance, aesthetics, functionality and ergonomics.
c. Thereby, the greatest advantage is, he is *assured* of the structural behaviour, performance and other parameters including the non-computable parameters of the building.
d. Physical trial and error is reduced as we reach to an optimal decision through a number of cycles of simulation.
e. Investment of time and cost is reduced.

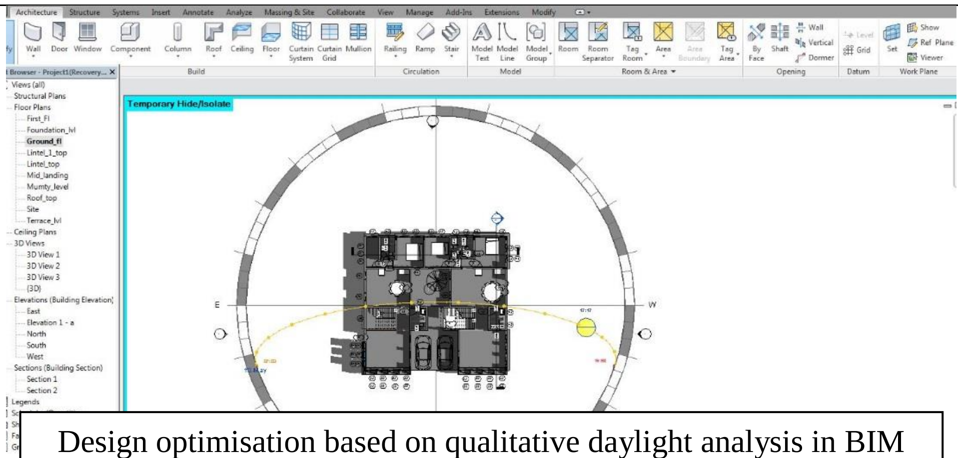
Limitations

a. The designer has to co-ordinate several domains to achieve the desired outcome.
b. The designer has to adopt a back and forth process. *The algorithm has its limitation and cannot optimize automatically till the desired condition is achieved.*
c. *The complexity of programming and computation increases greatly with the increase in the scale of the project.*

4.2.3 Experiment 3: Design of a single family residence

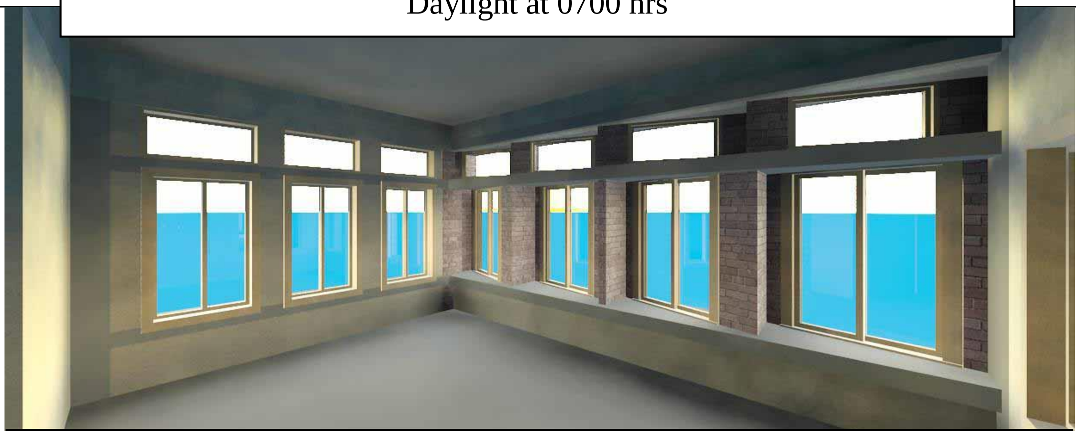
The design epistemology follows laws of Vaastushastra, for its expression in planning and circulation. The façade design is based on the daylight analysis (performance as the main parameter). Optimisation at both the levels, epistemological and ontological. The outcome was analysed for structure and performance. The design could satisfy the performance test in BIM environment at both the levels qualitative (virtual model) and quantitative (energy analysis report), so, its physical prototype was not developed.

Table 4: Daylight analysis in BIM for optimisation based on qualitative analysis



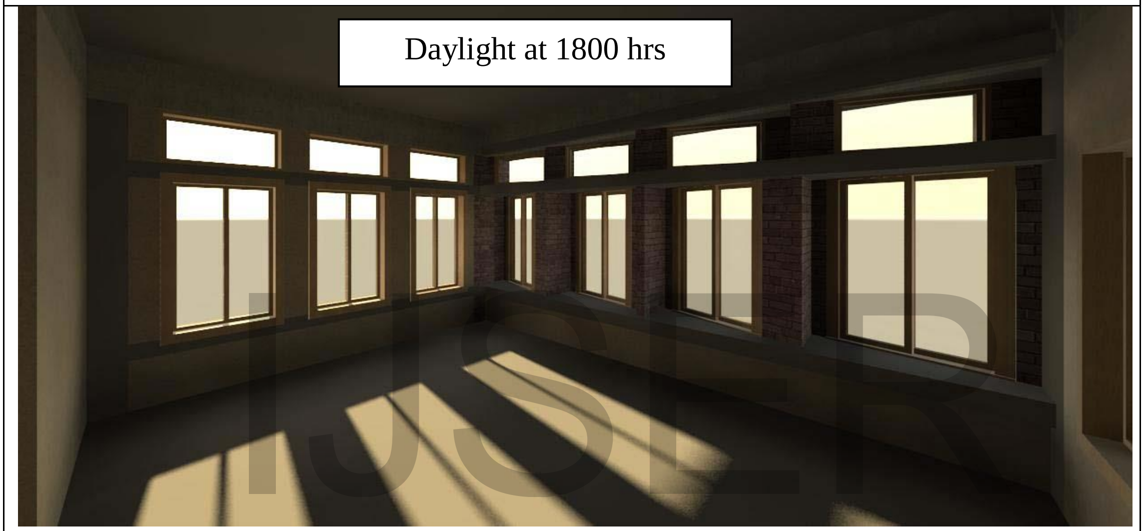
Design optimisation based on qualitative daylight analysis in BIM

Daylight at 0700 hrs



Daylight at 1200 hrs.

Daylight at1600 hrs



Daylight at 1800 hrs

Daylight at 1900 hrs

Advantages

i. The structure is an outcome of in-depth analysis for its performance and behaviour

ii. The factors taken into consideration were daylight, orientation, circulation, behaviour and activity pattern of the family, cultural context, availability of resources and funds.

iii. The factors then classified according to computable aspects and scripting (programming), and BIM was used to generate the final form.

Limitations

i. The process includes complexity into its programming.

ii. The process demands to work in parallel domains simultaneously.

4.2.4 Establishing the need for AI agent design

The analyses of data SECTION 3.1 AND 3.2 THROUGH 3.7.4, identified research gap FIGURE 23: RESEARCH GAP and observations of the experiments SECTION 4.2 show that,

The primary purpose of introduction of AI is to achieve results on multi-criteria problems. Based on the analysis shown in FIGURE 23: RESEARCH GAP and Observations of the experiments explained in the section 4.1 PRIMARY SOURCE OF data collection: Experiments and observations it is stated that the complexity of programming and computation greatly increases according to the design requirement. Automation will make it simpler for a requirement of *larger scale* and more *complex designs*. Programming of mere algorithms cannot achieve intelligent results such as to sense the neighbouring environment and respond accordingly, or learning through its exposure. It proves that the designer needs an advanced tool to handle such complexity. It *establishes the need to develop AI agent system for design processes*. To reduce the complexity of programming and to achieve automation into processes there is a need to include *intelligent systems based on learning and their advances. That establishes the need for AI agent into architectural designing.*

5 Conceptual design of AI agent system as an autonomous mediator model of designing

5.1 Artificial evolutionary system:

As discussed in sections 3.4, 3.7.2 and 3.7.4 the study focuses on bio-inspired AI for its significance into architectural designing and following diagram shows interpretation of artificial evolutionary system

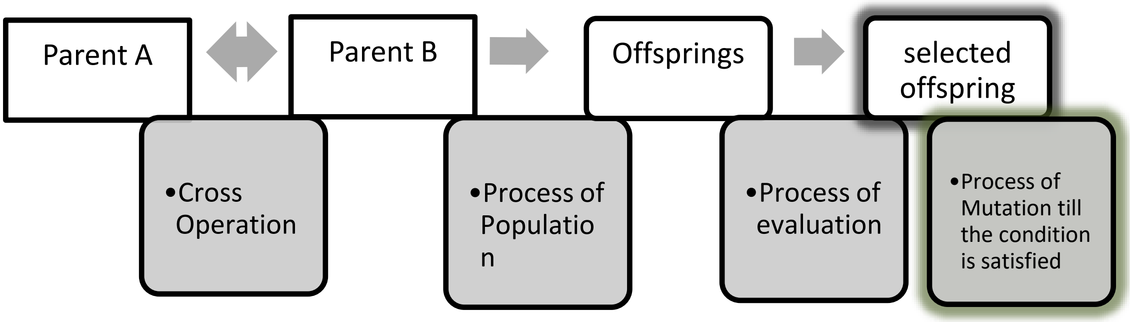


Figure 26: Artificial evolutionary system

5.1.1 Interpretation of Evolutionary system of AI into architecture

5.1.1.1 Workshop on design of AI agent based on evolutionary system of AI

Images below show an outcome of a *Workshop on Agent design based on artificial evolutionary systems* for a group of two school students. The aim of the workshop was to apply the intelligence of artificial evolutionary systems to achieve the best blend of two defined colours.

Algorithm 12.1 Evolution Strategy Algorithm

Set the generation counter, $t = 0$;
Initialize the strategy parameters;
Create and initialize the population, $\mathcal{C}(0)$, of μ individuals;
for *each individual*, $\chi_i(t) \in \mathcal{C}(t)$ **do**
    Evaluate the fitness, $f(\mathbf{x}_i(t))$;
end
while *stopping condition(s) not true* **do**
    for $i = 1, \ldots, \lambda$ **do**
        Choose $\rho \geq 2$ parents at random;
        Create offspring through application of crossover operator on parent genotypes and strategy parameters;
        Mutate offspring strategy parameters and genotype;
        Evaluate the fitness of the offspring;
    end
    Select the new population, $\mathcal{C}(t+1)$;
    $t = t + 1$;
end

(FLOREANO & MATTIUSSI, 2008)

Figure 27: Evolutionary algorithm

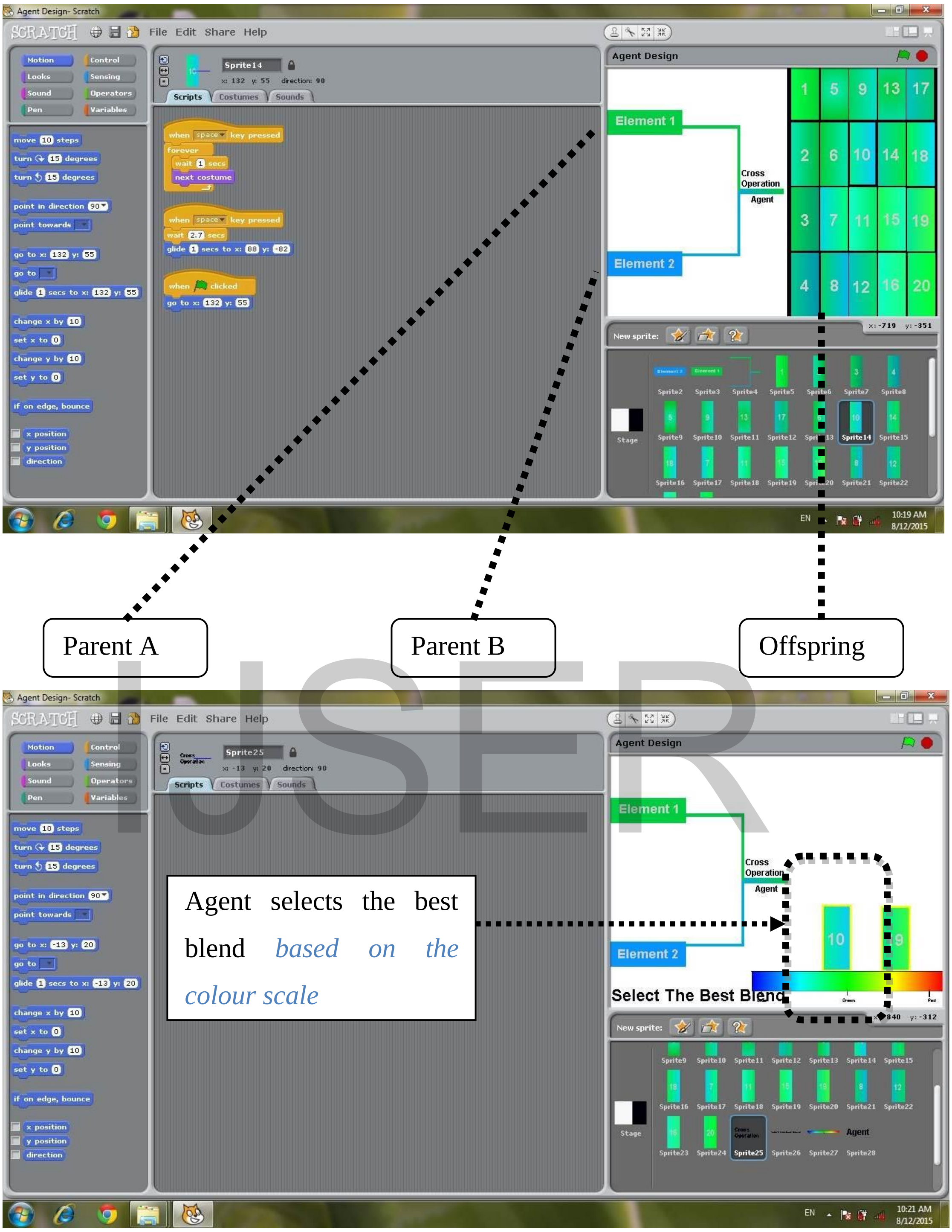


Figure 28: Outcome of the workshop

The properties of outcome depend on that of parents.

Variables: colours

Constants:

i. Color scale

5.2 Proposed multi-agent system (MAS)

The proposed MAS is based on the evolutionary algorithm. Initialize population for a fixed number of individuals. Evaluate the fitness, stop mutation, if the conditions are satisfied. Else, mutate offspring strategy parameters and genotype. Evaluate the offspring for fitness. Stop mutation, if the conditions are satisfied.

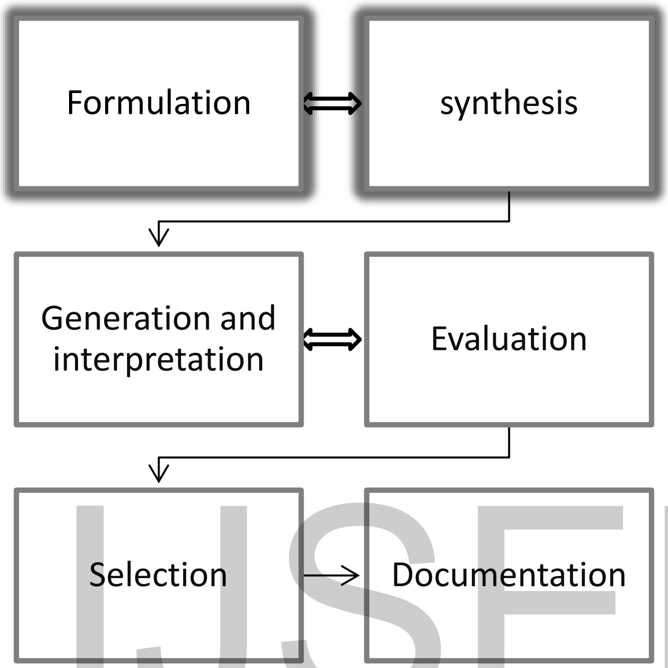


Figure 29: Autonomous mediator for architectural design

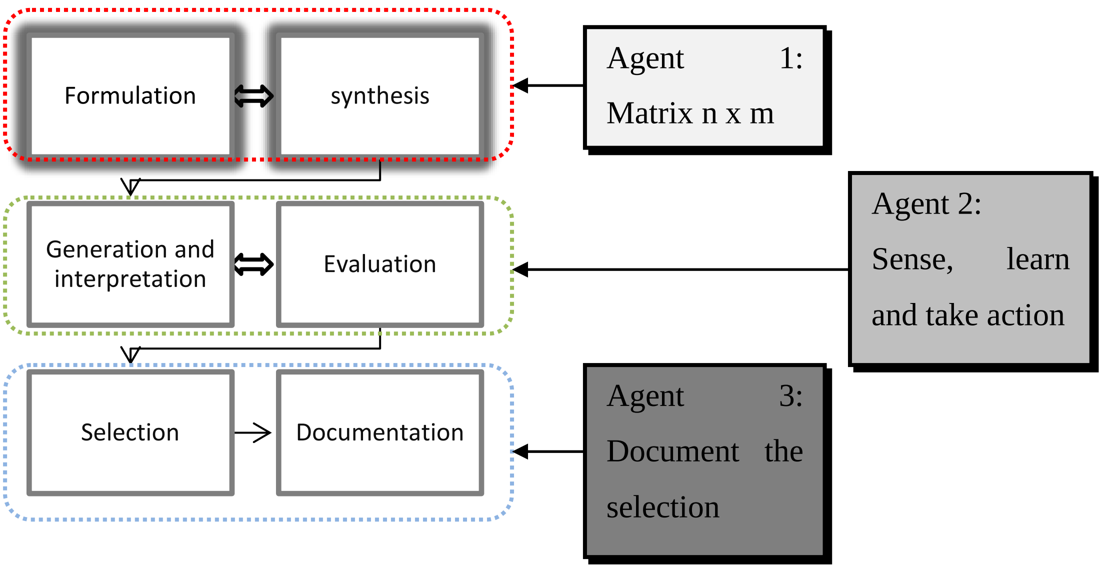
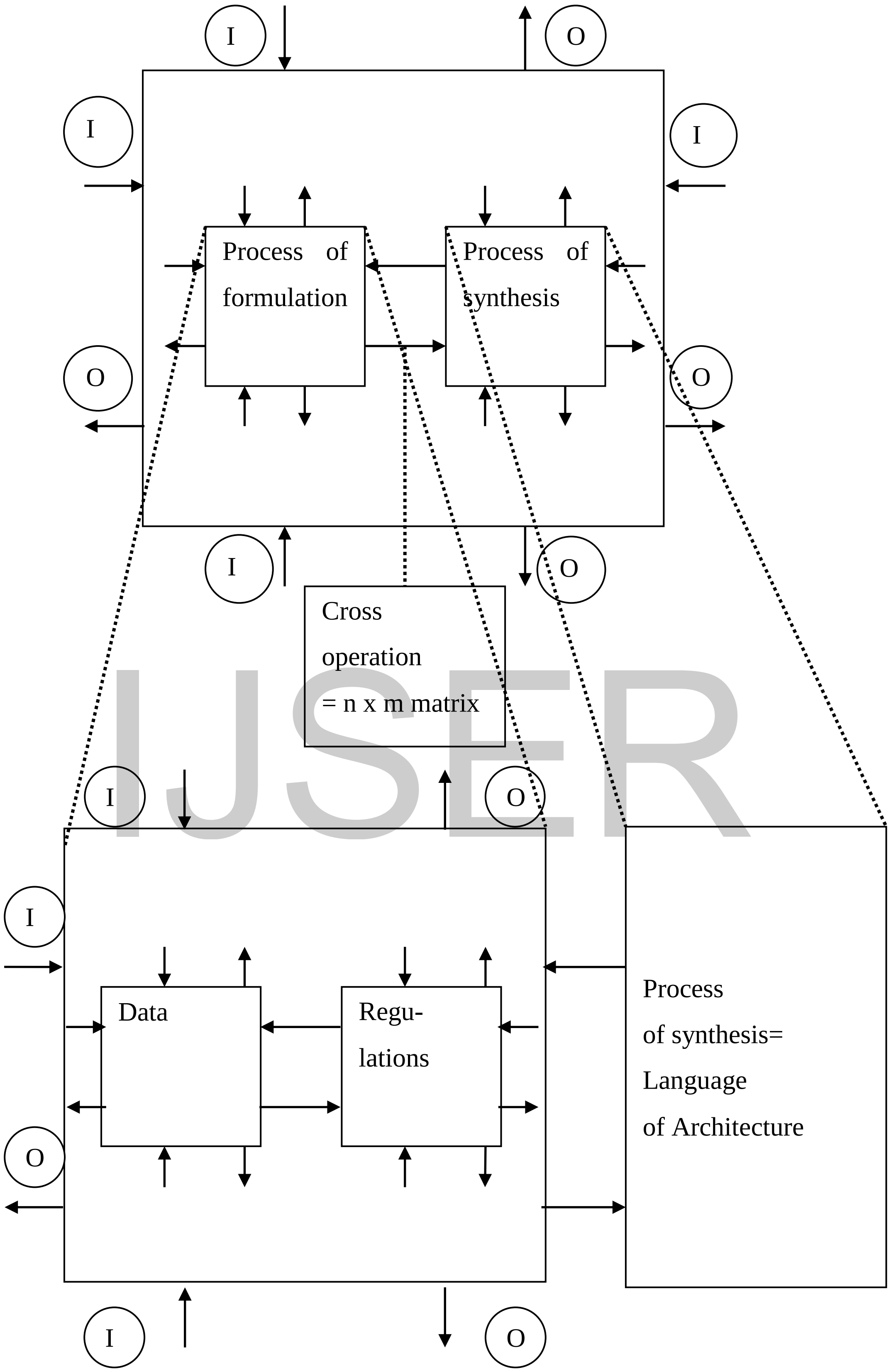
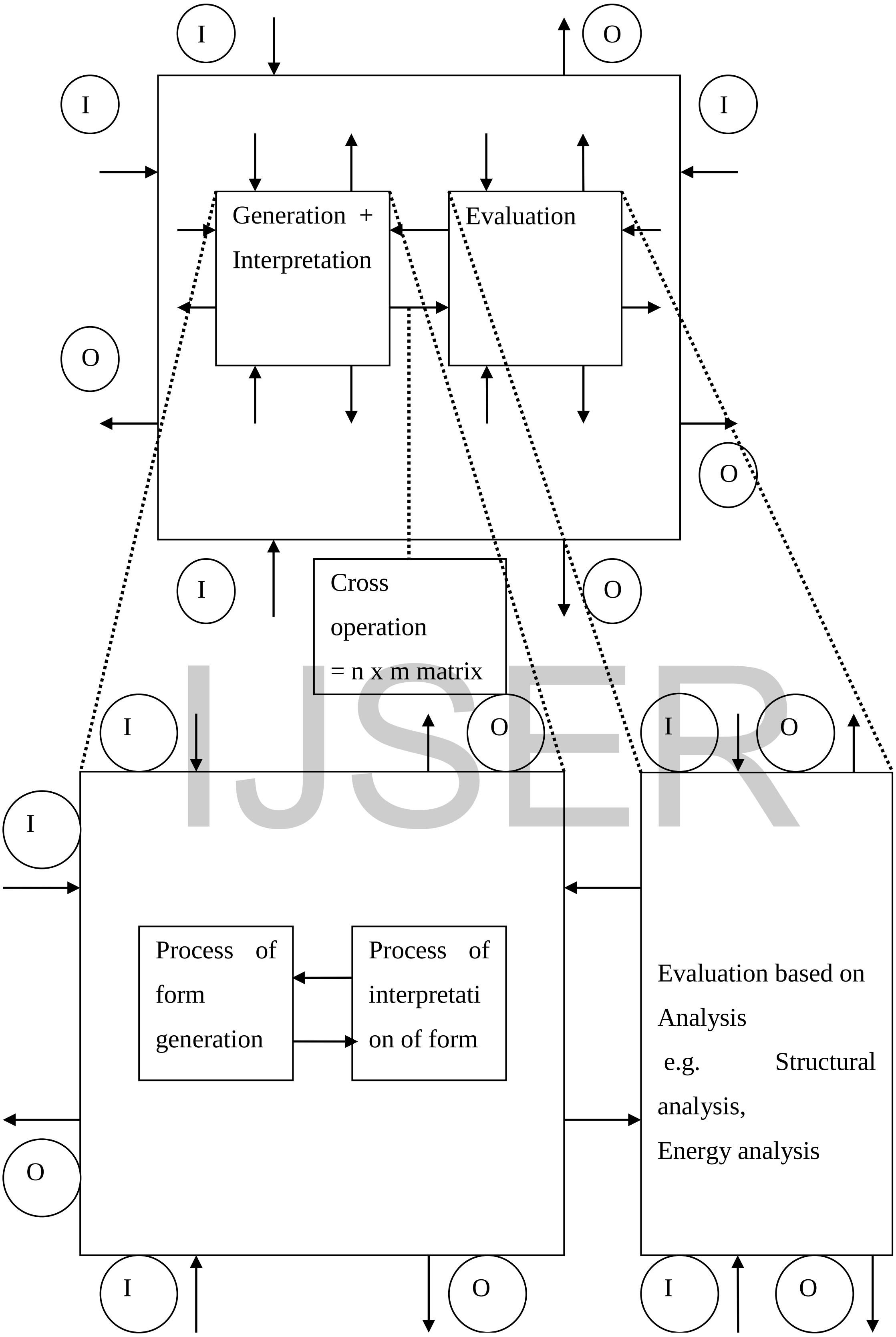


Figure 30: Multi agent system design



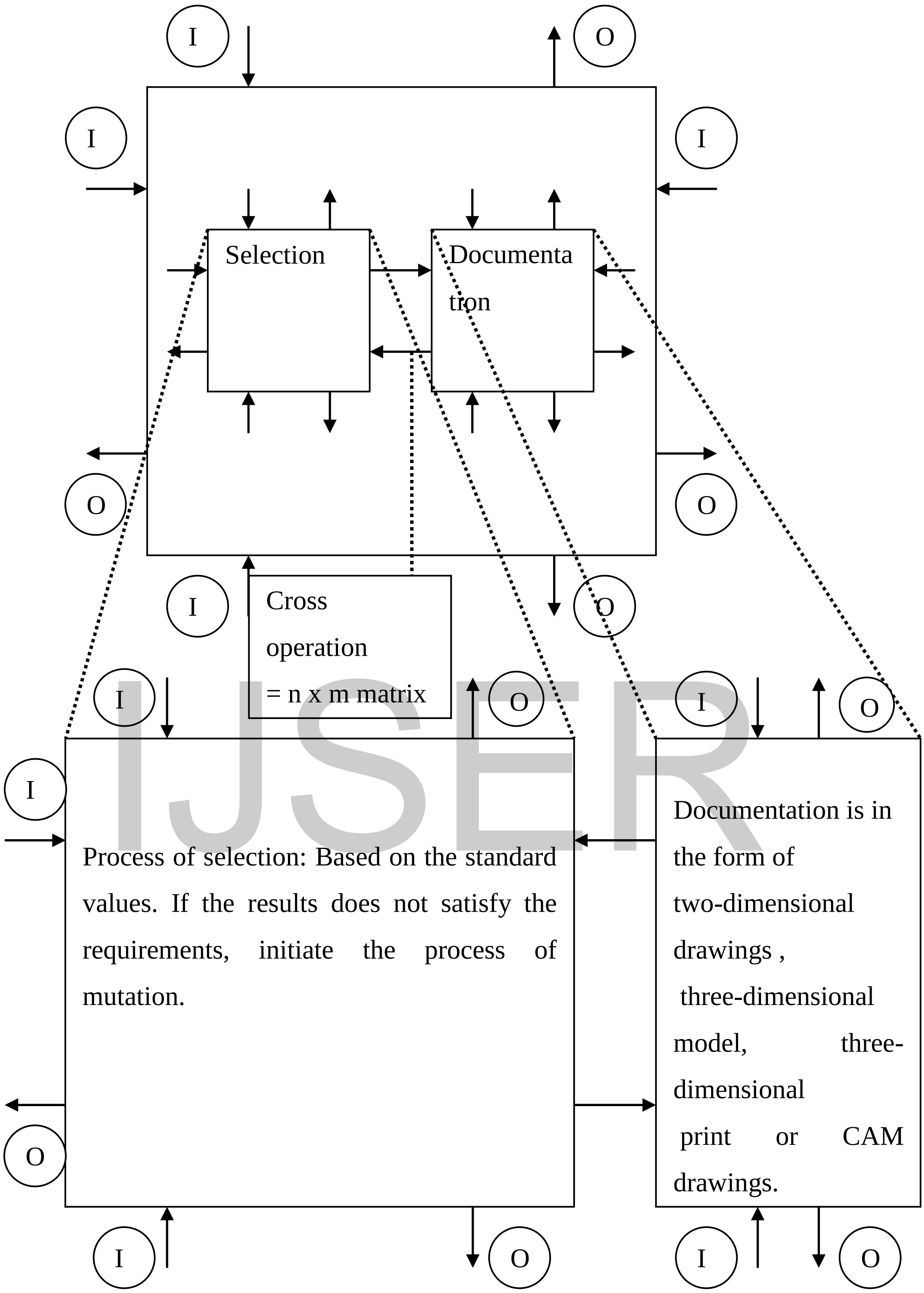
(FLOREANO & MATTIUSSI, 2008, PP. 1-99)

Figure 31: Design of Agent 1



(FLOREANO & MATTIUSSI, 2008, PP. 1-99)

Figure 32: Design of Agent 2



(FLOREANO & MATTIUSSI, 2008)

Figure 33: Design of Agent 3

6 Conclusions

6.1 Summary of the studies

SECTION 1.1.1 explains the initial concept of research that led to analyse the data based on secondary and primary sources of data collection. The background study supported to identify the relevant literature.

With an overview of the history of AI into architectural design, literature review supported the formulation of the research question., the data collection methodology was adopted in two ways viz.;

a. Analysis of case studies from secondary data collection sources as explained in SECTION 3.1
b. Experiments conducted on live project proposals of architectural design as explained in SECTION 4.2

The study further, explains the need for Artificial Intelligence into architectural designing. The theoretical framework for the model of designing is proposed based on the above data analysis and *identified fundamental theory of computation* as explained in SECTION 3.3. A conceptual design of the model of designing as autonomous mediator is proposed with the detailing on its epistemological and ontological construct. This model is proposed based on the *inter-disciplinary approach of the theory of architecture and that of computation.*

6.2 Summary of the findings

a. SECTION 1.1.3 explains the computable and non-computable parameters and their relation to the epistemology and ontology of the architectural design.
b. CHAPTER 2 Literature review establishes the significance of AI into architectural designing. Moreover, further directs to identify and comparatively analyse the comparable theories to address the research question.
c. Relation of the compound model of digital design FIGURE 12: COMPOUND MODEL and the computational design process is established as explained in FIGURE 14.

d. Based on the observations and findings of the Experiments as described in SECTION 4.2 and the findings mentioned above, a conceptual framework of AI FIGURE 15: CONCEPTUAL FRAMEWORK FOR AN AI agent and its relation to the Evolutionary-developmental model of computation 3.7.4. is proposed as a model of designing. This model of designing is defined as autonomous mediator. It is termed as *autonomous* due to its learning intelligence and *mediator* due to its derivative nature. (DJORDJE, 2013) (MORGAN & MORRISON, 1999)

6.3 Conclusion

This study arrives at a conclusion of a *hypothetical model of designing of multi-agent AI system to provide solutions to the specific requirements of the architectural design*.The proposed autonomous mediator i.e. the alternative model of designing has a flexibility in terms of changing the ontology of the agents, their learning environments and the parameters for their simulation. The applications of this model include interpretations, decisions and simulations into the design to help the designer for his design decisions. The scope of this study is limited to the conceptual design of the multi-agent system. *Further studies and future scope* may include evaluation and testing of this model and their analysis based on several parameters of the architectural design.

References

6th ASCAAD Conference 2012 CAAD | INNOVATION | PRACTICE. (n.d.). (pp. 49-68). Bhzad Sidawi.

Alex Cantu :: CD Draft. (2014, February 24). CD Draft a division of Cantu Design. Downey, CA. Retrieved from http://www.cddraft.com/projects/20avenue/grace-ave-inglewood

Alfaris, A., & Merello, R. (2008). The Generative Multi-Performance Design System. *Proceedings of the ACADIA 08 Conference*, (pp. 448-457).

Alfaris, A., & Rashad, A. (n.d.). A Performance Based Generative Design System Methodology for Sustainable Design in Practice.

Asish, R. (2008). *Smart Geometry as Architectural Exploration.* Taylor & Francis.

Axelrod , R. (1997). Advancing the Art of Simulation in the Social Sciences. In R. Dr.Conte, R. Prof.Dr.Hegselmann, & T. Prof. Dr. Pietro, *Simulating Social Phenomena* (pp. 21-40). Berlin Heidelberg: Springer Berlin Heidelberg.

Barnden, J. A. (1995). Artificial intelligence and neural networks. In M. A. Arbib, *The handbook of brain theory and neural networks* (pp. 98-102). Cambridge, MA, USA: MIT Press.

Batty, M. (2007). *Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals.* The MIT press.

Benenson, I. (2004). Agent-based modeling: From individual residential choice to urban residential dynamics. *Spatially integrated social science: Examples in best practice*, 42(6-7),67-95.

Burger, S., Burry, J., DeKestelier, X., Hesselgren, L., Parrish, J., Peters, B., & Whitehead, H. (2015, July 18). *Home page*. Retrieved from http://smartgeometry.org: http://smartgeometry.org/index.php?option=com_content&view=article&id=119&Itemid=78

Ching, F. D. (1979). *Architecture: Form, Space, and Order.* New York [etc.] : Van Nostrand Reinhold.

Corbusier, L. (2005). *El Modulor.* Apóstrofe.

Coyne, R. D., & Postmus, A. G. (1990). Spatial applications of neural networks in computer-aided design. *Artificial intelligence in Engineering*, 5(1), 9-22.

Darwin, C. (1964). *On the origin of species.*

Deshpande, M. V. (2011). *Algorithmis design strategies in architecture:Use of Fibinacci sequence as a generator for the logic.* Pune: Academic work for Savitribai Phule University of Pune.

Deshpande, M. V. (2012). Knowledge based form for architectural design. *WIA Mahacon National conference* . Pune: IIA , Pune Chapter.

Deshpande, M. V., kulkarni, M., & Uke, N. (2014). Intelligent design in architecture. *National Conference on Emerging Trends in Architecture and Allied Fields-NCETAA-2014* (pp. 155-166). Pune: Sinhgad College of Architecture Pune, Savitribai Phule university of Pune.

Djordje, S. (2013). The promise of performative: Relational, genetic and scripted models in architectural design. *Facta universitatis-series: Architecture and Civil Engineering, 11*(1), 47-59. doi:10.2298/FUACE1301047S

Douglas, R., & Martin, K. (1990). *Neocortex. InThe Synaptic Organization of the Brain.* (G. Shepherd, Ed.) New York,Oxford: Oxford University Press.

Engelbrecht, A. P. (2007). *Computational intelligence: an introduction.* West Sussex: John Wiley & Sons.

Epstein, J. M., & Axtell, R. (1996). *Growing artificial societies: social science from the bottom up.* Brookings Institution Press.

Floreano, D., & Mattiussi, C. (2008). *Bio-inspired artificial intelligence.* MIT Press.

Fogel, L. J., Owens, A. J., & Walsh, M. J. (1966). *Artificial intelligence through simulated evolution.* John Wiley & Sons.

Fogel, L. J., Owens, A. J., & Walsh, M. J. (1966). *Artificial Intelligence Through Simulated Evolution. [By] Lawrence J. Fogel ... Alvin J. Owens ... Michael J. Walsh.* New York: John Wiley & Sons.

Frazer, J. (1995). AN EVOLUTIONARY ARCHITECTURE.

Gero, J. S. (1994). Computational models of creative design processes. *Artificial Intelligence and creativity*, 269-281.

Gero, J. S. (1996, November). Creativity,emergence and evolution in design. *Knowledge-Based Systems, 9*(7), 9(7), 435-448. doi:10.1016/S0950-7051(96)01054-4

Gero, J. S. (Ed.). (2014). *Artificial intelligence in design'91.* Butterworth-Heinemann.

Gero, J. S., & Kannengiesser, U. (2004). The Situated function-behaviour-structure framework. *Design Studies, 25*(4), 373-391.

Google . (2014, February 23). Retrieved from : http://archsupply.com/wp-content/uploads/2013/10/generative-components-screenshot-1.jpg

Harold, F. M. (2001). *The way of the cell.* Oxford: Oxford University Press.

Harvey, I. (1992). Species adaptation genetic algorithms: A basis for a continuing SAGA. *Toward a Practice of Autonomous Systems: Proceedings of the First European Conference on Artificial Life*, (pp. 346-354).

Hebb, D. O. (1949). *Organisation of behaviour.* New York: John Wiley and Sons.

Hegselmann, R., & Flache, A. (1998). Understanding complex social dynamics: A plea for cellular automata based modelling. *Journal of Artificial Societies and Social Simulation*, 1(3),1.

Hesselgren, L., Sharma, S., Wallner, J., Baldassini, N., Bompas, P., & Raynaud, J. (2013). *Advances in Architectural Geometry.* Advances in Architectural Geometry.

Holland, J. (1975). Genetic Algorithms, computer programs that evolve in ways that even their creators do not fully understand. *Scientific American*, 66-72.

Holland, J. H. (1975). *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence.* University of Michigan Press.

Issa, R., & Robert McNeel & Associates. (2010). *Essential Mathematics for Computational Design.*

Jo, J. H., & Gero, J. S. (1998). Space layout planning using an evolutionary approach. *Artificial Intelligence in Engineering*, 12(3), 149-162.

Kant, I. (n.d.). A priori and a posteriori(philosophy).

Kelly, N., & Gero, J. S. (2012). Computational modelling of the design conversation as a sequence of situated acts. *Seventeenth International conference on computer aided architectural design research in asia* (pp. 121-130). Chennai: CAADRIA.

Kohonen, T. (1989). Self-Organizing Feature Maps. In T. Kohonen, *Self-Organization and Associative Memory* (pp. 119-157). Springer.

Love, T. (2000, May). Philosophy of design: a meta-theoretical structure for design theory. *Design Studies, 21*(3), 293-313. doi:10.1016/S0142-694X(99)00012-5

Luger, G. F. (2005). *Artificial Intelligence:Structures and strategies for complex Problem solving.* Pearson education.

Mattiussi, C., & Floreano, D. (2005). *Viability Evolution.* Lausanne, Switzerland: Laboratory of Intelligent systems,Ecole Polytechnique Federale de Lausanne (EPFL).

Mde. (2008). What is the promise of developmental evolution? Part I: Why is developmental biology necessary to explain evolutionary innovations? *Journal of Experimental Zoology (Mol Dev Evol)*, 288, 95-98.

Mitchell, W. J. (1990). *The Logic of Architecture: Design, Computation, and Cognition* (3, illustrated ed.). MIT Press.

Mitchell, W. J. (2006). FROM SKETCHPAD TO CITY OF BITS:A Story of Shifting Intensions. *Proceedings of the 11th International Conference on Computer Aided Architectural Design Research in Asia* (pp. 1-5). Kumamoto, Japan: CAADRIA.

Morgan, M. S., & Morrison, M. (1999). *Models as Mediators: Perspectives on Natural and Social Science* (Vol. 52). (M. Morgan, & M. Morrison, Eds.) Cambridge University Press.

Oxman, R. (2006, May). Theory and design in the first digital age. *Design Studies, 27*(3), 27(3),229-265. doi:10.1016/j.destud.2005.11.002

Pramar, V. S. (1973). *Design fundamentals in Architecture.* Somaiya Publications.

Protzen, J. P., Harris, D., & Cavallin, H. (2000). Limited computation, unlimited design'00. *Artificial intelligence in design'00* (pp. 43-52). Netherlands: Springler.

Quirk, V. (2012, December 07). *A Brief History of BIM.* Retrieved from ArchDaily: <http://www.archdaily.com/302490/a-brief-history-of-bim/>

Rechenberg, I. (1965). *Cybernetic solution path of an experimental problem.*

Rechenberg,, I., & Frommann-Holzboog. (1973). *Evolutionary strategie: Evolution.* Stuttgart.

Reffat, R. M. (2006, August). Computing in architectural design: reflections and an approach to new generations of CAAD. *ITcon*, 655-668.

Riitahuhta, & Asko (Eds.). (2004). Design Computing and Cognition '04. *First International Conference on Design Computing and Cognition" (DCC'04).* Boston, USA.

Sabda or sound http://bhagvadgitausa.com. (2015, 07 20).

Sakoda, J. M. (1971). The checkerboard model of social interaction. *The Journal of Mathematical Sociology*, 1(1), 119-132.

Salvan, G. S. (n.d.). *Architectural Theories of Design.* Goodwill Trading Co., Inc.

Schaller, T. W. (1997). *The art of architectural drawing: imagination and technique.* John Wiley & Sons.

Schon, D. A. (1992, April). Kinds of seeing and their functions in designing. *Design studies, 13*(2), pp. 13(2), 135-156. doi:10.1016/0142-694X(92)90268-F

Schumacher, P. (2009, JUN 26). Parametricism: A New Global Style for Architecture and Urban Design. *Architectural Design, 70*(4), pp. 14–23. doi:10.1002/ad.912

Simon, H. A. (1996). *The sciences of the artificial.* US: MIT Press.

Stojanovic, D. (2013). The promise of performative: Relational, genetic and scripted models in architectural design. *Facta universitatis-series: Architecture and Civil Engineering, 11*(1), 47-59.

Sutherland, I. (1963). SKETCHPAD-a man-machine graphical interface. *Doctoral dissertation, PhD thesis*. MIT.

Table-27. (n.d.). *DC Rules.Town Development*, 241. Pune Municipal corporation. Retrieved from www.egovpmc.com

Tickle, C. (2011). *Principles of Development.* Oxford: Oxford University Press.

Wagner, G. P. (2001). What is the promise of developmental evolution? Part II: A causal explanation of evolutionary innovations may be impossible. *Journal of Experimental Zoology*, 291(4), 305-309.

Wagner, G. P., & Larson , H. C. (2003). What is the promise of developmental evolution? III. The crucible of developmental evolution. *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution* , 300(1), 1-4.

Whitley, D., Rana, S., & Heckendorn, R. B. (1999). The island model genetic algorithm: On separability, population size and convergence. *Journal of Computing and Information Technology*, 7,33-48.

Yajnavalkya. (Before mid first millennium BCE). *Bṛhadāraṇyakopaniṣat* (Vols. IV,i,2).

Yajnavalkya. (Before mid-first millennium BCE). *Bṛhadāraṇyakopaniṣat* (Vols. IV,i,2).

Appendix 1: Glossary

Autonomous mediator	A model that is a derivative and generated from theory and whose role is to establish the structure and relationships which represent certain theory. However, within the research, which at the same time includes observations, descriptions and proscriptions, the role of the model comes closer to the role of the experiment, and the model is accepted as "autonomous mediator". **(Djordje, 2013) (Morgan & Morrison, 1999)**
Cognition	Cognition is the set of all mental abilities and processes related to knowledge, attention, memory and working memory, judgment and evaluation, reasoning and "computation", problem solving and decision making, comprehension and production of language, etc. Human cognition is conscious and unconscious, concrete or abstract, as well as intuitive (like knowledge of a language) and conceptual (like a model of a language). Cognitive processes use existing knowledge and generate new knowledge.
Epistemology	Theory of knowledge, It questions what knowledge is and how it can be acquired, and the extent to which any given subject or entity can be known,
Ontology	*logic* the set of entities presupposed by a theory, philosophical inquiry into the nature of being itself
Posteriori	Relating to or denoting reasoning or knowledge which proceeds from observations or experiences to the deduction of probable causes., in a way based on reasoning from known facts or past events rather than by making assumptions or predictions.
Priori	From the earlier, *A priori* knowledge or justification is independent of experience

Appendix 2

1. Slides