The Ecological Superblock - Computational Ecology Principles in Urban Systems Design

Thesis

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Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.21954/ou.ro.00012694

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THE ECOLOGICAL SUPERBLOCK
Implementation of Ecological Principles in the Architecture of the City

Aiman Tabony
February 2020
The Ecological Superblock
Computational Ecology Principles in Urban Systems Design

By
Aiman Tabony

Submitted to the Mphil/PhD Programme
in partial fulfillment of the requirements of the Open University
for the Degree of
Doctor of Philosophy in Architecture: Architectural Design
at the
Architectural Association School of Architecture

February 2020
ABSTRACT

The rapid, ongoing and upcoming climatic and ecological changes, coupled with the rapid acceleration in population growth, raise doubts and concerns regarding the ability of the existing urban systems to adapt to the future changes. Nevertheless, these changes represent a key opportunity to utilise ecological based design superblocks. The research departs from a critical reflection on the work of Hilberseimer’s “Decentralized City” and Soleri’s “Arcology”, who considered the city and the superblock to be a single and unified ecological system. It contextualizes the research within the larger scope leading the focus to the investigation of ecology and its subfield, the ecosystem. This narrows the study down to three dominant areas of research: ecology, computational ecology, and urban design. Through the integration of System Dynamic modelling method in the design process, the research investigates the implementation of ecological parameters, coupled with morphological and metabolic parameters and processes. The design methodology is proved by the development of a computational design model which integrates the System Dynamics model and the Evolutionary Design model. The models were examined through a set of design experiments of a superblock which was integrated with the flow of the dynamics of the climate and ecological system. The output of the design method is a multi-dimensional datascape, opening up new possibilities in the field of urban design and planning that are more robust in the face of changes in the environmental context.
Undertaking this Research has been a truly life-changing experience for me, and it would not have been possible to achieve without the support and guidance that I have received from many people.

I would first like say a very big thank you to my Director of Studies, supervisor, mentor and friend, Prof. Michael Weinstock, for all the support and encouragement he gave me. Indeed, his expertise was invaluable in the formulation of the research topic and the methodology in particular. Without his guidance and constant feedback this Research would not have been achievable. I am extremely grateful for our friendly chats at the end of our meetings and your personal support in my academic and business endeavours. I have been extremely lucky to have a supervisor who cares so much about my work, and who responded to my questions and queries so promptly. I would also like to say a special thank you to my supervisor, Prof. George Jeronimidis, for your patient guidance, encouragement and useful critiques of my research work you have provided throughout.

I would like to acknowledge my colleagues on PhD programme: Dr. Mohammed Maki, Milad Shokatbakhsh, Hyunjise Nam, Yujin Kim, Anna Font Vacaas and Dr. Elif Erdine, for their wonderful collaboration. You supported me greatly and were always willing to help me. A very special thank you to Arch. Enriqueta Llabres Valls for your invaluable advice and feedback on my research and for always being so supportive of my work. I am also very grateful to Arch. Dimitra Bra and Arch. Lungu Constantin, who all helped me in numerous ways during the various stages of my research.

I am indebted to my friends Nizar Jabareen and Arab Zabibi who were always so helpful in many ways. Special thanks to Mrs. Liliana Dumitrascu for being so supportive of my work throughout these years. I am also very grateful to Xavier Fernandez for his amazing sense of respect when helping me with the editing of the thesis.

I would also like to say a heartfelt thank you to my brother and sisters: Abeer, Lubna, Ola, Abeer, Ashraf and Amir for always believing in me and encouraging me to follow my dreams as well as for helping in whatever way they could during this challenging period. Finally, I drew inspiration from and I owe a great debt to my mother Jihad and my late father, the architect and the Engineer, Dr. Mahmoud Tabony (May God bless him and give him peace) who profoundly influenced me in all aspects of my life. They were particularly responsible for my thirst for education. I also wish to acknowledge and thank my children, Aya and Mahmoud, who have been a source of great happiness and pride and have given me the extra strength and motivation to get things done.

This thesis is dedicated to my family: my late father Mahmoud, my mother Jihad, my daughter Aya and my son Mahmoud.


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1. INTRODUCTION

"To design is to devise courses of action aimed at changing existing situations into preferred ones." — Simon
The research focuses on how design can address environmental and ecological emergencies. In this respect, the fragility of the planet and this challenging reality is not viewed as a problem that requires technical improvement of conventional solutions, yet rather as an opportunity for ecological design innovation. The study aims to develop a new design method and model to generate urban morphology based on ecological principles and parameters. It sets out to examine the potentiality of employing ecological thinking in design and suggests a new way of thinking about cities.

The devised design method is founded on the logic that human habitation is a complex system that is embedded in its own natural and cultural context; and its morphology, which is determined by ecological and metabolic processes, is capable of adapting to change. To achieve this, the study identified three domains that can be investigated in order to facilitate the formulation of the theoretical background needed to devise the design method and model. The domains are urban, ecology, and computation.

In the urban domain, two seminal proposals were investigated; namely the Decentralized City by Hilberseimer in 1943, and Soleri’s Archology in 1969. Both viewed the city as a functioning organism and a dynamic organizational model that can be adapted to different conditions. Basically, they were pioneering the integration of ecological thinking in design. In Hilberseimer’s proposal, he adopted a holistic approach towards the integration of agriculture in the city. His design model was based on the definition of ecology, which deals with the relationship between organisms and their environment. This view places the emphasis on the relationship between the parts of the city rather than merely on each single part separately. On the other hand, Soleri expanded upon the definition of ecology. For him, architecture, and ecology form two parts of the same entity. He proposed the name Archology as a combination of two words, these being architecture and ecology, which describes the city as an integrated “organism- or self-contained systems interacting with nature”. Based on this analysis, Hilberseimer and Soleri’s ideas regarding the ecological approach coupled with the latest computational advancement, present the potentiality for a novel design approach to the architecture of the city. Their ecological approach to design led to the second domain of investigation, namely ecology.

Scientifically speaking, the basic definition of ecology is: “the study of interactions between organisms (the biological system) and their environment (the physical system).” Based on this definition, the function of ecological thinking is to define and understand the interactions and the relationships. These interactions form an ecological system or ecosystem, and, within the ecosystem, there are continuous fluxes of matter, energy, and information in an interactive, open system. To understand and analyze the function, performance, and productivity of an ecosystem, it requires the application of mathematical and computational methods – namely computational ecology, which is the third domain of the study.

Computational ecology deals with the mathematical models which assist in understanding the interactions and behaviour of the ecosystem. Basically, the models describe the processes of material, energy, and information transfer within the ecosystem. These processes can be described by the well-known hydraulic metaphor diagram for ecological modelling. It describes the system as a pool or stock which represents the current state of the system; and any change of the stock implies a flow. The importance of representing these flows stems from the fact that they are the basis of decisions and actions in the system, and act as regulation and adaptation variables. The stocks and flows of the system can be expressed mathematically as integral and differential equations. Mathematically speaking, the value of the stock is the integral of inflow-outflow starting with an initial level of stock. Based on these principles, coupled with the advantages of computer technology in the 1940s, led to the development of a computational method, namely System Dynamic modelling, by J. Forester. His models include a System Dynamic model for the whole world as an ecosystem which describes the flux of material, energy, and information. This method proved to be useful in many disciplines and has been applied in research as a computational tool to simulate urban and ecological systems.

Having established the theoretical background, which defines the city as ecosystem, the research moved on to the next stage: focus on the formulation of computational design. The model is composed of two linked models that work together to simulate urban system dynamics behaviour and to generate urban morphology. The first model is the system dynamic, which is responsible for the behaviour simulations; and the second model is the evolutionary computation, which is responsible for morphology generation. Both models are widely used in many disciplines and have proved to be useful, though a thorough search of the relevant literature yielded up the fact that it is the first time that they have been combined into one, integrated computational design model which can be seen as both the novelty and the significance of the research.

The System Dynamic model mathematically formalises the structure and behaviour of the systems. Based on a sequence of system dynamic modelling experiments, the research presents a model of an integrated complex system which is composed of three sub-systems: water, energy, and agriculture. All of the sub-systems are linked together to simulate the behaviour of the system and generate data related to population growth and resource limits, among others. The model generates numerical data regarding the functionality, productivity, and thresholds of the system. Following this, the resulting outcome is transformed as design objectives data to the evolutionary design model.
The Evolutionary Design model - the second model - is a biologically inspired algorithm which is a method of solving multi-objective optimization problems. In multi-objective optimization, the task entails finding one solution which satisfies all the objectives; and is thus difficult. The search focuses on establishing a set of feasible solutions. Basically, the algorithm uses two separate spaces namely, a search space and a solution space. In this respect, the algorithm mimics the survival of the fittest processes of a natural ecosystem. The search space is the coded solution or the genotype; and the solution space is the space of the actual solution or the phenotype. The model is designed to search for a set of solutions which generate surface morphology in relation to the systems behaviour extracted from the System Dynamic model.

Following the formation of the model, it was necessary to define the environmental context and the spatial scales in order to carry out the experiments. The Mediterranean was chosen, which represents an ecologically sensitive area. Subsequently, three ecological systems were selected for examination – water, energy, and agriculture – which were expected to experience negative impacts in that region. The scale of the urban system, which was called “Superblock”, is one square Kilometre, the minimal/spatial unit of climatic modelling and simulation.

To examine the model, it was applied in a two-stage design experiment. The first set of experiments simulates the three independent ecological systems separately. Based on these experiments, a second set of experiments was carried out to explore the integration of three sub-systems into one integrated system. The outcomes were spatial surfaces covering the superblock responding to the function and performance of the ecological systems. The surfaces perform as ‘inhabited’ surfaces that can sustain and support living beings. For example, in the water system experiment, the model generated a surface which acts as a landform allowing the creation of ponds for rainwater collection. Morphologically, the surfaces were driven not only by system dynamic behaviour, but also by spatial design objectives, such as minimal water surfaces and maximum shorelines. In the case of energy, the generated surface acted as a skyline which harvests energy and inhabits population. The energy flow and its production were limited to the area of the generated skyline surface. Morphologically, all the solutions developed a skyline that inclined to the south to maximize exposure to the sun. And in the case of the agricultural system, it developed and generated a terraced land surface for effective farming of different types of crops. The resulted landform resembles the traditional Mediterranean agriculture system where crops with less need for water were allocated to higher level terraces and vice versa.

In the second set of experiments, the three previous systems were integrated into one system; and the collective interaction of the sub-systems determined the overall behavior and the morphology of the system. The resulting outcomes showed that the population growth was determined by the availability of resources, which can be defined as the carrying capacity of the superblock. As a matter of fact, one of the interesting observations was related to the system flexibility, when adding more subsystems to the superblock, the flexibility in each subsystem decreases. For example, the agriculture system reduced the production of the energy system because they were competing for the same production space. Therefore, the design required a compromise between the productivity of the subsystems.

The last part of the design experiment was the implementation of the generated productive surface in the design process. Basically, the aim of the resulting morphologies – productive surfaces - was to utilize them as spatial organizers and distributors of the urban systems. Essentially, it acts in two ways: first, it sets spatial boundaries and constraints of the morphology of the inhabited spaces; And secondly it provides a point cloud of multi-dimensional a data-scape of numerical and vectors data related to water, energy, and agriculture. For example, the data of the water surface informs the distribution, shape, depth, and size of the water pond. The same with the energy system; the data which confirms the potential of the solar energy production in each point and the minimal sun exposure. In the case of agriculture, the agriculture terraces, crop types and their forms were driven by the generated data; and their three-dimensional distribution was determined by the orientation and inclination vector of each point. Fundamentally, the process starts with productive surface generation; then they are translated to point-cloud data which informs the architectural materials, such as topographical surfaces, ponds, agriculture terraces and inhabited buildings. It can be followed by further developments, such as network analysis and public space distribution. The significance of this initial diagrammatic manifestation of the ecological superblock is not on the physical materialization of the morphology but on the data-cloud of the relationships and their mathematical expressions, which are the primary production of the research. These relationships inform each point, terrace, area and volume with the material and design possibility.

To sum up, first the research aimed to demonstrate the applicability of ecological thinking in architecture design. Secondly, the model is mutable and can be adapted to different environmental, climatic, and cultural conditions by expanding and adding more systems. The third point related to urban growth, because the urban system performs according to environmental interaction; urban growth cannot be achieved just by scaling up or by uniform repetition of the superblock. Therefore, urban growth can be achieved by expansion of the superblock in different directions, which can be called “carpet expansion strategy”. The last point is the contribution of ecological thinking to the paradigm shift in design, which shifts the focus from the concept of form and objects to the concept of dynamic processes and computation.
1.2. The Ecological Superblock

Urban Block has been a basic element of urbanism since the emergence of cities. With the advent of agriculture, houses were clustered in groups near the cultivated lands allowing for cooperation among citizens. The clusters evolved into a nested block system whose form was determined by climatic and topographical conditions: for example, houses were arranged around a courtyard for solar condition (Weinstock, 2010). Ancient cities, villages and settlements, whether they were planned or grown organically, were organized according to a nested block system of courtyard houses. Classic examples are cities such as Ur, Miletus, Rome and Beijing. The Spanish colonies in Latin America also adopted the gridiron block system (Morris, 2013).

An urban area that consists of a scaled-up block or aggregation of multiple blocks, limited with a defined perimeter space, is considered a superblock. Following this definition, the term superblock can be used to indicate various things, including a large neighborhood block, a whole neighborhood, an urban space, is considered a superblock. Following this definition, the term superblock in its contemporary form, is a by-product of modernism, developed in the early to mid 20th century, as a response to the increasing housing demand, changes in mobility patterns and industrialization (Blau and Platzer, 1999). It is primarily composed of residential units: a centre of shared public facilities and green areas. The first examples of the superblock were seen at the Berlin City Planning Exhibition in 1910 (fig) 1.1.1. Among them, the Niederschonhausen Superblock designed by Paul Mebes, consisting of multi-storey buildings accessible by pedestrian paths along courtyards, open to the streets. Inside the superblock there were large green areas for common use (Blau and Platzer, 1999). The courtyard and green areas were designed for residents’ use only. This type of spatial organization was considered an innovation, as opposed to the traditional urban block, consisting of rows of houses located along a street. Several similar approaches were developed in Europe in the same period, which likewise had internal access, green areas, playgrounds for residents and a clearly defined perimeter. Another, earlier application of the idea of superblock, coupled with the street hierarchy system, was carried out by Stein and Wright in terms of their design for Radburn, New Jersey (1928): which consisted of a cluster of superblocks forming a self-contained neighbourhood(fig) 1.1.2. Subsequently, a group of neighbourhoods would then comprise the city (Patricios, 2002). The superblocks are grouped around a central green space, with a system of hierarchical roads. The design of the Radburn neighbourhood model was, in essence, hierarchical, comprising four levels: enclave, block, superblock, and neighbourhood(fig) 1.1.3. The designers of Radburn argued that the utilization of the concept of superblock reduced the amount of land devoted to streets and allowed for the creation of a central garden for social use and climatic regulation (H. Wright, 1935).

The block and the superblock have been applied in many cities worldwide as urban arrangement strategies and design elements. Some of the more prominent examples are: 1) The Barcelona block designed by Centia, the planner of Barcelona’s extension beyond its walls in the 1860s, proposing the ideal industrial city block [100x100m, 1.2 hectares] containing a garden centre, surrounded by 20m wide streets, underground hygiene services (water, sewers, plus gas and telegraph) (Ildefons, 2018). 2) Chandigarh, where Le Corbusier planned a 1km X 1.4km grid that contained seventeen 1000m x 800m superblock neighborhood sectors (each of 96 hectares) containing several “urban villages” of 150 families. 3) Brasilia’s Superquadra, planned by Lurcio Costa (1956-60), was for smaller but had a higher density as Oscar Niemeyer used 6-storey slab blocks raised on pilotis. 4) The New British town, Milton Keynes, planned by Llewelyn-Davies, Weeks and Bor (1948), laid out as a 1x km grid, similar to Brasilia. 5) The Soviet Micropolitan (Microrayon), a residential superblock with a population between 10,000 to 30,000 inhabitants, including services such as schools, retail, services and playgrounds, among others.

Graham argues that the “enclave” is an urban element and organizational device of the city. His definition of enclave is a space defined by a perimeter with one or more entries and a clearly defined centre. It is like a field in the countryside, a piece of urban property with a wall around it or an open space like a square at the centre of a city surrounded by buildings, with the Forbidden City and the Rockefeller Center provided as examples. The scale of the “enclave” may range in size, from a small, single block to medium-sized city blocks (an urban village), to a large, modern superblock (a neighbourhood unit with a school) to Extra Large – a Megablock in a suburban patch(fig) - 1.1.4.

Superblocks exist as nodes in a large system of urban networks with a relatively high concentration of people, materials, energy and information. They can be viewed as dynamic, complex system with flows of material and energy through systems of networks and surfaces with a variety of ecological interaction processes between the ecosystem and the urban area. These ecological processes can be considered complex open systems related to the phenomena of adaptability, resilience, or open-ended models and flexibility. This idea of ecology and planning can be traced back to the work of Ian McHarg in the sixties and seventies, which showed that analysis and assessment of natural resources could inform us of the best places for and ways of developing land for social occupation.

In the 1960s, aiming to understand how cities work and the impact of the infrastructures that sustain them, the notion of city as a system replaced the traditional conception of the city as a module of physical structures and aesthetics. In this model, the system is compared
of a set of interacting subsystems with hierarchical organization, more likely to be in disequilibrium or even closed as far from equilibrium (Batty, 2013). This understanding exhibits the dynamic, evolving nature of cities, providing a better understanding of the principles of urban systems and their interaction with environmental systems. This includes urban forms, human actions, and how these inform the architectural morphology of the urban system.

The massive demand for developing new cities represents a key opportunity for using ecologically based design superblocks. A new configuration and model of the superblock, in all likelihood, has the necessity of coping with and adapting to the pressing challenges facing the world - including climate change, depletion of resources and population - and attempting to manage and regulate complex ecological processes. There is the model that can manage flows of resources, maximizing the production and recycling of material and energy, shifting the urban model from a model of consumption to one of production; thus, within its boundaries achieving a degree of self-sufficiency - the “autonomous”. Accomplishing this objective requires an understanding of the flow dynamics into and out of the urban system. A systemic approach to the ecological superblock has a methodological implication; that is, an urban system requires a scientific approach to design.

In spite of these assertions, the planning and designing of the superblocks failed to address these ecological issues. They performed as mere ‘containers’ of population and, in the best cases, they succeeded in providing services to their inhabitants, such as education and retail facilities.

1.3. Urban Metabolism

The Urban Metabolism notion was introduced in the 1960s as a scientific study of the material and energy inflow and outflow in urban areas. The concept of metabolism is much older, emerging in the nineteenth century as a way of describing the exchange of matter between organisms and their environment (Rapport, 2011)(fig)-1.1.5. It is defined as the sum of the chemical reactions that take place within each cell of a living organism and that provide energy for vital processes and for synthesizing new organic material. It refers to how living beings extract energy from their environments and use it to carry out activities including growth and reproduction.

In an analogical manner, cities function through their systems by circulating materials, energy, biomass and information. Here, cities are organisms that consume energy, food and water, among other materials, and excrete waste. This metabolic flow has an environmental impact that extends beyond the city limits. Therefore, the study of these metabolisms is imperative for design because it can reveal how urban morphology relates to the means of capturing and transmitting energy, materials and information. Grounded on the analogy of biological metabolism, urban metabolism is the energy, material and information which flows through human settlements, in which material inputs transform into useful energy, physical structure, and waste.

Urban Metabolism focuses on quantifying the flow of matter and energy in urban systems, aiming to optimize it, making cities less dependent on their wider hinterlands and more self-sufficient in terms of resource generation and waste disposal (Dinarès, Wolman (1965) coined the term Urban Metabolism, in response to deteriorating air and water quality in American cities. Wolman developed a model which allowed him to determine the inflow and outflow rates of a hypothetical American city with a population of 1 million people. He defined the metabolic requirements of a city, including all the materials and commodities needed to sustain the city’s inhabitants at home, work and play (Wolman 1965). This results from taking into consideration all technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and waste processing; which can be reduced to the inputs, outputs, and stores of energy, water, and materials of an urban area (Kennedy et al. 2011).

The notion of Urban Metabolism is used to describe a variety of processes, including the interactions between organisms and their surrounding ecosystem, the interaction between an urban area and its hinterlands, and the way in which social and ecological processes interact to produce urban environments (Rapport, 2011). Thus, Urban Metabolism can be a productive and useful way to conceptualize how an urban area functions. Odum suggests that city metabolism can be typically expressed in terms of energy flow (Odum and Barrett, 1971). Based on this notion, nature becomes the model of a city’s metabolism; the city is to become an artificial ecosystem. The metabolism of an ecosystem has been defined by ecologists as the production (via photosynthesis) and consumption (by respiration) of organic matter. Thus, Urban Metabolism can be computed and analysis conducted by utilizing ecosystem dynamic modelling.
2014). Their field of study focused on practical applications such as urban greenhouse accounting or mathematical modelling for policy analysis. However, in the urban design context, the metabolic processes have not been applied in relation to the morphological design and organisation. Considering the urban system as an ecological system or ecosystem, enables us to calculate the system’s dynamic and inform the urban morphology.

1.4. Ecological System

Ecological thinking about the architecture of a city requires adopting method and modelling approaches founded on the science of ecology in general and in terms of ecosystem modelling in particular. According to the definition provided by Tansley (1935), an ecosystem is an integrated system composed of interacting biotic and abiotic components (Tansley, 1935). It is considered to be the basic, fundamental unit in ecology comprising a community and its physical and chemical environment at any scale, within which there are continuous fluxes of matter and energy in an interactive open system (Arthur J. Wills, 1997). Ecosystems provide services by nature and are used by living beings.

According to the MEA - Millennium Ecosystem Assessment 2005, ecosystem services are grouped into four categories. First, ‘provision services’ including food, fuel and water. Second, ‘regulation services’ including control of climate change events, stabilizing processes, decomposition of waste, purification of air and water and erosion control. Third, ‘supporting services’, including crop pollination, seed dispersal, maintenance of biodiversity and cycling of nutrients. Fourth, ‘cultural services’ including cultural and recreational benefits. These services are provided by complex chemical, physical and biological processes, powered by the sun, and operate at different temporal and spatial scales (Millennium Ecosystem Assessment, 2005). Similar to natural ecosystems, cities provide the “services” through all of its systems which are collectively known as ‘infrastructure’. The deterioration and degradation of the ecosystems’ services as a result of human activities, coupled with the unprecedented increase in global population, bring the world to the threshold of ecological collapse (A K Salomon, 2009).

A significant advance was made in ecosystem modelling by the introduction of General System Theory (1949) principles in biology. The theory which was developed by Austrian Biologist Ludwig von Bertalanffy (1901-1972) put the emphasis on holistic and network approaches and on the interaction between the parts (Von Bertalanffy, 1968). These principles have indeed become fundamentals in ecological modelling. Among the scientists who have influenced the development of quantitative assessments of ecosystems are Raymond Lindeman (1915-1942), Eugene Odum (1913-2002) and Howard T. Odum (1924-2002)[fig.1.1.6]. Lindeman pioneered the concept of Trophic Dynamics. His work focused on the flow of energy up the food chain from the autotrophs to the top carnivores (Lindeman, 1942). H.T. Odum pioneered the Ecosystem Ecology and embraced Lindeman’s approach as well as the principles of trophic dynamics (Odum and Barrett, 1971). He proposed additional

![HT ODUM METABOLISM DIAGRAM](image)

laws of thermodynamics and founded Ecological Engineering. The system approach allowed for the linking of different disciplines, including Industrial Dynamic, which was developed by Forrester (1961) to describe the flows of matter and energy in industrial systems. His approach was generalised and applied to a system ecology context, in the 1960s and 1970s there was an increasing interest in ecological modelling that coincided with the computational power advancements of the era in the form of the digital computer (Forth et al., 2012). These models were mostly focused on population dynamics and biochemical models in the context of aquatic systems in the 1970s. In the 1980s, ecological terrestrial models were developed and published. Over the last few decades, a significant number of ecological model types have been developed to address ecological systems at different scales (Jørgensen, 2016).

H.T. Odum argues that in spite of the fact that ecological systems are different, they have enough features in common to justify describing basic patterns that are common throughout all ecosystems. These patterns set the underpinnings of ecosystem modelling. Four fundamental properties concerning the structure and function of ecosystems were identified by the author: 1) Ecosystems cycle energy. 2) Ecosystem cycle matter. 3) Ecosystems functions (internal variable) are determined by the environment (external variable). 4) Ecosystems require a holistic approach for examination and study due to the fact that they create whole systems (Jørgensen, 2009).

Ecological models of ecosystems have been developed and applied as a tool in environmental management. Jørgensen identified eleven different model types (Jørgensen and Bendoricchio, 2001). Jørgensen argues that these classical and widely used models are the Population Dynamic, Biochemical and Boenergetic models. Population dynamic models are used to describe the development of biological populations in terms of growth, mortality, age structure and distribution in populations. The model provided tracks the resources and negative effects

![ECOLOGICAL SYSTEM](image)
related to population development. This model is based on Lotka-Volterra models from the 1920s. The other two model types, Biochemical and Bioenergetics, apply the mass and energy conservation principle. These models describe the processes of mass, mass and energy transfer within the system. They mainly apply a differential equation system to express the dynamics of and changes in state variables which express the difference between the incoming and outgoing substances. Causality is considered one of the basic principles applied in these models. The straightforward nature of and simplicity with which these models can be understood, coupled with software availability, make them attractive in the development of many models. They are mainly used in environmental management and applied in describing states of ecosystems and their reactions to environmental processes.

### 1.5. Design Science

Design, according to Herbert Simon, is the devising of courses of action aimed at changing existing situations into preferred ones. Simon presented the scientific study of designing in the influential text ‘The Science of Design’ as a chapter in his seminal book ‘The Sciences of the Artificial’, in 1969. Simon suggests that the ‘The Science of Design’ is a “...a body of intellectually thought, analytic, partly formalizable, partly empirical, teachable doctrine about the design process’ (Simon, 1996). Thus, it could form a fundamental, common ground of intellectual endeavour and communication across the arts, sciences and technology. In this regard, the study of design could be interdisciplinary study accessible to all those involved in the creative activity of making the “artificial World” (Cross, 2001).

A number of topics and principles within the ‘The Science of Design’ are still relevant today. Amongst them are the creation of all possible “worlds” for the design problem, and an emphasis on processes and iterative computational and simulation methods. Most significantly for this enquiry is the argument concerning the relationship between the inner and outer environment of any designed artefact. This suggests that the interactions between the inner and outer environments of the artefact require a design process informed by the sciences of the natural world. These interactions formulate the possible alternatives of a design. In this approach, design is a problem-solving process formulated by establishing an objective. It is value-neutral, quantifiable and belongs to the mathematical field of research-centred problem solving and seeking the optimal solution.

Simon argues that designers can augment their limited capabilities by utilizing computers to seek out the optimal solutions, employing the logic of optimization methods, which can be formalized into “a standard mathematical problem”. Here the author places the emphasis on iterative computation and simulation methods. Herbert Simon developed his seminal work concurrently with other authors who followed a scientific approach to design. His work is considered as part of the Design Method Movement developed in the 1960s.

Another seminal figure of this movement is Buckminster Fuller who coined the term ‘design science revolution’ in 1961 (Glegg, 1973). Here the author was concerned about the need to optimize natural resources on a planetary scale and the impossibility of politics addressing this endeavours. The author argues that humanity should follow the principles of nature as a rationale for technological development; moving from a resource exploitation approach to a regeneration approach. His argument is that by naturalizing the principles by which humanity makes use of resources on earth it minimizes its impact until it becomes ephemeral. The vision of Buckminster Fuller has inspired planetary scale movements, the idea of Anthropocene and the recently coined Planetary Urbanism.

An important event within the Design Method movement in the 1960s was “The Conference on Design Methods”, held in London in 1962 (Cross, 1993). One of the main contributions of this conference was the need to develop design methods resulting from a multi-disciplinary collection of complementary perspectives. The idea of a multi-disciplinary approach to design was an ontological innovation broadly employed in the design process. Their main purpose was to connect and link all creative activities that employ scientific methods. The scientific approach to design led to the emergence of the design research discipline firstly defined by L. Bruce Archer as a “systematic inquiry whose goal is knowledge of, or in, the embodiment of configuration, composition, structure, purpose, value, and meaning in man-made things and systems.” The design experiments conducted in his research applied a number of these principles among others.

### 1.6. Design Research Domain

The scope of the research encompasses the investigation of the design implications for the development of an ecological superblock. An ecological superblock integrates ecological thinking and modelling approaches from ecology in the design method, thus generating its morphology, specifically, by applying principles from urban metabolism and ecological systems dynamics. Coupling these two fields is addressed through the application of Systems Dynamic Mathematical Modelling. The System Dynamic was developed as a methodology for modelling complex ecological systems.

Through a thorough analysis of the ecological aspects of two seminal visionary cities’ proposals: Hilberseimer’s “The Decentralized City”, and Soleri’s “Arcology”, the research aims to develop an ecological superblock, which employs principles from both cities by means of applying the System Dynamic model of the continuous fluxes of material, energy and information. To facilitate this, the research seeks to achieve its objectives through a comprehensive analysis of the ecological systems and ecosystem modelling methods. An overall review of the history of ecological modelling and their importance in the development in understanding of ecological systems.

In the domain of computational design, the research will focus on developing methods to study the evolution of the superblock, following the Evolutionary Optimisation Method integrating urban systems dynamics. It will do so by integrating (i) a
mathematical model of dynamic systems into (2) an Evolutionary Design Model of the morphology (EDM). The first model, the Systems Dynamic Model (SDM) is built based on systems theory, feedback and control theory. SDM has been used for a wide spectrum of applications including the modelling and simulating of social, economic, physical, chemical, biological, and ecological complex systems. Contrary to traditional analytical methods, SDM focuses on the system as a whole and on the interconnectiveness between its components and processes. The SDM model is coupled with that of EDM enabling the study of multiple optimization objectives and using the genes as a concept for the model to mutate and adapt to multiple scenarios. Mutability of the model is one of the characteristics that allows for modification and adaptation of the design scenarios pictured by the SDM. The focus of the design is placed upon the spatial formation (morphology) of the superblock, narrowing down the system modelling to four systems: (1) Population, (2) agriculture and aquaculture (3) water and (4) energy.

1.7. Design Proposal

The spatial and organizational principles of the superblock developed by Hilberseimer in his model for the “Decentralized City” will be considered as the point of departure, a primitive step in the design process. This primitive step will be introduced as an input into the computational model consisting of a mathematical model of urban dynamic systems linked to a generative model of urban morphology following the principles of the Darwinian Theory of Evolution. For the scope of this research, the structure of the System Dynamic Model is determined by four systems: population, energy, water and agriculture. System theory is adopted to: firstly, trying to understand how each system in isolation can be optimised and linked to urban morphology and secondly, in integrating the systems together. The integration of four urban systems into one dynamic system model will inform the morphology of the superblock. Parameters from the four systems will be coupled with parameters related to the morphology of the block which will be optimized by applying principles of evolutionary theory in the design method. The research questions of the research are grouped into three main categories, namely architecture of the city, ecology, and computation.

1.8. Research Question

The research questions concerning this research are divided into the categories of primary and secondary question. The primary is concerned with the theoretical implications of ecological computation in design and how the process is related to the architecture of the city. The secondary is related to the computational modelling of dynamic systems towards generating urban morphology.

- **Primary Research Question**: Can ecological parameters be coupled with morphological and metabolic parameters and processes to design a superblock that is fully integrated with the flows and dynamics of the climate and the ecological system in which it is embedded?
- **Secondary Research Questions**: Can a generative design approach be applied to the ecological superblock which can evolve and adapt to the external and internal governing parameters?

1.9. Design Methodology

This section describes the methodology used throughout the thesis in order to develop a design model capable of generating an ecological superblock embedded in different climatic and environmental contexts. This section can be divided into three stages:
- Background and Context Research
- Computational Model
- Design Experiments

1.9.1. Background and Context Research

Urban, Ecology and Computation: The research examines the intersection between 3 primary domains, the architecture of the city, ecology, and computation. In the architecture of the city field, a thorough analysis was carried out into the research of Hilberseimer and Soleri. This research has adopted the relevant principles extracted from their work which focuses on the scientific approach of calculation and empirical data collection in the design process. Additionally, the research employs the concept of the “settlement unit” as the basic productive and design unit in the city and is presented as “Superblock”.

Within ecology, a sub-domain is extensively researched, this being the ecosystem system concept. Following the definition of ecosystem as a fundamental unit in ecology, in turn the superblock is defined as an ecosystem. Based on this definition, the research adopted the analytical method of understanding and analysing ecosystems. The experiments undertaken during
the research define and examine the superblock as a system composed of subsystems in which the principles of boundary, behaviour and feedbacks become crucial in the design process. The superblock as an ecosystem functions as an energy, materials and information transformer. From this perspective, the studies of these inflows and outflows within the superblock can be seen as a metabolic study of cities (as defined by Wolman) and is known as urban metabolism. Analysing these flows in the contexts of the superblock, the research uses the notion of stock and flows as an accounting technique and as a framework for the analysis of the urban system. A stock can be defined as an asset at a particular point in time, whereas a flow represents transfers to or from a stock over a given time period.

Thirdly, there is the addressing of ecological computation by way of a thorough analysis of the historical development of ecological modelling. The analysis reviews the existing model types employed in computing and analysing ecosystems. Mathematical and computational methods are extracted from the “translation” of the ecological phenomena into formal mathematical computational problems. This technique and method, which involve ecological computation, are used in the modelling and simulation of the urban system including population growth models and biochemical dynamics models. In contrast to a statistical analysis which reveals relationships between data, the ecological models focus on the process and on the interaction between the system components. Employing these models in the architectural design process will shift the emphasis from the end result towards the generative process involved in the formation of the morphology.

1.9.2. Computational Design Model

The next stage focuses on the formation of the computational design model. It is composed of two linked models that work together to simulate urban dynamic systems behaviour and to generate morphology – the System Dynamic Model (SDM) and the Evolutionary Design Model – (EDM). The first model mathematically formalizes the structure and behaviour of the systems. The second model focuses on the formation of geometry based on parameters and data extracted from the SD model. SD modelling mimics the behaviour of complex systems and their functional relationship. This method is a computer-aided approach to the design of dynamic problems arising in complex ecological systems (Wallach et al., 2014). It is built to understand the behaviours of complex systems characterized by interdependence, mutual interaction, information feedback, and circular causality. Dynamic System Models are defined as a collection of parts that continuously interact over time and lead to the emergence of new properties. The design experiments start by understanding and simulating independent and later integrated urban dynamic systems. They are modelled as stocks and flows, the analytical result coming from the SDM is transferred as quantitative data to inform the morphology of the morphological model. The proposed methodology adopted to generate design of an ecological system comprises of multi ecological sub-systems. These sub-systems are linked to each other by flows of material, energy and information.

1.9.2.1 Design Experiments

The third stage consists of applying the developed modelling method to a two-stage design experiment. The first experiment simulates four independent ecological systems (population, agriculture, energy and water). Based on the simulation outcome of the systems behaviour, evolutionary models generate the geometry of a superblock. All design experiments undertaken over the course of this thesis were performed on a personal laptop using Stella (www.iseesystems.com) as an object-oriented graphical programming language designed for modelling dynamic systems. It provides a framework for observing the quantitative interaction with a system. The evolutionary models are built in Rhino 3D (www.rhino3d.com) as a digital platform and Grasshopper 3D (www.grasshopper3d.com) as a graphical programming language plug-in within a digital platform for generating the geometries. The simulation of the evolutionary processes relied on an evolutionary solver named Wallacei (www.wallacei.com).

The computational modelling of the dynamic urban systems simulates their behaviour and generates numerical data related to the quantitative parameters of the superblock forms. Once the independent systems models were modelled individually, they were coupled with each other in one integrated systems model. In chapter 4 the individual systems design experiments are documented and chapter 5 documents the integrated system design experiments.

1.10. Research Significance and Contribution

The aim of this research is to make contributions to two primary fields of study. The first is the realm of urban design and the second is in computational ecology with its application in design. In computational ecology, the research introduces computational models to analyse the structure, interaction and modes of behaviour of complex urban systems in order to inform urban morphology. The application of computational ecology has been utilized in urban planning and environment management as an analytical tool rather than a generative one. The contribution to the urban design field will be in the form of creating a dynamic system design model which can integrate subsystems of the ecological superblock.

Ecological computational models are scientific tools of ecology that can provide predictions of systems’ behaviour. This defines three key characteristics of computational ecology. First, it recognizes ecological systems as complex and adaptive that can be mathematically modeled (Wenjun, 2018). Second, the key outcome objective of any model and simulation is the data (Petrosky and Petroskaya, 2012). Finally, due to the fact that ecological systems are generally too complex to be comprehended in mathematical terms, it is argued that conceptual and abstracted models can be used as long as they can be confronted to empirical data (May, 2004). One of the key contributions of the research is the utilization of computational ecology simulation in
the generative processes of the urban morphology.

Regarding urban design, the generation of the ecological superblock emerges from analysing the flows of materials, energy and information through the system that informs the ecological design processes of the superblock. In this sense, urban morphology is determined by metabolic processes. Previous design models make no attempt to establish relations between the urban morphology and the metabolic processes of cities. Most studies of urban ecology adopt the natural sciences approach which addresses biological patterns and associated environmental processes in urban areas, as a subdiscipline of biology and ecology. From this perspective, urban ecology seeks to analyse the relationships between plant and animal populations and their communities as well as their relationships to environmental factors including human influences. (Endlicher et al., 2007)

Overall, the central contribution of the research is in two main areas. The first area is in the architecture of and urban design by developing a design methodology that integrates ecosystem modelling and urban design. The second area is in the development of a computational model, by developing a computational tool that allows one to do that.

1.1. Thesis Structure

Chapter 1: The city as the product of calculation

Chapter 1 presents an introduction to the research domains, topics, research questions and the proposed methodology. The chapter discusses the concept of the productive city and ecological computation models. It sets out the steps required in formalising the system dynamic model for the ecological superblock.

Chapter 2: Cities, Ecology and Computation

Chapter 2 discusses three main topics, the architecture of the city, ecology and computation. It discusses the concept of productive cities and the "settlement unit" as a design approach applied by Hilberseimer. In ecology, it reviews the concept of the ecosystem as a fundamental ecological unit. Finally, it explores the ecological modelling methods and techniques that can be applied in the research.

Chapter 3: Methodology - System Dynamic Modelling

The concepts discussed in chapter 2 are formalised as a design method in chapter 3. It discusses the system dynamic method for modelling complex dynamic systems based on principles of ecological modelling knowledge. It introduces stock flow modelling using the graphical programming "Stella" software.

Chapter 4: Design Experiments - Part 1

Applying the proposed method in chapter 3, four experiments were carried out which are documented in this chapter. The design experiments formulate system dynamic models for four independent urban systems (population, agriculture, energy and water). A detailed explanation of the experiment's setup, parameters and outcomes are presented.

Chapter 5: Design Experiments - Part 2

In this chapter, the four models of the independent urban systems are integrated into one dependent system dynamic model. It is the concluding experiment that examines the integration of four urban sub systems and their implications for the morphology of the ecological superblock system. Analysis of the simulation outcomes and conclusion are presented.

Chapter 6: Conclusion

This chapter concludes the thesis by reflecting on the limitations of the model, the contribution to the discipline and areas in which the research could further develop.
2. LITERATURE REVIEW

Urban Systems
Ecological Systems
Computational Ecology
2.1. Introduction

The literature review will examine the overlapping areas between the fields of Urban systems, Ecological systems and Computation Ecology. Adopting a cross-disciplinary approach, the analysis focuses on the intersection between the subfields of Urban System Dynamics, Ecological System Dynamics and Systems Dynamic Computation. The objective is to establish the relationship between the three domains and define key principles that can be transferred from one discipline to another. In the urban field, a study of two radical and seminal works, which addresses the design of a city as an ecological system, is carried out. The structure and the functions of the ecological system are analyzed in the section on the ecological field. Finally, Computational Ecology as a modelling tool of the ecological system, is explored. The three fields intersect in the topics related to system dynamics of urban spaces, ecology and computation. (figure 2.1.8)

Urban System Dynamics: Ecology in the urban field is primarily focused on the analysis and assessment of the environmental and climatic conditions for managing natural stresses and minimizing destructive environmental impacts. In the design discipline, it provides an inspiration and employs metaphors: city as a living organism and parks as green lungs. The word “Ecology” in design has been oversused and refers to any process or idea related to the environment. Furthermore, there is a relatively small body of literature that is concerned with ecological systems, urban design in general and superblocks in particular. However, there are some design proposals that attempt to employ the ecological system as a model for urban and architectural design. The proposals suggest a holistic mode of thinking which adopts a cross-disciplinary approach including architecture, urban design, ecology and biology, among others.

Ecological Systems: Ecology is defined as the scientific study of interactions between the biological system and the environment. These interactions form an ecological system or ecosystem. Since the introduction of the concept of ecosystem, it has been considered the fundamental unit in ecology. Therefore, the natural world is computed in terms of the flows and changes in the energy and the elements through the ecosystem. According to this definition, cities are considered dynamic interacting systems that transfer energy, material and information. Since the mid-20th century, the scientific investigation of ecosystems coevolves with the development of mathematical modelling that laid the foundations of Computation Ecology. This development led to the implementation of ecological models in different disciplines to tackle complex problems.

Computational Ecology: Although ecological models have been applied as planning and management tools in the urban context for decades, their application in architecture and urban design has not been employed. The introduction of computational applications of System Dynamics Modelling enable numerical and graphical simulations of system behaviour that can inform architectural and urban design.

The following chapter will examine the three domains separately and mutually. The analysis will provide the foundation for subtracting the key principles for their application in the design experiment and the research.
2.2. Reformulation not Reformation

"Reformations are showing their inability to correct system intrinsically wrong. What is in order is a reformulation, a radical reordering of our collective priorities" - Paolo Soleri

Cites around the world have seen unprecedented, rapid increases in population. Although they occupy just about 2 percent of the earth's surface, they account for 60-80 percent of global energy consumption, 75 percent of carbon emissions, and about 75 percent of the world's natural resource consumption (Environmental Development, n.d.). In addition, cities are identified as the key driver of climate change through anthropogenic emissions and the linear urban metabolism in cities. (Omann et al, Kennedy et al., 2007). In this context, a theoretical and practical debate has emerged on how cities should be designed, built and managed, as well as the fact that cities' models initiatives have appeared. They aim to reduce the adverse impacts of cities on the environment and mainly tend to focus on infrastructures for urban metabolism including, sewage, water, energy, and waste management within the city.

They adopt the concept of sustainability that was coined by Brundtland in 1987. It is defined thus; "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The core of it is that cities' claim is that they can respond to environmental crises and resource depletion and produce their own energy and food. Theoretically, practitioners and researchers have proposed a number of fragmented concepts and elements that constitute so-called sustainable development (Carco, 2016). In regard, the process of sustainable development is not considering a design problem, considering the fact that design is loosely connected to the process.

The "sustainable" models can be identified and labelled, as follows: "sustainable cities"; "green cities"; "digital cities"; "smart cities"; "intelligent cities"; "information cities"; "knowledge cities"; "resilient cities"; "eco cities"; "low carbon cities"; "livable cities"; and even combinations, such as "low carbon eco cities"; and "ubiquitous eco cities. Although each of these terms supposedly focuses on a specific set of management and design aspects of the city, research studies have shown that these terms are used interchangeably (de Jong et al, 2015). Moreover, there are no clear, universally acceptable definitions of these terms. They share key principles including minimizing the required production of energy, water, food, waste an gases such as carbon dioxide and methane. (Koh et al, 2010).

Among these models, the smart-city and the eco-city are the most ubiquitous in theory and practice; and Are described by their advocates as the urban innovative solutions based scientific design approach(Cugurullo, 2018). In principle, the two models represent two different approaches. The first approach, the Smart City relies on the integration of the information and communication technology into the city systems to improve and optimize their performance, particularly in terms of energy and transportation ("Inside Smart Cities," n.d.). The second, the Eco-city, attempts to obtain a balance between societies and ecosystems via urban design and behavioural change (Caporali, 2014).

Although the concept of smart cities emerged in the nineties of the last century, its roots can be traced back to the sides of the last century with the emergence of System Theory and cybernetics. (Krivý,2018). The term "smart city" has been used as a fashionable label in theory and practice to promote cities as innovative initiatives that aim to improve the functioning of cities, enhancing their efficiency and improving their competitiveness. Despite the ambiguous nature of the term and the lack of a universally acceptable definition, there is broad agreement on the key characteristics that define the smart city, which is the pervasive deployment of technology to improve efficiency and optimise performance of city systems, including people, energy, water, transport, communication and business (Taylor Buck and White, 2017). In 2015, the International Telecommunication Union (ITU), which is the United Nations specialized agency for information and communication technologies – ICTs – agreed on the following definition of a Smart Sustainable City: “A smart sustainable city is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects” (“Focus Group on Smart Sustainable Cities,” n.d.). The argument behind this definition is the premise that the city function and its urban metabolism management need a central ICT System control which continuously obtains data from different resources via real-time sensing. The ICT is central to the operation of the city. Therefore, the key principle involves integrating and coordinating different and separate technologies that can synchronize and communicate data. It is argued that these technological instruments drive cities to become “smart” by Integrating and synthesizing the data by “intelligence” functions as a means of improving the efficiency, equity, sustainability and quality of life (Batty et al, 2012). Having said that, the smart city is identified mainly in terms of its instrumentation which is the key driver of climate change through anthropogenic emissions and the linear urban metabolism in cities. Therefore, technology is the core concept of the smart city which aims to improve productivity, and the dominance of technological management tools over other aspects such as societal, environmental, economic or climatrical processes, implies that the smart city does not necessarily provide a model capable of addressing other crucial issues of city-making. Moreover, it ignores the significance and impacts of urban morphology on what is allegedly called "smartness" of the city.
Similar to the smart city concept, the eco-city emerged in the last two decades of the last century. In this case as well, there is no universally acceptable definition of the eco-city but there is a common view of the basic features among the available definitions which revolves around the principle of a city being in balance with nature. A definition of eco-city that was put forward by the Ecocity Builder Organization is: “The ecocity provides healthy abundance to its inhabitants without consuming more (renewable) resources than it produces, without producing more waste than it can assimilate, and without being toxic to itself or neighboring ecosystems” (“What is an EcoCity?,” n.d.). Another definition that is economically driven, introduced by the World Bank, reads: “Eco2 Cities are defined as cities that create economic opportunities for their citizens in an inclusive, sustainable, and resource-efficient way, while also protecting and nurturing the local ecology and global public goods, such as the environment, for future generations” (“Eco2 Cities – A Guide for Developing Ecologically Sustainable and Economically Viable Cities,” n.d.). Based on these concepts, eco-cities initiatives emerge in academic and planning discourses as necessary to tackle environmental issues. The key driver of the eco-city is the economic development that respects the planetary boundary while allowing for improvement in the general wellbeing of people (Register, 1987). Their objectives are to eliminate carbon waste, harvest energy from renewable resources, improve health, stimulate economic growth and integrate environment with the city (Amatohap et al., 2016). In addition to reducing the impact of cities on the ecosystem, they act as instruments to attract foreign investment in order to promote economic growth (Koh et al., 2016). In this respect the differences between smart city and eco-city are theoretical and, in practical terms they are essentially the same.

Although these models have been adopted mainly in policy and planning discourse, they make no attempt to consider or investigate the city form – morphology – and its implications for the city in terms of performance and impact on the environment. The models provide a framework for policy and act as a guide for processes regarding the development of the city yet lack any intellectual framework for design and physical manifestation of the urban areas. Moreover, examining the physical manifestation of these two types of model reveals doubts about their ability to achieve their ambitions and goals. In Critical Urban research by Cugurullo (Cugurullo, 2018), a variety of case studies were examined showing that alleged smart cities and eco-cities: (a) are far from their philosophical ideals, (b) rarely innovate but instead replicate traditional capitalist strategies of urbanisation, and (c) seldom keep their promises of sustainability. In addition, critics question the ability of the technologies in providing solutions to current and future problems. The key driver of the eco-city is the economic development that respects the planetary boundary while allowing for improvement in the general wellbeing of people (Register, 1987). Their objectives are to eliminate carbon waste, harvest energy from renewable resources, improve health, stimulate economic growth and integrate environment with the city (Amatohap et al., 2016). In addition to reducing the impact of cities on the ecosystem, they act as instruments to attract foreign investment in order to promote economic growth (Koh et al., 2016). In this respect the differences between smart city and eco-city are theoretical and, in practical terms they are essentially the same.

Another criticism suggests that these cities fail to integrate and interact with their environment. For example, a research study on the well-known eco-city Masdar and Hong Kong’s smart city has revealed that on a micro scale regarding the single building, single infrastructure and single technology underwent scientific experimentation before being integrated into the city. However, on a macro-scale, concerning the whole city and the region, there is neither scientific experimentation nor systematic methods regarding urban planning and design. (Cugurullo, 2018). Consequently, the major limitation of these models is that they are mostly focused on improving the local environment and global climate and less on the impact of urbanisation on the regional ecosystem and ecosystems services.

Moreover, these models have not introduced a holistic approach that can integrate all of a city’s components and systems into one functioning system. Despite the theoretical logic of systems thinking about sustainability and the smart-city and eco-city, the sustainable city-making models address the city problem by separating its components into isolated parts. In this sense, the urban problem is seen as a collection of isolated parts and not an integrated complex system that includes water, energy, agriculture, population, policies and economy among others (Orr, 2014). Their infrastructure and technologies are not designed as an integrated whole system but through a fragmented part. It follows the scientific worldview of reduction that breaks the wholes into parts; an approach that cannot deal with real world problems which exhibit properties such as emergence, tipping points and unpredictable events (Orr, 2014).

Based on this critical examination, it is evident that sustainability, including the smart-city and eco-city are not suggesting an alternative model to the traditional urban models. In that regard, they are not advancing strategies or design that can cope with the climatic and environmental challenges. In this context, a system approach to city-making is considered a paradigm shift from seeing parts to seeing wholes and from dealing with objects to dealing with processes. In fact, there is a widespread agreement that cities are more complex than the sum of their parts and developed through a multitude of individual and collective decisions from the bottom up to the top down (Batty et al., 2012). This system thinking can be traced back to the mid of the last century and based on the seminal research and writings of Ludwig von Bertalanffy, Herbert A. Simon, and Jay Forrester, among others. A system perspective of urban design can be seen through ecological thinking that is based on cause-and-effect relationship and feedback loops among coherent, organized, interconnected elements.

In this regard, introducing an alternative model based on ecological thinking can depart from the critical study and examination of urban ideas developed in the first half of the twentieth century. Two seminal works of Hilberseimer and Soleri show two antipodal yet complementary approaches. Hilberseimer adopted a holistic design approach towards the integration of agriculture into the city. On the other hand, Paolo Soleri expanded upon the traditional definition of ecology and the relationship between the natural world and man-made nature. Hilberseimer considered the city as a dynamic complex system and Soleri viewed the city an integrated organism. Both call for reformulation of the city rather the reformation. The following sections will explore their ideas and their relevance to contemporary city problems.
2.3.1. City in nature

"Reason is the first principle of all human work. Consciously or unconsciously, L. Hilberseimer follows this principle and makes it the basis of his work in the complicated field of city planning. He examines the city with unwavering objectivity, investigates each part of it and determines for each part its rightful place in the whole." Mies Van De Rohe (Hilberseimer, 1949)

The contemporary city and its systems are facing increasing stress as a result of rapid population growth, climate change and depletion of resources. This situation raises doubt in the ability of existing city systems to tackle these challenges. Nowadays, there is an increasing interest in food production, resources management and ecological design in order to ameliorate and adapt cities as they undergo changes. In this section, the research and work of Ludwig Hilberseimer, who carried out many research studies into the challenges and problems arising as a result of the development of industrial cities, will be reviewed. The objective of the review is to investigate the planning and design principles which were put forward and to examine their relevance to today’s cities.

The work and research of the German architect, urban planner and educator, Ludwig Hilberseimer (1885-1967), in the architecture of the city is considered one of the most radical and original projects in the field (Hilberseimer and Aureli, 2014). Similar to many of his contemporary architects in the early twentieth century, including Le Corbusier and Frank Lloyd Wright, he proposed design and planning proposals for the future city and metropolis. Hilberseimer’s projects and writing can be divided into two phases. The first is the “Berlin” phase, where he lived and worked after WW1 and developed his early principles concerning city planning and architecture (in the 1920s and 1930s). The second phase is the post-war North American one, after 1938, when he started teaching at Armour Institute (subsequently renamed Illinois Institute of Technology). Hilberseimer’s early 1924 project, namely the High-Rise City (Hochausstadt) for one million inhabitants is considered to be the first significant as well as iconic project of its kind and was published in Grosstadtarchitektur (1927). Later, in 1944, he published his second seminal work: the “Decentralized City”, after he moved to the United States.

Although the two projects seem distinct and contradictory, both can be considered products of calculation. According to Hilberseimer, his projects are, “theoretical examinations and a schematic application of the elements from which a city builds itself. It is a stipulation of their relationships to one another. An attempt to make possible a more economic formation of a city organism through the new organization and use of these elements" (Hilberseimer and Aureli, 2014). This review focuses on these two seminal projects – the metropolis and the decentralized city - and the research studies and methods employed in the design process.
2.3.1.1 Historical Research

To establish his argument within the two projects, Hilberseimer studied and analyzed cities of the past to understand and discover how the city form and structure developed. The research studies assumed that the success of cities in the past was determined by specific principles and structures (Spaeth, 1988). He saw the basis of architectural activity in anthropological, and perhaps Darwinian, terms, as humanity's struggle to dominate nature (Liebensohn and McCarthy, 1988). Thus, it is determined by the society that make its creation possible through material means. In his book 'The New Regional Pattern', Hilberseimer set out a "quasi-scientific" historical analysis and criticism of the city. By quoting Ortega Y Gasset, he argues that historical knowledge can be utilized as a technique to preserve and continue already advanced civilization and prevents societies from committing ingenuous mistakes of the past. Hilberseimer considered the creation and development of cultures and civilization as a dynamic process of the use and organization of the Earth and nature. By studying the cities of the past, he maintained that the growth and decline of cities depend on social, spiritual, political, and economic forces. These forces are influenced by the status of technology, the form of production and consumption and by the means of transportation (which can be regarded as the metabolic processes of the city). He argued that the unbalanced and inappropriate use of these forces would cause internal and external disorder and collapse (Hilberseimer, 1949).

To support his argument that the most important factor in the development of culture and civilization is the use of land, he provided three different historical examples of different methods of land use and organization. In the first example, he presented the inevitable collapse of Rome due to the fact that it was never a productive city. It flourished at the expense of its provinces spread over vast distances. When these provinces failed to support Rome – for different reasons - through agriculture and material products, it sank to its lowest ebb and its population reduced to one fifth. In the second example, the Inca Empire, Hilberseimer maintained that Ancient Peru had a high culture and civilization which was based on primitive means of production and on simple but efficient distribution and use of land. He argued that the prosperous and harmonious life and culture was a direct result of balanced agriculture and industrial production as well as equitable distribution of land and goods. This "developed" civilization was intercepted by the Spanish invasion and conquest which led to its collapse. For Hilberseimer these two examples present two opposing principles in regard to productive work and its relation to the city. He argued that the Romans had liberty without security whereas the Andeans had security without liberty. In the third example, Hilberseimer claims that the combination of liberty and security can be found in the medieval town. This security and liberty in society was based on free work and free exchange of industry and agriculture. The medieval town, by developing its industry and exchanging and trading its products for raw materials and agricultural products from the surrounding countryside and other towns, attained economic and political freedom.

In addition to the production and consumption processes and their impact on the prosperity and success of the city, Hilberseimer analyzed and studied the geometric structures and circulation systems of many eras, including Greek, Roman, Medieval, Renaissance and Baroque. In these historical studies he tried to identify an appropriate and reasonable model or pattern for consideration and development. He opted for the medieval city as an admirable model for examination and a possible city structure for further development (Hilberseimer, 1955). Such cities suggested to Hilberseimer the importance of the close proximity between dwelling and workplaces. They also demonstrated the pedestrian scale of the city structure which limited walking distances therein, in terms of negotiations among various parts of the city. These reflections and insights on the historical urban structure became a significant part of Hilberseimer's principles for the architecture of the city, particularly the integration of workplace and dwellings.

2.3.1.2 High-Rise City

In order to tackle the emerging problems of the modern city, Hilberseimer developed his first seminal study and project regarding the metropolis which was called the "High Rise City" (Fig.2.1.10) for one million inhabitants. It was conducted in 1924 and published in 1927 in Hilberseimer's book Grossstadt Architektur. Hilberseimer's proposal was based on the principles of mass production principles and organization, developed in particular by Henry Ford, among others. In contrast to the existing models of city plan which were based on horizontal zoning of the land, Hilberseimer proposed vertical zoning and attempted to reestablish the medieval principle of overlapping living and working areas.

The city consists of two levels: the lower for business and road traffic and the upper for the residential city and pedestrian circulation. It consisted of twelve by ten blocks over an area of 1400 hectares, each block 600 by 100 meters with 60-metre wide vehicular roads. The block split vertically into two zones; the lower zone consisting of five-storey office and manufacturing spaces, and the upper one rising up to fifteen storeys of apartments. The
apartment slabs which were 10 metres wide and stepped 8 meters back on to the street side created a pedestrian walkway. In order to expose the building to light and allow air flow, the two layers of the city – the commercial and the residential – were organized around courtyards which were 60 meters wide.

Hilberseimer computed the appropriate orientation of the residential slabs, the width and height of the block, street width and the distance between blocks in order to optimize two objectives which were the east and west solar exposure and the subway stop locations(fig)-2.1.11. Furthermore, he calculated the density which was increased by concentration and overlapping uses. His calculation resulted in distributing the building in such a way that the height of the buildings was exactly the same dimension as the width of the roads. The apartments were arranged at a north-south direction which is the long side of the block facing either east or west. He claimed that the solution for metropolitan housing problems can be found by applying this calculation method.

The high-rise city was influenced and inspired by Le Corbusier’s City for Three Million Inhabitants which Hilberseimer studied and analyzed. He argued that Le Corbusier made errors in calculating the density of the population and failed to solve the traffic problem of the modern city. According to Hilberseimer, Le Corbusier failed to concentrate on and increase the density but only worsened and gave order to the problem. The Highrise City as contrasted to City for Three Million Inhabitants, in terms of its form, is based on calculation and computation.

Hilberseimer insisted that his proposal was not a real project: “Cities are unique; their physiognomy is dependent on the character of their landscape and inhabitants and their function in political and economic life… city planning is no abstraction”. He later spoke extremely critically about his project: “The repetition of the blocks resulted in too much uniformity. Every natural thing was excluded; no tree or grassy area broke the monotony… the result was more necropolis than a metropolis, a sterile landscape of asphalt and cement, inhuman in every aspect” (Pommer et al., 1988).

2.3.1.-3 Decentralized city

In the 1930s, Hilberseimer shifted his ideas from the High-rise city towards the Mixed-Height settlement. After he moved to the US in 1938, he published his project the “Decentralized City” which started out as a series of research studies and projects that were carried out in Europe before his immigration(fig)-2.1.12. He conducted different experiments in order to understand the best orientation and combination of apartment blocks and single-family houses with regard to the requirements of optimal density, solar exposure and wind ventilation. The objective of the experiment was to calculate the density and the number of people per hectare according to the number of hours of solar insolation every day. The findings and results of the investigations
were presented as schematic diagrams and numerical data tables which inform a morphological organization of residential units. These explorations from the 1930s became leading principles in his development of the "Decentralized City".

Another crucial problem that he tried to tackle was that of traffic; unlike his High-Rise City he proposed a horizontal system rather than a vertical one. The system was dubbed the "fish-spine" street system by Hilberseimer, which became a basic unit replacing the "archaic" gridiron and block system. The basic units or the "Settlement Units" were connected to the main transportation arteries by industrial areas. Influenced by the ideas of decentralization and diversification(fig)-2.1.13 of production in the post-industrial city, Hilberseimer’s "Settlement Unit" integrated agriculture, industry and transportation into one system. According to Hilberseimer, the settlement unit is the basic unit of the urban, social, and productive unit, which is limited in size and contains all the necessary elements of a city. It was a semi-autonomous system, which was productive, non-hierarchical and consisted of isolated building types and programmes which were linked to each other by the landscape [fig]-2.1.14. It contained all the essentials of community and was divided into a traffic artery on one side with the green belt located in the industrial area, and, on the other side, the commercial and administrative buildings were situated.

Hilberseimer emphasized the size of the unit, to be effective, should be large enough to maintain “metabolic” processes including production, transportation, distribution of goods, and community life. Moreover, it should allow inhabitants the “possibility of change in life and work, yet be small enough to foster an organic and democratic community life”. The second factor that determined the size of the unit was the pedestrian scale and its "walkability", including housing, commerce, recreation and employment.

These settlements were determined by the landscape, topography, geography, natural resources and use of land and varied in size accordingly(fig)-2.1.15. The units could be combined, in groups, thus becoming an extended pattern creating a system of settlement units over a large region. Hilberseimer described this system as follows: "This decentralized city would combine the advantages of a small town with those of a metropolis. The metropolis can be located in the landscape. With its parks and gardens, it can, indeed, become part of the landscape”

2.3.1.4 Region and Ecology

The settlement unit principle became the abstract system that could theoretically be expanded across a region to form a city. Hilberseimer proposed the new regional pattern which comprised distributed settlement units and transportation and communication networks across the region. He defined region as an organic entity; productive, self-sufficient and economically well-balanced(fig)-2.1.16.

For Hilberseimer, the aim of the region is to create a balanced production, based on agriculture and an industry dedicated to products made from local raw materials. Communities within the region have the same share of production and each community is an interrelated part of the whole. Therefore, the region becomes an economic, social and cultural entity. In principle, a region should rely on self-sufficient living, whereby most of the products consumed by the population are produced within the region. Excess products can be exchanged for products that cannot be produced within the region. Exchange of goods can occur across the region as well as with other countries. This
exchange is based on mutual need rather than expansion and imperialism.

Hilberseimer's understanding of regional planning is based on the definition of Ecology: the branch of biology which deals with the relation of organisms to their environments, whereby the landscape can be seen as an integrated whole. All the components of the landscape, non-living and living beings, are in natural cooperation and comprehensive symbiosis. Considering the landscape as an organism places the emphasis on the mutual relationship between the part and the whole. The part affects the whole and the reverse is also true.

Therefore, regional planning is seen as a comprehensive task. Employing science can assist in determining the adequacy of the region to its purposes, intentions, and possibilities. Therefore, the study of the region's ecology became a prerequisite for regional planning and in determining the land use of a specific territory. The new regional pattern would be determined by the characteristics of the landscape, including geographical and topographical features, land use, agriculture and industry methods, decentralisation and integration and as well as by human activities. The method suggested for understanding the nature of a given region is by surveying and mapping all its elements. These elements include geographical, topographical, geological and hydrological features, the climatic conditions, growing seasons and resources.

Planning the landscape which comprises the forests, the grassland, the farms and the gardens becomes the main task. Defining and discovering the ideal relationship between these, so as to determine the quantity and land use distribution that shape the landscape is crucial to the planning process. It can be subject to the climatic and environmental conditions, including the hydraulic cycle and the amount of farmland that can maintain the landscape as a living entity. (fig)-2.1.17 (fig)-2.1.19

Hilberseimer suggested that planning of the region should be carried out by the application of principles which grows out of the order of things and is based on the investigation of facts and requirements. He considered the gridiron system of blocks that organize cities a wholly mechanical process which is more concerned with selling land than cultivating it. The development of each part of the city and of the region has emerged from its function and its appropriate location in the whole (Hilberseimer, 1949).

The new regional pattern, Hilberseimer argued, could be employed in three different planning systems. The first is a system which is predominately urban; the second predominately rural and the final one is a combination of urban and rural. The systems are flexible and can be applied to any particular situation by modification and adaptation. The systems are merely diagrams that provide an abstract scheme for the development of regional and urban transportation and settlement structures.

Hilberseimer asserted that city planning is the outcome of objectivistic economic, social and production processes, and considered it one of the main tasks of humanity in shaping the environment. As Mies Van De Rohe stated, city planning for Hilberseimer is the ordering of things in themselves and in their relationships with each other, which he expressed in the
following manner: “Reason is the first principle of all human work.” Consciously or unconsciously, L. Hilberseimer follows this principle and makes it the basis of his work in the complicated field of city planning. He examines the city with unswerving objectivity, investigates each part of it and determines for each part its rightful place in the whole.

In his radical project, the High Rise and the Decentralized City, Hilberseimer’s planning and design principles were based on the research and investigation of different elements, including historical analysis, building function and types, sun and ventilation analysis, transportation analysis, population distribution, pollution, security, and defence and production processes. The outcomes were concluded and reflected in his projects, particularly the solar study and its relation to density. Hilberseimer explained the form of his “High-Rise City” as follows: “The new city layout defines its street system with respect to solar orientation; its street and block sizes demand, with respect to light and air supply, a minimum distance between the buildings that is equivalent to their height; street width equals building height. This refers to street width and block depth since the building distance within the block must correspond to the building height, too.” (Hilberseimer 1927, 18-20). He claimed that this organization of the city was based on research that allowed him to find a solution for the metropolitan housing problem.

Hilberseimer was highly influenced by the urbanist Karl Hoepfner and his scientific approach to the necessary sun exposure of buildings, and, after he was appointed as a teacher at the Bauhaus, he conducted a deep research and design work into the best sun orientation (Poeschke, 2018). His experiments set included different residential building types and diverse orientation. He drew the conclusion that a southern orientation is ideal for a single family house but is, by contrast, inappropriate for multi-family apartment blocks (Hilberseimer, 2012). Additionally, he came to the conclusion that density should be determined by the requirements for the ideal sun orientation. The experiments allowed him to draw comparisons between high-rise and low-rise housing in relation to the best sun orientation and density. He presented his findings in diagrams and tables showing the densities related to different targeted standards of best solar exposure. It also presented the necessary distances between buildings for a four-hour insolation of rooms at the winter solstice. The research also gave examples of calculation of density according to different cities and locations and provided for comparison of the ideal form and size for each city.

Hilberseimer also carried out experiments to prevent pollution in the city, by calculating the orientation of the prevailing wind (fig)-2.1.18 in order to find the proper locations of industrial and residential areas in relation to one another. He stated: “Only when industrial and residential areas are brought into proper positional relationship to prevailing winds, is a true solution reached.” 55,56 (fig)-2.1.21.
future urbanization, predicated on human values and needs, accommodating but not dominated by the automobile (Spaeth, 1988). Moreover, Waldheim maintains that from the perspective of contemporary interests in landscape as the ordering element for decentralized urbanism, Hilberseimer’s plan for Lafayette Park offers an extraordinary case study in the radical re-conception of the industrial city. Lafayette Park is considered the most fully realized American example of a superblock strategy for the decentralizing post-war city.

### Conclusion

It can be argued that the importance of the reassessment of Hilberseimer’s research studies lies in the relevance of some of his planning and design principles to today’s city challenges. Hilberseimer’s planning, design and research studies provide significant insights into and reflection on the architecture of the city. Among these are the notion of a productive city and the integration of agriculture in the city, the city as a functioning organism and the holistic design and planning approach. Hilberseimer can be considered one of the pioneering architects and planners who introduced the notion of ecology, regional planning and their systemic interrelationship to the architecture of the city (HALK, 1998). For Hilberseimer the architecture of the city can be regarded as a dynamic organizational model that can be adapted to different conditions. He founded his designs and research studies on a scientific approach of calculating and through collecting empirical data such as solar radiation, wind, topography and availability of resources. Hilberseimer’s ideas and work can be taken as a point of departure for further and deeper research studies into the ecological architecture of the city. Combining these principles with the latest computational advancements and dynamic system modeling might indeed suggest a novel approach to the architecture of the city.
2.3.2. Arcology

“The city is the necessary instrument for the evolution of humankind.” —PAOLO SOLERI

“...In nature, as organisms evolve, they increase in complexity and become a more compact system. A city should similarly evolve, functioning as a living system. Architecture and ecology as one integral process, is capable of demonstrating positive response to the many problems of urban civilization – population growth, pollution, energy/natural resource depletion, food scarcity, and quality of life.” (“Arcology,” n.d.)

Arcology is a term coined and introduced by the visionary Italian architect Paolo Soleri to designate the principles of his systemic approach to the design of the new Ideal City (fig)-2.1.22. It is a blending of the two words, “architecture” and “ecology.” The term arcology refers to the fusion of the discipline of architecture and the science of ecology. For Soleri, ecological systems are considered as models of how architecture and cities should be built (Sanders, 2008). Soleri’s seminal book, Arcology: The City in the Image of Man, describes the concept which suggests a holistic thinking that adopts a cross-disciplinary approach including architecture, biology, urban design and ecology among others. The book shows visionary drawings of cities that are labelled “arcologies” (fig)-2.1.23. The model proposes a compact, three-dimensional form to provide a lean alternative to the urban sprawl city. Soleri’s lean hypothesis is essentially the consumption efficiency of resources by society without destroying ecological systems.

Arcology was conceived by Soleri as a complete “reformulation” instead of slow “reformation” and adaptation of architecture from the twenty-first century forward. He argues that small improvements produce only a ‘better kind of wrongness’. For Soleri, “reformulation” is the radical rethinking of the way humans / human beings live by creating a brand-new system replacing the pre-existing system. He proposed that cities should instead have a unity of the human body where the built environment and the living processes interact as organs (Soleri, 2012). He said that “Man must create a metropolitan landscape in his own image” (Carter, 2019). In this sense, all the urban systems integrate and interact with each other and with their immediate environment to increase efficiency and reduce waste. The integrated systems work together to maximize the circulation and efficiency of the flow of people, materials and resources and exploit solar orientation for climate adaptation, including cooling, heating, and food production. The compression of the arcology allows us to achieve more with less and promote new levels of human development (Grierson, 2003).
Fig. 2.22 Scanned Image of Paolo Soleri, Arcology
Soleri’s arcology, situated within the tradition of the utopia cities projects of the mid 20th century, bear a strong resemblance to the “futuristic” visionary “ideal cities” of Antonio Sant’Elia. However, Soleri’s spectacular and detailed drawings — including plans, sections and details — are seen as an elaborated scheme to be constructed. In this sense, arcology is not utopian in that it is not intended to be fully realizable (DIE, n.d.). Soleri rejected and criticized the modern city and especially the urban sprawl that leads to the abuse and exhaustion of natural resources. He argues that these cities did not learn from the ecological systems around them which could be appropriate models for human settlements. The proposed arcologies are cities consisting of single densely populated structures with a network of social interactions. Each arcology is site-specific, situated in specific environmental and climatic conditions. They make use of their close climate pattern and natural resources.

In contrast to the sprawl city that is characterized by wasteful consumption of resources, including energy, water, land and others, arcology seeks a more balanced relationship between morphology and the performance of the city. It grows upwards three-dimensionally while adapting to the natural and climatic surroundings. Therefore, arcology addresses the city as an architectural problem and employs urban design, coupled with principles from ecology science, to create a different urban environment. Denaturing urban living by creating “hyperstructure” arcology, aims to minimize the impact on nature. Soleri argues that the essence of arcology is the inversion of urban sprawl toward the inner limits of compact logistical efficiency. This efficiency can be achieved by densely populated three-dimensional forms and highly integrated residential, commercial, industrial, cultural, leisure and health uses.

2.3.2.1 Miniaturization

Soleri argued that the frugal city should be three-dimensional in order to shorten distances and save time. By shortening logistical distances relative to scale, the time and energy formerly required to maintain the system of novel evolutionary achievements, which advance forms of organic complexity, decreases.

Therefore, the city should become miniaturized by folding back into itself. Miniaturization which enables spatial closeness allows for the rigorous utilization of resources (Soleri, 2013). The key aspect of miniaturization is the integration of a dense complex three-dimensional settlement within the natural environment. In the book, Arcology: The City in The Image of Man, thirty arcologies are presented, ranging from a small scale prototype of 1500 inhabitants to a megastructure of 6 million. The heights of the megastructure vary between 800 to 1700 metres. The scale and vertically of the structure was displayed by showing a drawing of the Empire State Building in each arcology. Soleri asserts that vertically in and of itself is not a virtue and it could isolate and distance people from each other. Verticality can be arcological when it makes nexus between the social and ecological (Soleri, 2013).

Soleri puts forward three basic principles that define Arcology, which are drawn from his exploration into systems - especially ecological systems -, coupled with the evolutionary processes in nature. Living beings evolve to compact their forms into ever more complex systems of energetic flows. This process enables form in nature to be precisely adapted to their function (Grange, 1978). Moreover, he argues that the process of miniaturization may be one of the fundamental rules of evolution (Soleri, 1974). Soleri gives the example of the human brain as a demonstration of a complex function through miniaturized cells. He wrote: “Take one human brain, for example. If it were two dimensional it might cover an area of twenty or so square miles. There is so much going on within it that you would need thousands of miles of connectors for it to function. But the human brain, as it has evolved, is an example of enormous complexity which comes about because of its folding over, three dimensionally, back upon itself, and the notion of miniaturization is intrinsic to this process.” In this sense, miniaturization is the reduction of the amount of space and time required for systems to function.

In the design of cities, miniaturization implies the compacting of a massive number of people into a small space. Soleri proposed arcology as a miniaturized complex structure as an alternative to the sprawled city and capable of reversing environmental damage. Arcologies are models of vertical cities, drawing urban life inward. They minimize land and energy use and contain the population into a single, mixed-use complex building. They should enable populations to retreat from the natural landscape to the man-made environment which was labelled “neonature” (White, 1971). For Soleri society must become a true organism and this could be done through the process of miniaturization: it is the instrument to this end (Soleri, 1974). The application of the miniaturization principle allows for the conservation of the earth’s resources by occupying a minimal footprint on the earth and developing three-dimensionally. Soleri considered the liberation from the surface of the earth as a step ahead in the evolution of humankind.

The “neonature” is achieved by miniaturization through utilization of technology: each arcology is supposed to be an industry in itself with its original standardizations, its automated systems, a cybernetic organism growing of its own volition (Soleri, 1974). In this regard, arcology is understood as a technological manifestation where ecological architecture and technology are one and the same (White, 1971). Technology in this regard is necessary to build ecological architecture. Soleri believed technology is the means to obtain a symbiotic relationship between the city and its inhabitants. Technology in itself with its original standardizations, its automated systems, and its own volition is called “superorganisms” which constitute cells, function in a cybernetic manner and show self-organizing system properties (DIE, n.d.). Individually situated in the inner core of these mega structures and their by-products, such as heat and wind, which can be used to provide heat to the remainder of the environment. Thus, this process eliminates wasteful duplication of energy production.
2.3.2.2 Arcosanti

Parallel to his theoretical proposals, Soleri tried to demonstrate his methodology of ecological models and to put his arcology principles in built prototype to the test. In 1970, he started the construction of Arcosanti: the experimental arcology prototype in the semi-arid desert of Arizona, which was named Arcosanti (fig). Its name comes from the word “cosa” (thing) and “anti” (before), meaning “before things”. From the thirty arcologies he proposed in his book, “Arcosanti” was the only arcology that was actually built and it is the only manifestation of an arcology that exists. Arcosanti is a sort of school-construction site in which the students engage in communal living by building an ecological environment. It was financed by the manufacturing and selling of handcrafted items using sand, especially win-bells cast from ceramic and bronze. Despite the volunteering work and sales income from the artifacts over 40 years, it was not enough to complete more than about three percent of the project. Nevertheless, in 1976, Newsweek magazine described Arcosanti as “probably the most important experiment undertaken in our lifetime” in urban architecture ("Paolo Soleri," 2013).

Despite the fact that Arcosanti is not a city, it is considered an urban laboratory and a prototype of arcology that has been erected by over 7,000 workshop volunteers over the past 5 decades (Rae, 2016). It was planned to populate five thousand people on only 15 acres, which is 10 times the population density of New York City. It provides experimental learning opportunities to test architectural concepts and demonstrates how ecology addresses human habitat in an extreme climate. It is an attempt to achieve a livable environment to validate the Arcological model. Among the urban and environmental challenges that have been tackled: the habitat’s impact on natural resources, food and energy consumption, self-containment habitat, population expansion and land use (Grierson, 2003).
In addition to the growing interest in the concept of arcologies among professionals, the term has become popular within the gaming community. It was introduced as part of the future cities in the SimCity computer game (fig. 2.27). SimCity is a city-building and urban planning simulation game that allows its players to design and manage their dream city. It is seen not just as a game but also as a potential pedagogical and research tool for design (Hockey et al., 2010). The game is based on real world urban politics and planning decisions, including land use and zoning. In SimCity 2000, the ideal is defined as a city with arcologies that are linked via an underground transportation system and powered by a nuclear power station (“The depressing suburbanisation of SimCity,” n.d.). Following Soleri’s principles, Arcologies, in the game, are densely populated superstructures and almost entirely self-sufficient. For example, one of the arcologies is designed for extreme climates, to house tens of thousands of people and its intricate porous outer surface is designed to “breathe”, keeping the interior spaces warm in winter and cool in summer (“The Real Story Behind Sim City’s Arcologies,” n.d.). The Arcologies blocks are a solution that the player can build when the population grows significantly. In the game, the introduction of the arcologies is considered part of the approach to future city building and marks a shift from the existing, traditional way of planning and designing.

2.3.2.-4 Conclusion

For many decades, Soleri’s work was almost completely ignored by his peers and regarded as little more than a curiosity. There were strong criticisms of the arcologies: it was said that they were dangerous, authoritarian, unconsidered and unorganized megasturctures (Carter, 2019). Criticism centred on the lack of research studies, including engineering, statistics and a historical review. The numbers and figures in his proposals representing population, density, surface acreage and other parameters were without clear evidence or reason. Soleri mentioned that his plans should not be taken literally and that their understanding should remain in the general context of his book. Later he admitted that he thought people were impressed or depressed by his models and plans and that caused the idea to get lost (Carter, 2019).

Having said that, with the increasing concerns over climate change, overpopulation and resources depletion, his work both attracts attention and generates interest (“Paolo Soleri - Telegraph,” n.d.). He rejected the concept of a modern city and the way of living in these cities. Soleri made a significant contribution to architecture and urban design by placing the emphasis on the ecological awareness in design and building cities. He has extended the traditional definition of ecology to include the interaction and relationship between the natural and the artificial world which he called man-made nature. For him, architecture and ecology are two parts of the same entity. In this regard, arcology, which is not a mere container, attempts to address the most urgent environmental and social problems of human habitat. The resurgence of ecological ideas and ecological thinking in discussions of urban design and architecture in the last two decades (Reed and Lister, 2014), makes reconsidering Soleri’s ideas and rethinking arcology more relevant.
2.4. Ecology

2.4.1. Introduction

The emergence of civilization coincided with the use of different tools and fire to modify and alter the environment in order to survive. The services supplied by nature, including water, air, energy and food required a knowledge and understanding of natural processes and the interactions between living beings and their physical environment. These interactions influence many aspects of the natural world, including the distribution and abundance of organisms, biodiversity, and the transformation and flow of energy in nature. The scientific study of these relations and interactions is the science of ecology.

The word ecology was coined in 1866 by the German scientist Ernst Haeckel. It is derived from the Greek “oikos”, meaning “house” or “place to live” or “environment” and logos, meaning “study of”. Literally, ecology is the study of organism “at home”. Essentially, ecology is defined as the study of interactions between organisms and their environment. Behind this basic definition of ecology lies a broad scientific discipline of studying environmental relationships ranging from individual organisms to the whole biosphere. Organisms can be studied at many different levels, from proteins and nucleic acids, to cells, to individual, and finally at the levels of population, communities, and ecosystems, to the biosphere as a whole.

This broad range of subjects can be organized by arranging them as levels of ecological organization (fig).
as an ecological spectrum and as an extended ecological hierarchy. This hierarchy creates a structure in which all the levels are nested within one another, in the sense that each level is composed of groups of the components existing in the level below. For instance, Population is defined as group of individuals of a single species that live in a particular area and interact with one another. In turn a group of populations of different species that live in the same area create a community. Odum argues that ecology is largely concerned with the levels beyond that of the individual. The population and community levels are the primary subjects of ecological enquiries.

The ecological studies often examine not only the effects of the biotic (living) component of the natural system, but also those of the abiotic (non-living) environment. Odum, in his seminal book “Fundamentals of Ecology (1953), suggests that the interaction between the biological system and the environment form an ecological system or ecosystem.

The ecosystem is considered to be the basic, fundamental unit in ecology comprising a community and its physical and chemical environment at any scale within which there are continuous fluxes of matter and energy in an interactive open system. (Arthur J. Willis, 1997) The following section will examine the components, structure, functions and services of the ecosystem.

2.4.2. Ecosystem

The term ecosystem was coined by A.G. Tansley in 1935 in his seminal paper entitled “Vegetational Concepts and Terms”. According to his definition, an ecosystem is an integrated system composed of all the components of an ecological system, biotic and abiotic, that influence the flow of energy and elements (Tansley 1935). He describes the ecosystem as ‘…. a whole system, including not only the organism complex, but also the whole complex of physical factors forming what we call the environment of the biome - the habitat factors in the widest sense.’ The importance of this definition is that ecosystems are dynamic interacting systems functioning as energy transformers and nutrient processors composed of organisms within a food web that require a continual input of energy.

One of the first studies into the function of the ecosystem was carried out by R.L. Lindeman in 1942 in a Minnesota lake. Lindeman considered the lake as an integrated system of biotic and abiotic components in order to investigate the energy cycling and transformation among trophic levels over time (Lindeman, 1942). He grouped the components of the ecosystem (the lake) into categories based essentially on energy obtainment (fig-2.1.31). Lindeman (1942, p. 400) posited that ‘The ecosystem may be formally defined as the system composed of physical-chemical-biological processes active within a space-time unit of any magnitude’, and he regarded the concept of the ecosystem to be of ‘fundamental importance in interpreting the data of dynamic ecology.’ (A. J. Willis, 1997). The theoretical study was published in a paper titled the Trophic-dynamic Aspect of Ecology and became one of the most fundamental pieces of research into ecosystem science.

In the fifties and sixties of the last century, Odum and others conducted for the first time experiments at the scale of an entire ecosystem. The objective of the experiments which took place in a watershed was to determine whether logging, burning, or pesticide and herbicide use had had a significant effect on nutrient loss from the ecosystem. Odum argues that functionally an ecosystem has two components – autotrophic and heterotrophic – and four constituents – abiotic, producer, consumer and decomposer. The concept of the ecosystem, for Odum, is that the main function in ecological thought was to emphasize obligatory relationships, interdependence and casual relationship. He argues that although ecological systems are different, they have enough features in common to justify describing basic patterns that are common throughout all ecosystems. According to the structure and the function of the ecosystem, there are four all fundamental properties of ecosystems: 1) Ecosystems cycle energy. 2) Ecosystems cycle matter. 3) Ecosystems functions (internal variable) are determined by the environment (external variable). 4) Ecosystems require...
a holistic approach for examination and study due to the fact that they are whole systems (Jørgensen, 2009). He suggested a method to represent these relationships and interactions by visualizing the ecosystems as a language that could be broken down into components and their feedback, similar to electrical circuits. This representational language for ecological simulation models, derived from electronic circuits, has become the primary tool to visualize performance and energy flow using arrows of feedback.(fig)-2.1.33.

2.4.3. Ecosystem Productivity:

The biosphere functions and works depend largely on the production of energy in the form of biomass by the photosynthetic processes of primary producers including green plants. Energy in an ecosystem originates with primary production which is one of the most important ecosystem processes. The primary production is the generation of chemical energy by autotrophs derived from the fixation of carbon – the conversion of CO₂ into sugar and other forms of biomass during photosynthesis and chemosynthesis. Having said that, the main part of the energy on Earth comes from photosynthesis by producer organisms (mainly plants). The primary production is the source of energy for all organism generated by conversion of light energy from the sun into chemical energy (organic substances) that can be used by autotrophs and consumed as food by heterotrophs. Part of the fixed carbons goes directly into plant growth and some is stored as non-structural carbohydrates, which act as stored energy in the plants’ tissue. Therefore, an ecosystem that absorbs, transforms, and stores energy integrates inseparably physical, chemical and biological processes. Due to the fact that the assimilated energy is stored as carbon compound in their leaves, carbon is considered the currency employed for the measurement of primary production. The primary production is measured as the production of new organic matter in the ecosystem per unit area or volume during a specific period of time. The amount of total carbon fixed by all primary producers in the ecosystem is called “Gross Primary Production” (GPP). A proportion of the GPP is lost as respiration by the plants (autotrophs). The difference of the gross primary production minus respiration by primary producers is called Net Primary Production. NPP is the form of energy in the form of biomass available in an ecosystem for consumption by heterotrophic organisms. The rate of production of biomass by heterotrophs is a secondary productive. Primary production is a crucial process in the ecosystem; it is the conversion of inorganic forms of energy into organic forms. The rate of production of biomass by heterotrophs varies significantly from one ecosystem to another. Environmental factors, including climate, have a crucial influence on the rate of the photosynthesis that controls the primary production (Molles, 2015). For example, patterns of natural variation such as temperature, moisture and nutrients limit the terrestrial primary production. In the same way aquatic primary production is generally limited by nutrient availability(fig)-2.1.33. It is argued that there is a positive relationship between nutrient availability and the rate of the primary production in an aquatic system (Molles, 2015). Furthermore, plant diversity has a significant impact on primary production. In addition to this, primary production in terrestrial and aquatic ecosystems can be affected by consumers through trophic cascades. Consequently, ecosystems with greater primary production support higher levels of secondary production. The concept of primary productivity is related to the ideas of energy flow in an ecosystem (Odum, 2013).

2.4.4. Energy Flow in Ecosystems

The organisms in the ecosystem are grouped and categorized according to how they obtain energy. The transfer of food energy from the source in plants through a series of organisms with repeated eating and being eaten is referred to as the food chain (Odum and Barrett, 1971). The food chain is defined as the movement of energy from a producer to a final consumer through the ecosystem links which Lindeman referred to as ‘trophic level’. Each feeding category, or trophic level, is based on the number of steps by which it is separated from autotrophs (plants). The number of levels is limited, usually to four or five. Lindeman’s experiments tried to quantify the food chain processes by considering the efficiency of energy transfer between trophic levels.

Ecosystems are composed of organisms within a food web that require a continuous input of energy to balance that lost during metabolism, growth, and reproduction (Golley, 1993). As mentioned earlier, ecosystems organisms are divided into two functional components: the primary producers (autotrophs) and secondary producers (heterotrophs). The primary producer - self-nourishing - drives its energy by using sunlight to convert inorganic carbon into organic carbon while the secondary producers – other-nourishing - use organic carbon as their energy source.
Odum recognizes four constituents that constitute the ecosystem:
1) abiotic substances, basic inorganic and organic comonomers of the environment; 2) producers: autotrophic organisms, largely green plants which produce food from inorganic materials; 3) consumers: heterotrophic organisms, mainly animals which consume other organisms; 4) decomposers, heterotrophic organisms, mainly bacteria and fungi, which break down dead organisms.

Consequently, organisms can be categorized and grouped according to their function. For instance, “herbivores” are heterotrophs which consume autotrophs, while “carnivores” are heterotrophs that consume non-living organic materials derived from either autotrophs or heterotrophs. All these organisms are functionally grouped as “consumers.” Therefore, the feeding relationships among the organisms defines the organism’s trophic level. Furthermore, the trophic level is determined by the number of feeding steps by which it is separated from the first trophic level which is the autotrophic. The components that make up the trophic level can be quantified in terms of biomass, while the dynamic processes of the flow of energy and materials among the components are quantified in terms of rates.

The food chain describes the relationship between one trophic level and adjacent trophic levels (Odum and Barret, 1971). Essentially, the food chains have 3-5 trophic links with 15-20 species depending on the physical characteristics of a specific ecosystem (Tumar and Min, 2018). For example, areas with harsh climates, such as the Arctic or the desert, have a much shorter food chain than a temperate or tropical one (A K Salomon, 2009). The reason for the short length of a food chain is the inefficiency of energy transfer along the chain. Lindeman visualized a pyramid energy pyramid within the ecosystem, with less energy reaching each successively higher trophic level.

As Odum explains in his seminal textbook “Environment, Power, and Society” – only about 10% of energy stored in the organic matter of each trophic level is converted to organic matter at the next trophic level. Most of the stored energy is lost (about 80% to 90%) as heat at each energy transfer process. Accordingly, the shorter the food chain — or the nearer the organism to the first trophic level — the greater the energy available to that population. The energy transfer between trophic levels is expressed as the energy efficiency which is defined as the output of energy per unit of an energy input. Similarly, trophic efficiency is estimated as the amount of energy at one trophic level divided by the amount of energy at the trophic level immediately below it. The trophic efficiency allows one to estimate the primary production required to sustain a specific trophic level. Trophic efficiency incorporates the proportion of available energy that is consumed (consumption efficiency), the proportion of ingested food that is assimilated by the consumer (assimilation efficiency), and the proportion of assimilated food that goes into producing new consumer biomass (production efficiency) (Cain et al., 2017).

Thus, energy and masses of elements including carbon are the “currency” used for the measurement of the structure and functioning of the ecosystem. One of the most influential energy flow models was developed by E.P. Odum and was presented in his seminal book “Fundamentals of Ecology”. He depicted ecosystems as a series of simple energy flow diagrams representing the use and transfer of energy by all the organisms at each trophic level (fig-2.1.32). Energy cannot be cycled or reused and most of it enters ecosystems as light and leaves as heat. In contrast, nutrients are regenerated and retained largely within the ecosystem (Ricklefs, 2008). Carbon and all other nutrients (e.g. nitrogen, phosphorus, etc.) that are available in plants, the atmosphere, and water can be incorporated into complex organic carbon compounds in biomass. The process of decomposing the carbon compound releases the nutrients again in inorganic forms. The availability and supply of the nutrients is determined by the decomposition of the plants and their consumers. Indeed, without the decomposition processes life in the ecosystem would cease.

Ecosystems grow and develop according to the laws of energy transformation (thermodynamics), the biochemistry of organisms. The processes of production, growth and consumption require energy. All ecosystems develop to maximize power intake and useful consumption through natural processes of design selection during self-organization. The maximum power principle was formulated by Lotka (1956) who suggested that the systems which prevail are those capable of developing designs that maximize the flow of ‘useful’ energy. Lotka (1922) suggested that the maximization of power for useful purposes was the criterion for natural selection. Darwin’s evolutionary law, which applied to organisms, was developed into general energy law which is also applied to the selection of design relationship. Thus, systems that prevail are those with the ability to adjust to operate at the peak of power efficiency. Odum employed this principle to explain and describe the structure and processes of ecosystems (Howard Odum, 2007). The scientific definition of power is the rate of the flow of useful energy and it is measured in term units. The ability of a system to function is maximized power principle was formulated by Lotka (1956), who suggested that the systems which prevails are those capable of developing designs that maximize the flow of ‘useful’ energy. Lotka (1922) suggested the maximisation of power for useful purposes was the criterion for natural selection. Darwin’s evolutionary law, which applied to organisms, was developed into general energy law which is also applied to the selection of design relationship. Thus, systems that prevail are those with the ability to adjust to operate at the peak of power efficiency. Odum employed this principle to explain and describe the structure and processes of ecosystems (Howard Odum, 2007). The scientific definition of power is the rate of the flow of useful energy and it is measured in term units. The ability of a system to function is maximized.
determined by its power rating: the larger the number the larger the role. Odum defines maximum power as a maximization of useful power.

2.4.5. Ecosystem Services

Ecosystem services describes the services provided by nature and used by human kind from food to timber production to soil renewal to water purification and personal inspiration. They are the conditions and processes through which ecosystems sustain and fulfill human life. Ecosystems include forests, streams, living reefs and others which serve to perform a diversity of ecosystem services and control the geosphere. Human life is dependent on a wide range of these ecosystem services, such as water purification, generation and maintenance of soils, pollination of crops, climate regulation, flood control, and decomposition of matter (K A Brauman and G C Daly, 2009).

According to the MEA - Millennium Ecosystem Assessment 2005 - ecosystem services are grouped into four categories. First, ‘provision services’ including food, energy and water. Second, ‘regulation services’ including control of climate change events, stabilizing processes, decomposition of waste, purification of air and water and erosion control. Third, ‘supporting services’, including crop pollination, seed dispersal, maintenance of biodiversity and cycling of nutrients. Fourth, ‘cultural services’ including cultural and recreational benefits. These services are provided by complex chemical, physical and biological processes, powered by the sun, and operate at different temporal and spatial scales. The pressure on Earth’s systems as a result of human activities, coupled with the unprecedented increase in global population, deteriorate and degrade the ecosystem services. Some regions of the world even risk ecological collapse. (A K Solomon, 2009)

Since resources and energy are limited, actions including redistributing and redirecting resources determine the functionality and the services of the ecosystem. For example, an ecosystem which could be managed as a producer of simply one service, such as agriculture, may yield a greater return than one being managed for multiple services. However, it is argued that biodiversity services and diverse systems are more resilient and therefore provide services more reliably. For example, genetic diversity enhances the survival and the evolution of the ecosystem. There is growing evidence to suggest that biodiversity and cycling of nutrients. Fourth, ‘cultural services’ including cultural and recreational benefits. These services are provided by complex chemical, physical and biological processes, powered by the sun, and operate at different temporal and spatial scales. The pressure on Earth’s systems as a result of human activities, coupled with the unprecedented increase in global population, deteriorate and degrade the ecosystem services. Some regions of the world even risk ecological collapse. (A K Solomon, 2009)

Understanding and examining ecosystem services can be approached in two ways: the first according to the type of service which may be provided by various ecosystems and the second approach by the variety of services that may be provided by a single ecosystem.

2.4.6. Ecosystems as Systems

The scale of the ecosystem is dependent on the function and properties of ecosystem, for example, the whole biosphere can be viewed as a single system that is made up of smaller subsystems including forests, seas, deserts and living reefs. Similarly, these subsystems have subsystems within subsystems such as organisms and non-living components interacting together. The evolution of these systems is constrained by physical and system laws and by the environment and its properties (H Bossel, 2009). Respecting these constraints maintains the system’s persistence. It is argued that a system usually adapts to its environment in a process of coevolution. For example, a fish’s form and its mode of motion are governed by the laws of fluid dynamics of its aquatic environment. (H Bossel, 2009)

Although there are no isolated systems in the real world, defining the boundary to an ecosystem simplifies the study of the structure, as well as the function and the behaviour of the system (Howard Odum, 2007). Ecosystems as systems exhibit properties that produce behaviours which are distinct from the properties and behaviours of its components. The ecosystem interacting components give the system emerging properties more than just the sum of its parts. For example, a forest as an ecosystem is much more than the trees that make it up: it is a system unit with emerging distinctive properties characteristic of a forest. A System can be considered as a complex system if it is composed of many different subsystems, processes and interactions. Two main organizing principles can be identified in the evolution of complex systems, the first is hierarchy and second subsidiarity. Hierarchy means that the whole system is made up of nested subsystems. Each subsystem enjoys a degree of autonomy and is responsible for a specific function which contributes to the whole system; whereas, subsidiarity means that each subsystem has the responsibility and the means to maintain the persistence of itself.

The biosphere system as mentioned earlier, is maintained by a finite rate of energy input (mostly solar energy) and a finite stock of matter. Local ecosystems are constrained by the flux of energy and by the local rate of material recycling. H.T. Odum developed an energy language which describes this flux of energy which is a useful tool for incorporating much information into an energy flow diagram. The symbols used allow us to consider not only the flows but also the feedback mechanisms and the rate regulators. H.T.
2.5. Computational Ecology

Introduction

The History of Ecological Modeling

Ecological Modeling Approaches

Ecological Models and Systems

Computational Tools

The old folk wisdom about “the forest being more than just a collection of trees” is indeed the first working principle for ecology. (Odum)

2.5.1. INTRODUCTION

Understanding and analyzing biological and ecological phenomena — whether on the molecular scale or ecosystem level — by way of mathematical models, led to the emergence of new mathematical and computational fields (Lamm and Unger, 2011). Mathematical and computational methods can be extracted from the “translation” of the biological and ecological phenomena into formal mathematical models. By employing these methods and techniques, practical solutions for a wide variety of complex computational problems can be found. For example, evolutionary computation which was inspired by biological computation, could be employed to solve optimization and search for problems by mimicking the natural evolutionary processes whereby organisms, populations and ecosystems adapt to their environment, employing evolutionary computation to solve optimization. Another example is models of neural networks which mimic the behaviour of the brain and can be used to model complex patterns and predict problems. The computational models and techniques based on principles derived from ecological research studies are referred to as ecological computation.

Computational ecology constitutes the computational methods and techniques applied in studying ecological systems. A number of seminal studies led to the transition of ecology from the descriptive field into the analytical based theory discipline. The introduction of the mathematical tools for ecological problems by Lotka, Volterra and Gause marked the change: they formulate the general principles of ecosystems which Odum refined in the middle of the last century. These seminal studies generated a widespread interest in mathematical ecology and ecological modeling. By the end of the last century, computational ecological models became common across the whole range of ecological applications in studying ecosystems including forests, climate change and evolutionary ecology. It is argued that the application of models in ecology is almost compulsory in order to understand the function of a complex system such as an ecosystem (Jørgensen and Bendoricchio, 2001). This chapter reviews the ecological computational models and their applications.

2.5.2. The History of Ecological Modelling

The study of the diversity and forms of life in general and ecology in particular was the domain of natural science being mostly descriptive. As an emerging science, ecology, as a sub-discipline of biology, started relatively late using quantitative methods mainly from outside biology. Ernst Haeckel, who named and defined Ecology as a new science, applied qualitative methods to study ecology, including conceptual approaches, verbal descriptions, and graphical representations (Jopp et al., 2010). The quantitative approaches to ecology emerged from the domains of economics, physics and demography. Scholars
in these fields introduced quantitative studies and approaches of the population-environment relationship.

One of the first quantitative studies came from the discipline of political economics in the early 19th century. It was conducted by the seminal figure Thomas Robert Malthus (1766-1834) who put forward the population growth theory. He published a book: “An Essay on the Principle of Population,” one of the most influential books about population (Hiltnenko and Yatsenko, 1999). He was one of the first to introduce quantities consideration in the population context (Tinbergen et al., 2011). He stated that overpopulation was the root of many problems in industrial society. He argued that population growth is directly linked to natural resources availability and development. (Malthus, 1878). For Malthus, this relation – population and natural resources is expressed mathematically, the population increases exponentially, whereas resources follow a linear growth. This discrepancy between the arithmetic and geometric growth is the main source of tension and instability (Jopp et al., 2010). Therefore, the maximum size of population that can be sustained in a particular environment, is called the carrying capacity. If the population size is too large to be supported by the resources available, then population will outpace their local carrying capacity. Due to fact that resources are limited, the exponential growth cannot continue endlessly. Accordingly, the growth rate decreases and finally levels off at the carrying capacity of the environment. In order to model the population growth in relation to limited resources, ecologists developed what is called the Logistic Growth Model (fig)-2.1.35. Although Malthus’ major consideration was in political economics, he considerably influenced ecological computational modelling.

Another major development in modelling population growth was introduced by a Belgian mathematician who describes the growth intensity in relation to resources. His function, named Verhulst equation or logistic equation, is still widely used in ecological computation and modelling. In the 1920s, the chemist and statistician, Alfred Lotka (1880-1949), and the mathematician, Vito Volterra, independently developed the equations that describe the interaction of a predator and prey population (Vaidyanathan, 2015) (fig)-2.1.36. Their simple two-species mathematical model, which is called the Lotka-Volterra model, is considered the first ecological model and has been extensively used to model ecological populations. (Fath et al., 2011). The model describes one species as predator and the other as prey. The prey are assumed to reproduce exponentially, and the predators consume (kill) the prey proportionally to the product of the number of prey and predators. This behaviour is described by a mathematical model that consists of a system of two coupled nonlinear differential equations. The model, which is general and simply fails to describe real-world population dynamics because it ignores significant parameters, including competition, disease, and mutualism. However, the Lotka-Volterra model has undergone an immense development of the prey-predator model to include more factors and parameters. (Wiken and Kristensen, 2019).

A significant advancement was made in the field of ecological modelling by the introduction of general system theory (1949) principles in biology. The theory, which was developed by Austrian Biologist Ludwig von Bertalanffy (1901-1972) put the emphasis on holistic and network approaches as well as on the interaction between the parts (Von Bertalanffy, 1948). He defines the system as a complex of interacting elements within themselves and with their environment, adding that they can qualitatively acquire new properties through emergence (Von Bertalanffy, 1948). The system theory has a wide range of practical applications for interdisciplinary and co-operation (Breckling et al., 2011). The introduction of system perspective significantly contributes to the transition of ecology from qualitative to quantitative studies (Odum and Barrett, 1971). The concept has become widely applied in describing and analysing processes and behaviours of biological and ecological systems (Allen and Starr, 1992).

A remarkable contribution to the development of quantitative assessments of the ecological system was made by the scientist Raymond Lindeman (1915-1942)(fig)-2.1.37. In his well-known classic paper on the Trophic Dynamics from 1942, he laid the foundation of the science of the ecological energetic, attempting to quantify the concept of food chains and food web between trophic levels. Lindeman pioneered the concept of trophic dynamics that focused on the flow of energy up the food chain from the autotrophs to the top carnivores (Lindeman, 1942). This was one of the first formal investigations into the energy flows and cycling of nutrients through ecological systems (K Salomon, 2009). This study was carried out in an aquatic system, a senescent lake, Cedar Creek Bog, in Minnesota. Lindeman’s conceptual model considers the lake as an integrated system of biotic, species composition, and abiotic components where the food web and processes driving nutrient flux affected the processes of ecological succession (Lindeman, 1942). By conducting this study, Lindeman introduced for the first time the ecosystem concept in the quantitative assessment of ecological systems. In addition, he presented the concept of
the metabolism of the ecosystem by applying energy theory to the transfer of food and energy between taxa (Currie, 2011).

Odum’s ecosystem approach was embraced by the brother Eugene Odum (1913-2002) and Howard Odum (1924-2002). They developed this approach and made it a paradigm in ecology by the 1960s and 1970s (Odum and Odum, 1976). The paradigm, Ecosystem Ecology, sought to understand the reciprocal metabolic connections between biological and physical components of systems. The spread of the ecosystem concept was prompted by Eugene Odum’s seminal book ‘Fundamentals of Ecology’ (1953). They pioneered the well-known visualization of an ecosystem as energy circuit diagrams that give information of thermodynamics constraints, feedback mechanisms, and energy flow (H. T. Odum and R. Pinkerton, 1955) advanced their maximum power output theorem, which stated the systems that survive are those that can maximize power flow. Maximum power flow is accomplished at low energy efficiency. Furthermore, H.T. Odum introduced the concept of ecological engineering which was described as “the engineering of new ecosystem beings … that uses systems that are mainly self-organised” (Odum, 1963). One, primarily based on the work of Odum, aims to describe urban metabolism in terms of energy equivalents.

Ecological models attempt to capture the characteristics of ecosystems. The system approach allowed for the linking of different disciplines, including industrial Dynamics which was developed by Forrester (1961) to describe flows of matter and energy in industrial systems. His approach was generalized and applied in the system ecology context. In the 1960s and 1970s there was an increasing interest in ecological modelling, coinciding with computational power advancements in terms of the digital computer (Fath et al., 2012). These models were mostly focused on population dynamics and biogeochemical models in the context of aquatic systems in the 1970s. In the 1980s, ecological terrestrial models were developed and published. In the last few decades, a significant amount of ecological models types have been developed to address ecological systems at different scales (Jørgensen, 2016).

2.5.3. Ecological Models and Systems

As mentioned earlier, the development of quantitative assessment and consideration in ecology was due to the introduction of the system dynamic and system analysis methodologies. The principles of the methodology were derived from General System Theory which was put forward by Bertalanffy and others. The concept of system became widely applied in a number of disciplines including biology and ecological systems. Odum (1975) argued that cybernetics, hierarchical structure and holistic perspectives are a need of being adapted to deal successfully with the complexity of the system in focus (Odum, 1977; Patten and Odum, 1981). Application of system theory principles are applied in all aspects of analysing and describing an ecological system. Analysing and understanding the system modelled is an integral and essential part of the mathematical modelling process of a system (Texter et al., 2011).

A system is an abstract description of a number of components which are hierarchically constructed and interact with each other. The components can be grouped into sub-systems which interact with other components or subsystems. The hierarchical organisation of the component and the sub-systems produces larger functional wholes and, as a result, new properties emerge that were not present or evident within the next level down (Odum, 1977). The first step in the system analysis process is the definition of the boundaries of a system that distinguishes between the interior of the system and its surrounding environment.

Mathematical models assist in understanding the behaviour of a system in focus and showing the relationship between the different components and the subsystems using mathematical equations. Thus, mathematical modelling can be seen as an abstract and simplified picture of reality (Krenzling, 2013). Moreover, they provide knowledge, understanding and predictions about the system-of-interest by generating simulations under different scenarios (Grant and Swannack, 2011). Accordingly, models can be seen as a formal representation of knowledge.

2.5.4. Ecological Modelling Approaches

Dynamic population, Biochemical and Bioenergetic models

Ecological models have been developed to be applied as tools in environmental management. Jørgensen identified eleven different Model types (Jørgensen and Bendioriocho, 2001). Jørgensen argues that the three classic, widely used models are the Population Dynamic, Biochemical and Bioenergetic. As a result of the increasing use of these models in 1970s, new problems and questions arose, leading to the development of new types of models. Among these models are structural dynamic models, fuzzy models, artificial neural networks models, spatial models, individual based models and ecotoxicological models.
Nevertheless, the three classic models remain dominant and are extensively used in modelling population dynamics, matter and energy flows.

Population dynamic models are used to describe the development of biological populations, including growth mortality and age structure as well as population distribution. The model provides an understanding and tracking of the resources, and the effects of toxic substances on the development of a population. This model is based on the Lotka-Volterra models from the 1920s. There are two approaches to the mathematical modeling of population dynamics. The first approach is called Population State Modeling which considers all the individual members of a population as identical and having similar behavior. In addition to the Lotka-Volterra models for predator-prey, there are a number of population models that use this approach, including logistic growth models and Malthusian growth models, among others. The second approach is called individual states (I-state), which assumes the existence of variation among individuals. Models based on this approach divide the population into subsets of individuals with identical characteristics. The models are generally structured according to different categories including age, size, growth rate and others (Pastorok et al., 2016).

The other two model types, biochemical and bioenergetic, apply the mass and energy conservation principle. These models describe the processes of mass, energy and information transfer within which they are expressed as the difference between the incoming and outgoing substances. Causality is required in understanding and developing these models, coupled with software availability, making them attractive in the development of many models. They are mainly used in environmental management and applied to describe states of ecosystems and their reactions to environmental processes.

All three model types can be applied in two versions: a dynamic version, applying differential equations, and a steady-state version, applying algebraic equations. For solutions to problems with average situations or worst-case situations, steady-state models are used. A dynamic model becomes a static model when all its differential equations are set to zero to obtain the state variable values (Jørgensen and Bendoricchio, 2001).

2.5.5. Computational Tools

Computational Ecology utilizes computers to address the complexity of the ecosystems. The computational tools should be selected based on the objectives and level of details of the model (Jackson et al., 2000). There are a variety of computational tools currently applicable that allow us to build and simulate models. These tools range from the qualitative conceptual model at the lowest level to the general programming computer languages such as C++, Basic, and Java. Between the two extremes, there is a series of "gradient" of different tools (fig)-2.1.39.

For example, the modelling system is a customized software that follows specific methods that cannot be modified or changed. In this software, the model can be constructed relatively quickly by utilizing modelling systems programs such as STELLA and VENSIM. Instead of writing code, these softwares create models by choosing and dragging icons while the software run the built-in codes. On the other extreme, programming languages are designed for model development and coding the methods by the modeller (Voinov, 2010). They allow the modeller full control over the process of the model construction. Employing this approach could be time-consuming and requires knowledge of and skill in programming languages.

Between these two extremes, there is extendable system modelling and the spreadsheets softwares, among others, which allow for specific codes to be added in order to allow changes and more control over the process. The difference between the several tools is mainly in the degree of control over the model construction. The more control required, the more programming and coding knowledge is needed. Although the System Modelling approach has limits on what can be modelled and detailed, it is still useful and time saving in terms of the simulation of systems without becoming involved in the syntax of programming language (Jackson et al., 2000).
2.5.6. Conclusion

Mathematical modelling plays a significant role in ecological research, due to the fact that it provides an alternative to the large-scale experiments in the real environment. In ecology, replicating field experiments under controlled conditions is hardly feasible. Accordingly, mathematical modelling and computer simulation are powerful research tools that are widely applied in the environmental management of ecosystems. Although cities and urban systems meet the definition of ecosystems, according to Tansley and Odum, the ecological model application is barely even in existence. Urban system consists of all the elements of an ecological system, including population, carrying capacity, matter and energy flow. Adopting the ecological modelling approach in architecture and urban design requires the simulation of the urban system behaviour. This process involves following a holistic approach and a systematic method of model building. It requires clear and explicit mathematical problem formulation as well as clearly specific baseline information for model validation. Similar to the ecological model that does not describe the accurate real-world, the urban system model still does not have a mathematically accurate or clear description of the system. For example, some social and cultural interactions are hard to define mathematically. This creates difficulty in understanding how the results of computation should be analyzed in this regard. However, simulating the urban system requires the translation of the model into a computer code. Prior to applying the numerical methods to the code, a design of the model should be developed. The modelling process includes defining all the components of the urban system and subsystems and the system boundaries. Once the exterior and interior environments have been defined, the exchange of mass and energy with their surroundings can be determined. Having established the system components, and boundaries, the conceptual model can be set up by applying the visual circuit energetical diagram. Accordingly, the flows through the system should be expressed mathematically. These flows represent what Odum called Urban Metabolism in terms of energy equivalent. By implementing the mathematical model on computer software, simulation can be run to describe the system behaviour through graphs and numerical data. In turn, this data, (including logistical growth, carrying capacity and trophic dynamics) can be exported to inform the morphological design process of the urban system.
2.6. Conclusion Literature Review

The analysis carried out in this chapter aimed to put forward the intellectual framework of the research. The review study of the three domains, namely urban systems, ecology and ecological computation, situated the scope of the investigation on the overlapping areas of the three fields. In the urban system domain, the review focused on the radical and iconic projects which attempted to propose alternatives to the modern city based on ecological thinking. Two of the most original projects were selected as subjects of study: Hilberseimer’s “Decentralized City” and Soleri’s “Arcology. Considering the city and the superblock, in particular, as ecological systems led to the investigation of ecology and its subfield: the ecological system or ecosystem. In the second part of the review, a thorough analysis of the development of the concept of ecosystems was carried out; and a number of principles were extracted to be implemented in the superblock design. The last domain of study, Computational Ecology, highlighted the quantitative description of the ecosystem by applying computational methods and tools. A number of relevant principles from the three domains were adopted and applied in the experiment throughout the research.

Despite the broad difference between the work of Hilberseimer and Soleri, they both placed the emphasis on ecological awareness in design. For them, the study of Territorial Ecology became a prerequisite for urban design. Although they address the subject in a different manner, they also shared several key ideas of ecological approach as covering the design of the cities. Among these are: 1) Holistic thinking in adopting a cross-disciplinary approach including ecology, biology and urban design. 2) Integrating the city into nature. 3) The city as a productive system. 4) The city as a self-contained urban system which contains all the necessary elements of city. 5) The city morphology is subject to the climatic and environmental conditions in relation to its productivity. These principles, as Soleri stated, are drawn from the explorations into ecological systems coupled with evolutionary processes in nature. Interestingly, both proposals were conceptual and lacked deep analysis or thorough research into ecological systems; although Hilberseimer conducted sun orientation and wind flow experiments, which determined the density of his proposal. From an ecological point of view, their city systems remain at the descriptive level without influencing the flow of energy and elements. It can be approached by understanding and examining the services that it may be providing.

Understanding and analyzing ecological systems, by applying the concept of the ecosystem, requires mathematical models which are almost compulsory in order to understand the function of a complex system such as an ecosystem. Mathematical models assist in understanding the behaviour of a system in focus and showing the relationship between the different components and the subsystems using mathematical equations. Although there are several types of models that can be applied in the quantitative assessment of ecological systems, there are three classic models that are widely used. The first are the population dynamics models, which are mainly based on Malthusian models and the Lotka-Volterra models, which describe the development of biological populations. The other two are the biochemical and bioenergetic models based on the Underman and Odum ecosystems approach which describes the processes of mass, energy and information flows through the ecosystem. A significant contribution to the modelling approach was made by Odum through the introduction of a visual description of the ecosystem as an energy circuit-diagram providing information about the energy flow. Advancement in computational power and software led to the development of more complex models that can be utilized for ecosystem analysis.

The literature analysis has provided the intellectual foundation for the experiments carried out in the following chapters. The superblock is seen as an ecological system which provides the basic services of water, solar energy harvesting and agriculture to sustain living beings. It is modelled as an ecosystem composed of three subsystems that transfer water, energy and material through the superblock. In the first part of the experiments, each is modelled as an isolated system in the superblock, simulated and analyzed in relation to the population growth and its effects on the morphology of the superblock. In the second part, the experiment examined the integration of the three systems and their interaction among themselves as well as their impacts on population growth and the superblock morphology.
3. Methodology
3.1. Introduction

This chapter lays out the foundation for the methodological approach of the research into the System Dynamics Thinking methodology. System Dynamics (SD) is based on the notion of system thinking and feedback concepts are applied to handle non-linearity, multiloop and time-lag characteristics of a complex dynamic system. (Sterman, 2000). SD methodology can be applied to model and simulate complex dynamic systems to understand the dynamics of systems and design strategies in order to employ them in the architecture design process. SD depends on formalised methodology consisting of methods of problem definition, dynamic hypothesis, modelling, and system analysis among others. Essentially, systems must be modelled and simulated to understand them as must design management and development strategies. For this purpose, these principles of systems dynamic thinking are addressed and coupled with the chosen computation platform, namely STELLA.

Due to the fact that the mathematical solution for complex systems is extremely difficult, only a process of step by step numerical solution can be applied (Bala et al., 2017). This process is called simulation and is used in place of a real system. Forrester’s System Dynamics Methodology has become the formalised computer modelling methodology utilised in modelling and simulating complex dynamic systems. SD modelling essentially consists of a problem statement, a causal loop diagram, a stock-flow diagram, scenario planning and modelling. In this research, the system dynamics method is realized by modelling interlinked urban systems of superblocks which are characterised by local interaction leading to global behaviour of the system.

Presently, Systems Dynamics are widely applied in medicine, as well as in social sciences, including economics (Dracko, 2010). Its application in urban and regional planning systems has been developed, particularly in the fields of planning policy and natural resources management. Most of these models do not consider the morphological aspects of the city or architectural artefacts. In the following chapter, system dynamics modelling techniques will be coupled with the information gained from chapter 2, leading to the designation of the full scope of the System Dynamics method.
3.2. System Dynamics Methodology

System Dynamics principles were initially developed and introduced by Dr. Jay Forrester, in the sixties of the last century, as a modelling and simulation method for industrial management. Based on system theory and feedback control theory, SD has been used for a wide spectrum of applications including the modelling and simulating of social, economic, physical, chemical, biological, and complex ecological systems. In the SD method, a system is defined as a collection of parts that continually interact over time which leads to the emergence of new properties.

Contrary to traditional analytic methods, SD focuses on the system as a whole and on the interconnectedness between components and processes. Systems Dynamics methodology was realised by modelling and simulating the system in the study. Broadly speaking, there are, with variations, six fundamental steps in constructing system dynamic models. They are, as follows: (1) Defining the "problem" (2) Conceptualizing a system (3) Formulating the model (4) Testing and evaluating the model (5) Utilizing the model (6) Implementing a strategy.

3.3. System Dynamics Modelling

Ecological modelling is an iterative process, as shown Fig. 3.40. It starts by defining the problem and setting up the objective of the model. Defining the problem starts by setting the boundary and the objectives of the system to be addressed. The system boundary must be specified spatially and temporally, the spatial defines the size of the system and its hierarchy level in the overall ecological system. The temporal boundary is needed to understand how the system evolves over a time span and which variables and processes are static or dynamic. The choice of the boundaries depends on the complexity and the level of detail within the system.

The system boundary should contain that portion of the whole system which includes all the important and relevant variables to address the purpose of the design problem. Thus, the boundary encompasses the smallest number of components within which the dynamic behaviour is generated (Forrester, 1968). The dynamic behaviour of the system is driven and generated solely from variables and interaction within the system boundary (Forrester, 1970). Therefore, system boundaries are crucial in identifying the internal and external dynamic of a system and in determining whether given sub-systems are open or closed (Zomorodian et al., 2018).

The next step involves gathering and collecting data and information regarding the system under study and identifying the significant variables and major factors generating the dynamic behaviour of the system. The availability of the data is crucial for the accuracy and the realism of the model. Once the data has been gathered, and the boundaries established, the identification process of the system can be set up. Therefore, the model should include all variables and factors relevant to the system’s objectives. All these variables and factors must be included inside the system boundary.
the model must be validated against observed data and literature estimates (Fath et al., 2012). Consequently, sensitivity analysis can be tested by changing the parameter’s values and observing the changes in the state variables.

3.4. The System Dynamic Modelling Elements

Dynamic Hypothesis, Causal and Feedback Loops, Stocks and Flows

The dynamic hypothesis, feedback loops, stocks and flows are the most important aspects of the SD approach and have become the basis of SD Modelling. Following the definition of the problem, a dynamic hypothesis must be constructed to describe the dynamics of the problem. The dynamic hypothesis is a conceptual model representing the causal loops diagram that targets defining the critical feedback that generates the system’s behaviour. It determines the structure of the system which changes in the dynamic behaviour of the system (Sterman, 2000). Based on the dynamic hypothesis, the reference dynamic behaviour of the system is represented by a causal loop diagram. The causal loop diagrams are used to describe basic causal mechanisms hypothesized to generate the reference mode of behaviour of the system over time. Fig.3.42

The next step is to search for the relationship between the variables and track the development of the feedback loops. The structure of the feedback loops - which generates the reference dynamic behaviour of the system - is represented in the form of a causal loop diagram. The feedback loop principle is considered one of the most important properties of SD which facilitates simulating the behaviour of systems. A feedback loop consists of two or more causal links between connected elements of the system in such a way that a change in variables of one element causes a change in variables of the others, which in turn directly causes a change in the variable of the initial element. Recognizing the main components and feedback loops between them is crucial for the accuracy and efficiency of the model. Feedback loops generate a nonlinear behaviour, even if all constitutive causal relationships are linear (Pruyt, 2013).

Feedback loops can be positive or negative, see Fig.3.42. The positive one generates exponentially escalating behaviour in such a way that if there is an initial increase in variable A this eventually leads to an additional increase in A and if there is an initial decrease in A this leads to an additional decrease in A. This type of feedback loops behaviour is self-enhancing. By contrast, the negative feedback loop generates balancing behaviour in such a way that if there is an initial increase in variable A this leads after some time to a decrease in A, and if there is an initial decrease in A this leads to an increase in A.

Based on the causal loop diagram and feedback loop, SD models can be constructed using a Stock-Flow Diagram (Fig.3.43). The SFD is the underlying physical structure of the system in the form of stocks and flows. The stocks, which are also named the levels or the state variables, represent the current state of the system. The last element is the rate of the flows which change the stocks. It consists of stocks variables, flow variables, auxiliary variables, parameters and constants and causal links between variables see Fig.3.45. A stock variable - also called a level - accumulates, integrates flows over time. It changes as a result of incoming and outgoing flow variables. It can be increased by increasing its inflow rate as well as by decreasing its outflow rate. Generally, the change in stocks is slow, even when the flows into or out of them change unexpectedly. For this reason, stocks act as delays or buffers or shock absorbers in systems (Meadows, 2008). The second building block is the flow variables which can be inflows or outflows. Flow variables regulate the states of the stock variables. If the difference between the inflow and outflow is positive, then the stock variable increases, and a negative difference decreases the stock variable. Inflow and outflow variables also determine how fast the stocks are changing and can be decoupled by the stocks variable from each other and become independent and temporarily out of balance with each other (Meadows, 2008). Accumulation in stocks creates the dynamic behaviour of the system. The stock equation can be represented by the first-order finite difference equation, and it can be expressed as Fig.3.43.
These fundamental components are the basic blocks in construction models of dynamic systems which is also applied in computer modeling and simulation processes. SD has developed an experimental modeling approach to complex systems by running iterative simulations and experiments by computer. (Richardson, 2011). Forrester argued that the advances in computer technology and computer simulation, among others, led to the development of SD (Forrester, 1958). A significant boost to the System Dynamics modeling approach was provided by the introduction of STELLA, the first icon-based modeling software by the System Thinking scientist Barry Richmond, in 1986. The STELLA software will be used to illustrate the development of models throughout this research.

3.5. The Computation Platform - STELLA

STELLA is an object-oriented graphical programming language designed for modelling system dynamics which provide a framework for observing the quantitative interaction with a system. It provides a set of graphical objects with their mathematical functions for easy representation of the system’s structure and the development of a computer code. In STELLA, the models can be easily and quickly developed and modified. It can address ecological problems with highly nonlinear relationships and constraints. The software is used to create, develop and analyse complex ecological dynamic systems models, among others. It allows one to achieve this complexity by developing the model in three levels. The first level is the general model structure which points out the interdependencies between the components within the system. In this level a Causal Loop Diagram (CLD) is developed. The second level is the flowchart that determines the quantitative interactions between the system’s variables. The last level is the specification of a differential equation – the equation process is automatic.

Fundamentally, the model is developed in two main stages. The first stage is the development of a Causal Loop Diagram (CLD), while the second stage involves converting the latter into a stock-flow chart. The flowchart used in the model development STELLA uses symbols similar to the Forrester feedback dynamics diagrams. In the Forrester diagrams, figure Figure 3.44, rectangles (A) represents state variables (stocks or level) which are the focus of the system study. They accumulate material which is controlled by flow variables which is represented by the valve shapes (D). The valves define the rate of the material inflow and outflow through the stocks – the system behaviour - according to mathematical equations represented by the rate equation (C). The auxiliary variables (G), constant parameter (H) and information channel (E) symbols provide information from the inner and outer environment of the system which is required for the flows equations. The inflow and outflow of the material matter, or population, agriculture produce, energy, water, fish, pollution, buildings, lands etc. (D) Converters - converters accept parameters and provide information which may contain constants or equations. (F) Connector - a connector depicts interaction between variables. It connects stocks, flows and converters of the model and allows information to pass between them. They are drawn as arcs. STELLA develops the differential equation directly from the conceptual diagram (the flowchart).

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<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Component</th>
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<tbody>
<tr>
<td>Stock</td>
<td></td>
<td>Represents the amount of energy, material, or population</td>
</tr>
<tr>
<td>Flow</td>
<td></td>
<td>Represents the in-flow and out-flow to and from the stock which is the rate of change of the stock</td>
</tr>
<tr>
<td>Converter</td>
<td></td>
<td>Contains parameters</td>
</tr>
<tr>
<td>Connector</td>
<td></td>
<td>Transfer of information - connects stocks, flows, and converters</td>
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STELLA models are created by clicking on icons and placing the icons on a canvas. Subsequently, the structure of the model is established by connecting these components through the connectors which passes on the information. Once the structure of the model is established, initial conditions, parameters values and functional relationships can be specified for state variables. A representation of the most basic model of dynamic population can be represented using the symbols as shown in Fig.3.45. In this model, the population size is represented by the stock and is affected by the flows which represent the birth and deaths. The number of the births and deaths is determined by the population size and the birth and death rate provided as parameters in the converters. The information is passed on between the relevant part of the system through the connectors (arrows). The model consists of two feedback loops, the positive feedback loop generating population growth and a negative feedback loop decreasing the population. Therefore, the simple population model shows population increase by birth rate and decrease by death rate and it can be expressed in equation Fig.3.47.

3.6. Ecological System Dynamic Models

3.6.1. Population Dynamics Simulation

Modelling and simulation population growth system utilizing the STELLA modeling software can be seen as a process, divided into four main steps: 1) Defining the conceptual system structure and developing the causal loop diagram which determines the system behaviour as shown in Fig.3.49. 2) Converting the conceptual model and causal loop diagram into a stock-flow diagram described by the generic symbols of the software (stock, flow, converter, and connector) as represented in Fig.3.50. 3) through the application of mathematical equations that describe the system behaviour over time as shown in Fig.3.51. 4) Simulating the system is the last step, where simulation under different scenarios is carried out and analysed for further processing Fig.3.52.

The development of the structure and the feedback loops of the system starts by drawing the causal loop diagram as shown in Fig.3.49. The three fundamental variables of the model are population, birth rate and death rate. Birth rate increases the population and, in turn, population raises the birth rate. However, the increase in population increases the death rate which brings about a decrease in population. In terms of the birth rate-population cause-effect relationship, both are positive, while the death rate-population cause-effect relationship one is positive – increasing the death rate, and the other is negative – decrease in the population. Therefore, the model includes two fundamental loops which are the regeneration loop (R) and the balancing loop (B). The regeneration caused by the birth rate that generates new births and adds to the population. The balancing result of death is that it reduces the population. Hence, births creates a positive loop, while the deaths create a balancing loop.

The next step is to draw the stock-flow diagram based on the Causal-Loop as shown in Fig.3.49. In the causal loop, the population is represented as a stock (population level). The birth rate is an inflow (population per year) into the stock population and the death rate is an outflow from the stock. Therefore, the

![Causal Loop Diagram](image)

![Population Stock Flow Diagram](image)

![Population model equations](image)

![Population growth simulation graph](image)
and it is a positive feedback loop and death decreases the population and it thus a negative feedback loop. Having constructed the stock-flow diagram, the subsequent step is to apply a mathematical equation that describes the growth rate and death rate in the population. The final step is to determine the time duration of the simulation and execute the runs as shown in Fig 3.52.

3.6.2. Sensitivity analysis

Sensitivity analysis allows one to assess how sensitive the model behaviour is to the change in the parameter’s values. The procedure is carried out by running the model several times by setting different values for a parameter, followed by drawing comparisons between the different simulation outcomes. It is important for two reasons: firstly it displays the level of accuracy needed in the estimation for validation of the model (Bala et al., 2017). Second, it tests if the parameter significantly affects the behaviour of the model and whether or not it should be chosen for additional data collection (Sterman, 2000). In the population analysis, the change was assigned to the parameter of the birth rate with the assigned values of 0.02, 0.03, 0.04. The simulated population shows, as expected, an exponential growth in the three different values. It displays evidence that the change of 1 percent in the birth growth could increase the population by about three times.

![Sensitivity analysis and population growth](image)

3.7. Agriculture Dynamic System

Urban agriculture and farming have given rise to great interest in urban and architecture design due to the considerable impacts they have had on ecological systems. The proposed model describes an urban system that consists of population and limited land area suitable for agriculture. The agricultural system predicts, over time the area needed for the amount of the agricultural produce required, in terms of calories, in relation to the size of the population. In the model the land suitable for cultivation is a limited resource. The calories available are computed from the area cultivated and calories yielded. The model calculates the self-sufficiency indicator, which is the ratio of calories available to the calories required, varies, both with changes in calories available and population. The area cultivated is increased by transfer of land suitable for agricultural cultivation. Self-sufficiency indicator value 1 means surplus food and less than 1 means a shortage in food supply.

Following the modelling method described earlier in this chapter, the agricultural modelling and simulating processes were based on the four modelling steps: causal loop, stock-flow diagram and mathematical equation application and simulation. Fig.3.54 shows the main structure, and the causal loops of the system. It consists of three interrelated stocks: population, available land and cultivated land. The cause-effect relations form two main loops: the first defines the relation between the population and the available land and the second represents the relation between the population and the cultivated land. It is obvious that increases in the population leads to an increase in cultivated land and a decrease in available land. This behaviour can be seen as two feedback loops: one is a negative or balancing loop, and the second is a positive or regenerating loop.

The next step in the stock-flow diagram construction is the translation of the causal loop into the structure and the definition of the relationships by applying the generic symbols of Stella, as shown in Fig.3.55. The diagram shows two sub-models: the population sub-model (at the top) and the land sub-model (at the bottom). The relation between the two subsystems is determined by the parameters of the consumption per capita (calories) and the agriculture yield (i.e., calories available at any given time). Having constructed the stock-flow diagram, it was followed up by applying the mathematical equation of the system behaviour as shown in Fig.3.56. The equations describe and mathematically simulate the system behaviour in term of population growth and provision of agricultural land.

The last phase is the simulation of the system over time and the generation of results the results as numerical and graphical data as shown in Fig.3.57. It shows the simulated area cultivated, the area increase rate, the population and self-sufficiency indicator, for a simulation period of 100 years. The cultivated area initially increases up until about 60 years and reaches the upper limit of available land suitable for agriculture and subsequently remains constant. The self-sufficiency indicator increases up until about 30 years and then decreases due to an increase in the population. It has a value above 1 from the twenty-ninth year until about the sixtieth year. The results suggest that, in order to achieve self-sufficiency, the design must consider limiting the growth of population or allocate more areas to agriculture production.
START TIME = 0
STOP TIME = 100
DT = 0.25
INTEGRATION = EULER

INITIALISATION

EQUATIONS

(s=stock, f=flow, c=converter)

- \( s_{\text{available land}} = 500 \)
- \( s_{\text{Cultivated land}} = 0 \)
- \( s_{\text{population}} = 10000 \)
- \( c_{\text{fractional birth rate}} = 0.025 \)
- \( f_{\text{birth rate}} = s_{\text{population}} \times c_{\text{fractional birth rate}} \)
- \( c_{\text{Average life time}} = 65 \)
- \( f_{\text{death rate}} = s_{\text{population}} / c_{\text{Average life time}} \)
- \( c_{\text{Land increase rate}} = 0.05 \)
- \( f_{\text{land increase}} = s_{\text{available land}} \times c_{\text{Land increase rate}} \)
- \( c_{\text{yield}} = 2.4 \times 1780000 \)
- \( c_{\text{Calories available}} = s_{\text{Cultivated land}} \times c_{\text{yield}} \)
- \( c_{\text{Calories per capita}} = 2000 \)
- \( c_{\text{Calories required}} = s_{\text{population}} \times c_{\text{Calories per capita}} \times 365 \)

- \( c_{\text{Self-sufficiency indicator}} = s_{\text{Calories available}} / c_{\text{Calories required}} \)

POPULATION

- \( s_{\text{population}}(t) = s_{\text{population}}(t - dt) + (f_{\text{birth rate}} - f_{\text{death rate}}) \times dt \)

INIT population = 10000
INFLOWS:
- \( f_{\text{birth rate}} = s_{\text{population}} \times c_{\text{fractional birth rate}} \) (UNIFLOW)
OUTFLOWS:
- \( f_{\text{death rate}} = s_{\text{population}} / c_{\text{Average life time}} \) (UNIFLOW)
- \( c_{\text{Average life time}} = 65 \)

CULTIVATED LAND

- \( s_{\text{available land}}(t) = s_{\text{available land}}(t - dt) + (-c_{\text{land increase}}) \times dt \)

INIT available land = 500
INFLOWS:
- \( c_{\text{land increase}} = s_{\text{available land}} \times c_{\text{Land increase rate}} \) (UNIFLOW)
OUTFLOWS:
- \( s_{\text{Cultivated land}}(t) = s_{\text{Cultivated land}}(t - dt) + (c_{\text{land increase}}) \times dt \)

The model has 14 variables:
- Stocks 3 Flows 3 Converters 8
- Constants 5 Equations 6 Graphicals 0

Fig.3.54 Causal Loop Diagram

Fig.3.55 Agriculture Stock Flow Diagram

Fig.3.56 Agriculture model equations

Fig.3.57 Cultivated Area in relation to population size

Fig.3.58 Agriculture model equations

Fig.3.59 Causal Loop Diagram

Fig.3.60 Agriculture Stock Flow Diagram

Fig.3.61 Agriculture model equations
3.8. Conclusion

The methodology described and discussed in this section lays the foundation for a system dynamic modelling and behaviour simulation. Through its utilisation, the focus on the application of System Dynamics in design shifts from the concept of form to the concept of dynamic process, when it comes to the design problem. Another advantage of SD is that it allows for the examination and clarification of a subsystem, coupled with the analysis of its interaction and links (Guo et al., 2001). Defining the components, feedback loops and the dynamic hypotheses become the foundation of the definition of the design problem. Therefore, the design process starts by constructing the Dynamic System Model following the SD procedures including the mathematical description of the system. Although it has been widely used in different fields of natural and social science and engineering, its use in the urban and architecture fields is limited to the resources management policy decision.

SD describes the behaviour of a system that emerges from the interaction of the system components between themselves and their environment. The behaviour of the system is defined by the structure of the system which is, in turn, defined by the feedback loops. Thus, it can predict the complex system change under different scenarios, which is very useful in studying and exploring solutions for urban system design. The notion of carrying capacity and imposing limits on growth define the level of the assumed stable state. In the case of an urban system such as a superblock, the SD model can be used to predict resources availabilities and critical thresholds for the state stability of the system regarding water, energy, population and agriculture.

Although SD cannot effectively describe or simulate morphology, it can certainly facilitate the design of a system in terms of how resources should be transformed to achieve the objectives of the system model. By integrating SD with the qualities of ecological system (ecosystem) processes, the notion of settlement unit and ecological computation, which are all addressed in chapter 3, the objective is to generate a superblock as a dynamic system which consists of subsystems. The SD is applied to facilitate the design and planning allocation, and the combination and distribution of resources.
4.1. INTRODUCTION

Addressing the concept of ecological principles in design, this chapter aimed to explore the developed method of modelling and simulating ecological systems, coupled with an evolutionary design model, in order to generate morphologies related to the system performance in a superblock. The experiments utilized an integrated model that consisted of two sub-models: the System Dynamic model and the Evolutionary Design Model (SDEDM). Three ecological systems which provide ‘service functions’, including water, energy and agriculture, were chosen to be explored in the SDEDM. For each system a separate experiment was designed, set up, carried out and analyzed (Fig.4.60, Fig.4.62 and Fig.4.64).

The objective of the experiment is to generate morphologies of surfaces in response to the function and performance of the system in study. The surfaces perform as ‘inhabited’ surfaces that can sustain and support living beings. The surfaces’ function is defined as follows: 1) The water system generates landform that allows for the creation of ponds for rainwater collection; 2) The solar energy system creates a skyline surface that is able to generate sufficient solar energy within the superblock; and 3) The agricultural system develops a terraced land surface for effective farming of different types of crops. The morphological aspect of each experiment was ‘ecological surfaces’, which were assessed and analyzed. The surfaces act as the spatial distribution and organizers of the superblock.

A set of three separate experiments were designed, set up and carried out for each system. A hypothetical one square kilometre (1000X1000 metre) superblock situated in the middle latitude around the Mediterranean region was utilized as the site of the experiments. Three sets of climatic data - sun irradiation and rainfall rate - used in the experiments, represented the average of the highest, middle and lowest values.

Each experiment was divided into two parts: System Dynamic Modelling and the Evolutionary Design Modelling. In the first part, an SD model was modelled to describe and simulate the system. The construction of the model was very basic and included the minimum number of components that could represent the system. All of the systems included sub-models of population dynamics (growth) in order to explore the impact of the system on the population growth. The assumption is that the system, as a representative of vital resources, as in natural systems, can have a positive or negative impact on population growth. In the second part, the simulated results of the SD were exported as design objectives to be achieved through the evolutionary design model. The SD outcomes were applied in the evolutionary solver as the objectives of the algorithm (Fig.4.60, Fig.4.62 and Fig.4.64).

Each system was simulated under three climatic conditions for the purpose of examining the effects of the environmental conditions on population growth and the morphological outcomes. Following the SD simulation, the evolutionary design simulations were conducted and the Pareto Front solutions were selected and clustered into three groups according to K-mean algorithm. For practicality, the average solution of each cluster was selected for further morphological analysis and assessment. Figure 1, Figure 2, and Figure 3 show the pseudocode of the SDEDM model for each system.

4.2. Design Experiments setup

The following section describes graphically the experiments’ setup and the possible outcomes based on the methodology devised in chapter three. Each experiment, a design model, consists of two sub-model, the System Dynamic model and Evolutionary Design model. The simulations and their outcomes generate three-dimensional data that drive the morphological design of the system.
4.2.1. Water System-SDEDM (System dynamics evolutionary design model)

Fig.4.60 and Fig.4.61 represent the Water system design model graphically. The first figure shows the integrated design model of the Water system. On the right side is the System dynamic that is composed of three sub-systems, population growth, building footprint and water collection. On the right side is the pseudo-code of the evolutionary design model which display the different components of the algorithm, the gene pool, the input data, genotype/phenotype, and the design objectives. In Fig.4.61 depicts the simulations results in three-dimensional datascape relating to the morphology of the water system.
4.2.2. Solar Energy System-SDEDM (System dynamic evolutionary design model)

Fig.4.62 and Fig.4.63 represent the Energy system design model graphically. The first figure shows the integrated design model of the Energy system. On the right is the System dynamic that is composed of three sub-systems, population growth, building footprint and energy harvesting system. On the right side is the pseudo-code of the evolutionary design model which display the different components of the algorithm, the gene pool, the input data, genotypic/phenotypic, and the design objectives. In Fig.4.63 depicts the simulations results in three-dimensional datascape relating to the morphology of the Energy system.
4.2.3. Agriculture System-SDEDM (System dynamics_evolutionary design model)

Fig. 4.64 and Fig. 4.65 represent the Energy system design model graphically. The first figure shows the integrated design model of the Agriculture system. On the right is the System Dynamic, which is composed of three sub-systems: population growth, building footprint and agriculture producing system. On the right side is the pseudo-code of the evolutionary design model which displays the different components of the algorithm: the gene pool, the input data, genotype/phenotype, and the design objectives. In Fig. 4.65 depicts the simulations results in three-dimensional datascape relating to the morphology of the Agriculture system.
4.3. The Location

The Northern mid-latitudes between 30°–60° latitude. The Mediterranean, located between about 30° and 45° latitude (Fig.4.66). Scientists have described the Mediterranean region as a "climate sensitive area" due to the expected rise in the average temperature and the decrease in the total precipitation (Giorgi and Lionello, 2008). Recent studies have shown that the reduction in rainfall and widespread warming will be evident over most of the Mediterranean region (Christensen et al., 2007).

The prediction points out that the region is likely to warm up at a rate of about 20% more rapidly than the global annual mean surface temperature (Lionello and Scarascia, 2018). The impact of these changes, coupled with population growth and urbanization – that will reach about 500 million ("Middle East & North Africa | Data," n.d.) on the population, urban systems and ecosystems has far reaching consequences and poses a high risk for the population and the environment (Lionello and Scarascia, 2018).

Due to climate change alone, fresh water availability is likely to decrease significantly (Field, 2014). This situation will be exacerbated with the projected increase in demand for irrigated agriculture to maintain food security. (Schwabe et al., 2013) Moreover, the effects of the temperature and precipitation change will affect the natural and managed ecosystem. The increase in aridity poses the main threat to the biodiversity and ecosystem survival (Gouveia et al., 2017). The overall biodiversity on land and in the sea can be lost due to these ecological changes. They can also lead to the endangerment of renewable natural resources and environmental services including maintenance of biodiversity, soil, water, and climate regulation, among others.

In addition to climatic factors, social, economic and environmental changes lead to changing diets and an increase in the demand for food products (Paciello, 2015). Although the demand will be higher, the crops and fish are projected to drop in many areas as a result of the climatic and environmental factors (Cramer et al., 2018). Ocean warming and acidification are most likely to affect aquaculture and fisheries which are essential for food security in the region. In the Mediterranean region there is a shortage in fish products: they import more than they export. Studies have shown that, by 2040-2069, more than 20% of exploited fish and invertebrates could become extinct due to climate change (Cheung et al., 2016) For this reason, the expected climate change poses threats to food security in the region and represents a considerable challenge.

The current and future changes place the emphasis on the three interrelated ecological systems: the water, agriculture and energy, and how they can be designed as an integral part of urban ecological systems. The experiments in this chapter address the three key factors that are driving the impacts of climate change: namely temperature, precipitation and agriculture. These parameters, coupled with population, will be modelled as ecological systems of the ecological superblocks, simulated and analysed under different climatic conditions.
The first two separate experiments deal with Energy and Water; the first examines the potential of energy harvesting from solar radiation and the second examines water collection and distribution. The third experiment examines agricultural systems combined with the energy water models from the first two experiments.

4.4. Dynamic System modelling of Urban Systems

In an urban context, water, energy and agriculture systems span a wide spectrum of challenges and scales, all of which might be characterized as complex systems problems (Tumer et al., 2014). Although they are complex and difficult to comprehend, they are mostly designed as individual and separated systems, neglecting the consequences for other systems. This isolation exposes their analysis and design to the risk of not properly addressing or incorporating all the relevant factors (Bowden, 1991). To address this problem, a system-thinking approach is needed, coupled with a holistic approach to accommodate all the elements of the problem. Resources and systems, in the real world, overlap and interact through complex feedback processes operating at multiple temporal and spatial scales (Cilliers et al., 2013).

A systematic approach to problem solving has become widespread in its utilization, including strategies for tackling ecosystem services, agriculture systems and resources integration (Bommarico et al., 2013). Complex problems exhibit several key characteristics: 1) system components interacting; 2) causal relationships; and 3) the fact that behaviours are dynamic. To address these systems as complex problems, the experiments utilize the System Dynamic (SD) method to model the three systems. SD is a scientific framework for addressing complex, nonlinear feedback systems (Sterman, 2010). In general, SD modeling methods have proven to be useful in addressing ecological and complex systems for description and management purposes. In terms of urban design, and the superblock design in particular, SD has not been used or considered as a design tool. To examine the potentiality of the model as a design tool, this research introduces the SD as a key tool in the design process. Following the experiments start by developing an SD model for each system. The process has five general steps: (1) problem articulation; (2) development of a dynamic hypothesis; (3) formulation of a simulation model; (4) testing the simulation model; and (5) strategy design, experimentation, and analysis (Sterman, 2010).

The initial value and parameters were estimated from the primary and secondary data collected from different research studies, statistical year reports of The World Bank, UN Habitat, NOAA Climate and The UK Government, (“World - Solar irradiation and PV power potential map | Data Catalog,” n.d.), (“Average floor area by Borough - London Datastore,” n.d.), (“Average precipitation in depth (mm per year) | Data,” n.d.), (“Who | 3. Global and regional food consumption patterns and trends,” n.d.), (“Average area by Borough - London Datastore,” n.d.), (“Average area by Borough - London Datastore,” n.d.), (“Pareto in 1896 (Pareto, 1896). The optimal concept, which is called Pareto optimum defines a solution as Pareto optimal if there is no other feasible solution which would decrease some criterion without causing a simultaneous increase in at least one other criterion (Caetano, 2006). Generally, using this method never gives a single solution but a set of solutions, which is called the Pareto optimal set.

The objective of the SD is to construct a model of the system by extracting structures essential to its working mechanism, and simulating its behaviour, based on an analysis of feedback structures inherent to the system. Having articulated the problems, water, energy and agricultural causal relationships are established in order to identify key drivers of morphological parameters and corresponding consequences of parameters. As a result, the fundamental functioning mechanism of the water, energy and agriculture systems was established conceptually, in relation to the causal relationship between each component of each system and its subsystem. Three SD computer simulation models were developed based on the causal feedback loops. Following this, the models were validated by testing the behaviour pattern in each experiment by applying different values to the parameters. The tests compare the model to empirical reality for applicability of the model and whether the model is useful in meeting the modelling objectives.

The design ‘scenarios’ for the systems were created for a period of 100 years, by creating three different set values for the exogenous variables (climate and environmental) to predict the status of the system under extreme conditions. The values represent three different climate zones with the mid-latitudinal zone around the Mediterranean region. The precipitation values were 200, 600, and 800 mm as annual averages and the radiation, 800, 1200 and 1800 kwh. The extreme scenarios were created to simulate the conditions under which the system can support a superblock and what size of population.

Following that, the preferred simulation results exported to the generative design model as data input. The simulation experiments are realized using object-oriented modelling software, namely STELLA.

4.5. Evolutionary Design Model and Multi Objective Optimization

Optimization problems fall into two categories: the first is the single objective optimization problem and the second is the multi-objective optimization problem (MOP). Unlike single objective optimization, in the MOP, two or more objectives are optimized simultaneously. The multiple objectives are usually in conflict with each other and inhibit the simultaneous optimization of each objective. Moreover, a solution that meets one objective may diverge significantly from another objective. Therefore, the task to find one solution that satisfies all the objectives is difficult and the search focuses on establishing a set of feasible solutions. Mathematically speaking, there is no single solution for multi objective optimization, but there is a set of solutions. This set of solutions generated makes a compromise among the objective by employing the optimality concept introduced by Vilefred Pareto in 1896 (Pareto, 1896). The optimal concept, which is called Pareto optimum defines a solution as Pareto optimal if there is no other feasible solution which would decrease some criterion without causing a simultaneous increase in at least one other criterion (Caetano, 2006). Generally, using this method never gives a single solution but a set of solutions, which is called the Pareto optimal set.
The graph of the Pareto optimal set is called the Pareto Front. Although the solutions along the Pareto Front are mathematically equal and valid, they have different values for each objective (Konak et al., 2006). Actually, the Pareto Front solutions are of no preference and the selection of the final optimised solution is usually made on the basis of subjective preferences for the conflicting and diverse objectives (Konak et al., 2006). Most of the multi-objective optimization approaches, about 90%, aimed to approximate the true Pareto Front for the MOP (Horn et al., 1994).

There are primarily two types of methods to solve MOP: the analytical method and the numerical one (Xu, 2013). The analytical method seeks to reach an exact solution and involves strict mathematical proofs and strict problem characteristics which are not compatible with many realistic problems (Xu, 2013). On the other hand, the numerical method seeks to achieve an approximate solution. This method requires a defined decision variable and objective variables feedback from the optimisation problem. This method is more appropriate to real-world problems. Numerical optimization methods are a heuristic search algorithm which is inspired by natural systems behaviours. Basically, the algorithms are divided into four categories: 1) biology inspired algorithms; 2) Physics inspired algorithms; 3) Geography inspired algorithms; and 4) Social inspired algorithms (Behera et al., 2015).

One of the most widely utilized evolutionary algorithms in research studies and design is the Genetic Algorithm (GA), developed by John Holland in the 1960s, which is inspired by biology. GAs seek to explain the adaptive processes of natural systems and to design artificial systems based upon the natural systems (Holland, 1975). GAs use two separate spaces: namely a search space and solution space.

The search space is the space of the coded solution which generates the coded solution or the genotype. On the other hand, the solution space is the space of the actual solutions or the phenotype, which is generated by mapping the coded solution. Evolutionary algorithms in general, and GA in particular, mimic the survival of the fittest processes of natural ecosystems. GA generates a new solution via two basic operations: crossover and mutation. In the crossover, two solutions, called parents, that contain genomes are combined to form a new solution, called offspring. The parents are selected from the whole population by fitness, so the new solution – the offspring – is expected to inherit the genome which makes the parents fitter. The iterative process of the crossover allows the genes which lead to the fittest solution to appear more frequently in the population, eventually leading to convergence to the fittest solution. The mutation process introduces random changes in the characteristic of the genome. Due to the fact that the mutation rate is usually very small, the new genome will not be very different from the original one. The mutation process reintroduces genetic diversity which leads to escaping the local optima that might be reached by the convergence caused by the crossover process.

The genetic evolutionary pseudocode is summarized in Fig.4.69. This algorithm works as follows: Randomly initializing the genotype of every individual in the population. Then the algorithms begin running the main loop, evaluating the individuals – phenotypes – and assigning fitness values to them according to how they meet the objectives of the problem. The scores then determine the number of copies of each individual, which are placed into a temporary area called the ‘mating pool’. Then, at random, two individuals are picked as parents and offspring are generated by the use of a crossover operator. The genotype
of the offspring is formed by randomly allocating genes from parents. Then the mutation operator is occasionally applied, with a low probability, to offspring. Applying crossover and mutation, offspring are generated throughout the population. The process of evaluation and reproduction continues until the GA has run for the specified number of generations (Davis, 1991). Although evolutionary search has a random element to its exploration of the search space, the search is directed by selection towards better solutions (Bentley, 1999).

The GA is one of the most popular approaches for generating non-dominated solutions – Pareto optima – for MOP. An excessively large number of non-dominated solutions might make the selection process of the final preferred solution complex and impractical. Making the searching process more practical can be achieved by introducing controls on the resolution of the Pareto-set approximation, by dividing the population of the Pareto sets into clusters and creating subpopulations.

One of the most commonly used clustering algorithms is the K-mean clustering algorithm (Jain, 2010). The K-mean algorithm was introduced by Macqueen in 1967. It separates data into K sets as it is a partitioning clustering approach (Morissette and Chartier, 2013).

In the following experiments, the GA algorithm is utilized to generate Pareto fronts for the ecological superblock and the preferred solutions area is selected by clustering the population into three clusters and choosing the average solution of each subpopulation. This is followed by analysis of the morphology of the three selected solutions - one preferred solution is selected. Each experiment has three runs, representing different climate zones by applying different climatic data for the experiments.
4.6. WATER
4.6.1. Causal Relationship of water collecting system

The system behaviour is derived by the dynamic hypothesis which seeks to define the critical feedback loops that drive the system behaviour. The key factors influencing water collecting are rainfall rate, average consumption per capita, water recycling and population. The system is described by (two or three) feedback loops. The population growth generates two feedback loops: a positive loop (reinforcing) and a negative loop (balancing). The first increases the volume of the water in the reservoir and the second decreases it. In addition, the population growth generates a positive feedback loop to the built area stock.

On the other hand, the built land area generates negative feedback loops to the population growth, and the increased built area limits the population growth. Fig. 4.70 shows the initial dynamic hypothesis of the water supply system in relation to population size, which is based on standard assumptions of how a water supply system typically works.
A SD simulation model was developed based on the causal feedback loop shown in Fig.4.70. The model was composed of three sub-models: a population growth sub-model, land use sub-model, and water supply sub-model (collecting and distributing). The population sub-model modelled the change in the population rate growth due to changes in the availability of land for building and the availability of water, which represent the carrying capacity of the system. The first element of the carrying capacity, the footprint area, is affected by the changes in the morphological parameters, which are the area per capita demand and the average height of the buildings. The second element, the water carrying capacity parameter, is determined by the precipitation rate, catchment area and the consumption per capita. Fig.4.73 shows the stock and flows diagram of the population sub-model.

The land use area which models the changes in the land area demand by the population, is determined by the size of the population and morphological parameters, the average floor area per capita and average building heights. Fig.4.74 shows the stock-flow diagram of the sub-model.
4.6.3. Model validation

To validate the system behaviour of the model, a set of tests were conducted. The tests examined the population growth concerning the land required for built areas. Three runs of the model were executed under three different built area conditions, 50k m², 100k m², and 150k m². Fig. 4.76 shows the comparison of the simulated behaviour of the population growth in relation to the built area land. The simulated behaviours indicate that the model is numerically sensitive to the change in the value of the parameters. The behaviour pattern shows that decrease of the built area limits the growth of the population. This prediction represents reality, and the model generates expected behaviour.

4.6.4. Simulation

The System Dynamics model was developed to address the self-sufficiency of a superblock level in terms of water supply. The model was simulated to test the behaviour of the system under three different climatic conditions. The change was in the value of the average annual precipitation, the model simulates the values of 200, 400, and 600 mm.

Run-01 - In this run the precipitation parameter was set to 200. The system model was tested by applying two initial conditions of the population size for 4000 and 6000 people. Fig. 4.77 shows the simulation results of the system with a population of 4000; it indicates that the maximum population growth that the water system allows is about 7000 people after nearly 35 years. It also shows that the maximum volume of water needed to support this population size is 740 k cubic metres. Fig. 4.78 shows the simulation results with an initial population of 6000; the graph indicates that the system collapses and cannot support the growing population. From this observation, it can be concluded that the system capability to support a specific size of population depends on the time duration of the evolution of the system, among other parameters.

Run-02 - In this run the precipitation parameter was set to 400. The system model was tested by applying two initial conditions of the population size for 4000 and 6000 people. Fig. 4.79 shows the simulation results of the system with a population of 4000; it indicates that the maximum population growth that the water system allows is about 18,000 people after nearly 30 years. It also shows that the maximum volume of water needed to support this population size is 2000 k cubic metres. Fig. 4.80 shows the simulation results with an initial population of 6000; the graph indicates that the system collapses and cannot support the growing population. The effect of the initial population on the stability of a system can be explained by the fact that the population increases the volume of water recycling, and, by doing that, can support additional growth.
Run-03 In this run, the precipitation parameter was set to 600 and the initial population parameter to 10,000 people. The system model was tested by applying two initial conditions of the rate of consumption 50 and 30 cubic metres/capita population. Fig.4.81 shows the simulation results of the system with a 50 cubic metres/capita; it indicates that the maximum population growth that particular water system allows is about 28,000 people after nearly 40 years. It also shows that the maximum volume of water needed to support this population size is 2000 cubic metres.

Fig.4.82 shows the simulation results with a consumption value of 30 cubic metres/capita; the graph indicates that the system supports the growing population, and it reaches the maximum size of 42000 after about 40 years. This run proves that the rate of consumption affects the stability of the system, and it can act as a regulating element in the system.

SD Water conclusion

The simulations have demonstrated that SD could be a useful tool for understanding the morphologic limitations of a superblock in relation to the volume of water catchment. Setting up water self-sufficiency as a design objective, the model can predict the limits of population growth and the impacts of the climate, consumption rates and morphological conditions on the superblock in the system. The model proved that specific population sizes could be supported by the water resources only if the system grows gradually over time and accumulates resources to sustain the population. In Run 01, it showed that when the system evolved, it survived and supported 7000 people, but it collapsed and failed to sustain 6000 people when it was applied as the initial condition. Moreover, the model has proved that not only changes in the parameters lead to changes in the system behaviour, but also the time duration of the system’s evolution is crucial to the performance of the system. At the end of this phase of the experiment, the outcomes that proved to be self-sufficient in different climatic conditions were exported as objectives to the evolutionary design model designated for water pond design in the superblock.
4.6.5. Water - Evolutionary Design Model

In this stage of the experiments, an evolutionary design model is developed to achieve two goals. The first is to evolve a solution – population – of landform that collects water in superblocks. The second is to achieve the volume capacity of the water resulting in the three simulated dynamic system model. The primitive form of the superblock is a square-shaped superblock with the dimensions of 1000 metres by 1000 metres. The superblock is located in the northern mid-latitude region; specifically Latitude 35, from whence the data were derived Fig.4.66.

The primary objective of the experiment was to achieve morphological variation for the superblock generating landform that can store sufficient water volume which is generated through the variation of morphological composition. To achieve this, the design problem was formulated to optimise meeting the values of the water volume required in the superblock, minimizing the surface of the water pond in order to minimize evaporation and maximizing the ‘shores’ of the ponds.

Having defined the objective, the next step is to set the gene pool that defines the superblock. The model operates with three genes: 1) The landform grain; 2) The proportion of the water surface from the overall area of the superblock; and 3) The depth of the water ponds. The only morphological characteristic of the superblock is the topographical form of the source created by the genes. The genes control the quantity of grain – grid points – and the distance between them. The second gene controls the surface area of the water. The last gene determines the water depth and, as a result, controls the highlands. The land cut and filled area balance, and changes in the depth of the grains affects the heights of the highlands. Each gene is defined by numeric domain which, along with the number of genes impacts the size of the numeric range on the size of the search space. Therefore, the domain of each gene is limited to the range that is required based on previous knowledge. The different domain range values are: 1) the number of the landform grain is between 4 and 30, 2) the surface water percentage is between 25 and 65; and 3) the water depth is 1 to 10 metres.

The parameters of the evolutionary solver were set to 50 solution and 100 generation in order to maximize variation and explore the fitness landscape in search for optimal peaks. Other parameters such as crossover, mutation rate and archive size are set to the solver default. The run time for each run lasted about ten hours. From all the solution, Pareto Front solutions were extracted and clustered into three groups. Following that, the average solution of each of the clusters was selected and analyzed. The experiment consists of three runs geared towards optimizing the superblock for three different conditions. The results of the simulations of the Rainfall System Dynamic for the values 200, 400 and 600 mm were exported as objective functions in the solver.
4.6.6. Analysis and Exploration of Design Solution

In this section, in-depth analysis studies were carried out for three runs of the water experiments, named RUN-01, RUN-02 and RUN-03, representing 200-, 400- and 500-mm average precipitation, respectively. Each run generates 5000 solutions; the solutions set along the Pareto optimal surface were selected and grouped into 3 clusters by applying the K-mean algorithm. Then, nine solutions were selected, including three that represent the average of each cluster. Based on the exploration of the selected solutions, three solutions that showed the potential of satisfying design options were chosen for further study. The first one is the selection of nine solutions from Pareto optimal surface solutions. In the second part, from the nine solutions, three were selected for further analysis. The final part of the investigation was cutting one satisfying solution and conducting a further morphological analysis.

Part 1 of the analysis is presented in the figures as follows: 1) Run-01, Fig.4.84, Fig.4.85 and Fig.4.86. 2) Run-02, Fig.4.91, Fig.4.92, and Fig.4.93. 3) Run-03, Fig.4.98, Fig.4.99 and Fig.4.100. The analysis of each solution shows the plan of the system, the numerical data of the system related to spatial aspects and a diamond chart of the fitness criteria. The plan indicates location and form of ponds whose characteristics are represented in numerical data, including depth, height, and volume, among others. The diamond charts provide the value of the fitness criteria (meeting the objective) diagrammatically and numerically. The Pareto graph shows the representation of Pareto optimal surface. The graph indicates the distribution of the solutions and the values of the ranking of each fitness criteria in each solution. The graphs of the standard deviation show the standard deviation graphs of each fitness criteria. The graphs indicate the amount of variation in the solutions in each generation regarding each fitness criteria.

Part 2 of the analysis is presented in the figures as follows: 1) Run-01, Fig.4.87 and Fig.4.88. 2) Run-02, Fig.4.94 and Fig.4.95. 3) Run-03, Fig.4.101 and Fig.4.102. The graphs show the analysis and exploration of the Pareto optimal surface by applying the K-mean clustering method that clustering the solution into three clusters represented by three colours red, blue, and green. The average solution of each cluster was selected for further morphological analysis, including elevation and slope studies as shown in the Fig.4.88, Fig.4.95 and Fig.4.102.

Part 3 of the analysis is presented in the figures as follows: 1) Run-01, Fig.4.89 and Fig.4.90. 2) Run-02, Fig.4.96 and Fig.4.97. 3) Run-03, Fig.4.103 and Fig.4.104. The images show the selected satisfying design solution. In the first set of images, the solution is presented in a plan, and a three-dimensional view showing the water ponds distribution and the water flows directions, including the numerical data of the spatial characteristics. The second set of images shows morphological analyses including water flow, aspect, slope and elevation Fig.4.90, Fig.4.98 and Fig.4.104.
FIRST RUN 200 mm RAINFALL

Part 1 - 9 solution

DATA Input 1: Carrying Capacity
DATA Input 2: Total Volume
DATA Input 3: Depth of Reservoir
DATA Input 4: Height of Dry Area
DATA Input 5: Length of Shoreline
DATA Input 6: Wet Surface Area

Fig. 4.83 Water System, run 01, Pareto front solutions.

Fig. 4.84 Water System, run 01, deviation graphs.

Fig. 4.85 Water System, run 02, 9 individual solutions.

Fig. 4.86 Water System, run 02, standard deviation graphs.
Part 2 - 3 solution

Gen: 66 | Ind: 19
FV.1: maximize water capacity
FV.2: maximize shoreline
FV.3: minimize surface
Data Input 1: Carrying Capacity_Total Volume
Data Input 2: Depth of Reservoir
Data Input 3: Height of Dry Area
Data Input 4: Length of Shoreline
Data Input 5: Wet Surface Area

Gen: 50 | Ind: 23
FV.1: maximize water capacity
FV.2: maximize shoreline
FV.3: minimize surface
Data Input 1: Carrying Capacity_Total Volume
Data Input 2: Depth of Reservoir
Data Input 3: Height of Dry Area
Data Input 4: Length of Shoreline
Data Input 5: Wet Surface Area

Gen: 44 | Ind: 47
FV.1: maximize water capacity
FV.2: maximize shoreline
FV.3: minimize surface
Data Input 1: Carrying Capacity_Total Volume
Data Input 2: Depth of Reservoir
Data Input 3: Height of Dry Area
Data Input 4: Length of Shoreline
Data Input 5: Wet Surface Area
Input of Water: 400mm

Explanation of Fitness Criteria:

FV.1: Maximize water capacity
FV.2: Maximize shoreline
FV.3: Minimize surface

Simulation results run 02

Data Inputs:
1. Carrying Capacity_Total Volume
2. Depth of Reservoir
3. Height of Dry Area
4. Length of Shoreline
5. Wet Surface Area

Water Harvesting Dynamic System-200
DATA Input 1: Carrying Capacity_Total Volume
DATA Input 2: Depth of Reservoir
DATA Input 3: Height of Dry Area
DATA Input 4: Length of Shoreline
DATA Input 5: Wet Surface Area

SECOND RUN_400 mm RAINFALL

Fig. 4.90     Water System, run 02, 9 individuals-solutions
Fig. 4.91   Water System, run 02, Pareto front solutions.
Fig. 4.92   Water System, run 02, Standard Deviation Graphs

Fig. 4.91. Water System, run 02, Pareto front solutions.
Fig. 4.92. Water System, run 02, Standard Deviation Graphs.

DATA Input 1: Carrying Capacity_Total Volume
DATA Input 2: Depth of Reservoir
DATA Input 3: Height of Dry Area
DATA Input 4: Length of Shoreline
DATA Input 5: Wet Surface Area
Opposite page: exploded view of ground simulations er run off, aspect, slope, elevation and the terrain.
Simulation results run 03

Input of Water : 600mm
DATA Input 1: Carrying Capacity, Total Volume
DATA Input 2: Depth of Reservoir
DATA Input 3: Height of Dry Area
DATA Input 4: Length of Shoreline
DATA Input 5: Wet Surface Area

FV.1: maximize water capacity
FV.2: maximize shoreline
FV.3: minimize surface

Explanation of fitness criteria

FV.1: maximize water capacity
FV.2: maximize shoreline
FV.3: minimize surface
THIRD RUN_600 mm RAINFALL

![Water system, run 03 9 individuals.](image1)

![Water system, run 03 Pareto Solutions.](image2)

![Water system, run 03 standard deviation graphs.](image3)

### DATA Inputs
1. Carrying Capacity_Total Volume
2. Depth of Reservoir
3. Height of Dry Area
4. Length of Shoreline
5. Wet Surface Area

165 166
Data Input 1: Carrying Capacity_Total Volume
Data Input 2: Depth of Reservoir
Data Input 3: Height of Dry Area
Data Input 4: Length of Shoreline
Data Input 5: Wet Surface Area

Fitness Criteria 1
Rank: 450 / 500
Fitness Value: 483774.418166

Fitness Criteria 2
Rank: 454 / 500
Fitness Value: 334357.35

Fitness Criteria 3
Rank: 30 / 500
Fitness Value: 0.000055

Fitness Criteria 1
Rank: 171 / 500
Fitness Value: 3444.514574

Fitness Criteria 2
Rank: 168 / 500
Fitness Value: 1824.08

Fitness Criteria 3
Rank: 356 / 500
Fitness Value: 0.000253

Fitness Criteria 1
Rank: 461 / 500
Fitness Value: 493297.580523

Fitness Criteria 2
Rank: 457 / 500
Fitness Value: 337050.15

Fitness Criteria 3
Rank: 5 / 500
Fitness Value: 0.000053

Fitness Criteria 1
Rank: 307 / 500
Fitness Value: 186928.441603

Fitness Criteria 2
Rank: 317 / 500
Fitness Value: 145625.2756

Fitness Criteria 3
Rank: 135 / 500
Fitness Value: 0.000063
The experiment explored a water collecting system from rainfall and its effect on population growth. The simulation aimed to define the condition of the maximum carrying capacity of the superblock in relation to water.

It tests three different conditions of rainfalls. The results are divided into two categories: numerical and morphological. The numerical were generated through the SD simulation of the system and the morphological through the evolutionary design model. The SD simulated the system according to the variables values, including the rainfall, water consumption per capita, initial population and population growth rate. The model generated different results for the carrying capacity for different variables values. The key results of the SD were the maximum water volume that could be collected and distributed over one square kilometre. This data became the main objective of the evolutionary design model. The outcomes of the evolutionary model can be categorized into groups: 1) scattered separate ponds and 2) clustered groups ponds. The first group are characterized by smaller ponds and larger quantities. On the other hand, the second group is a smaller number of ponds which are much larger in size. It can be observed that the smaller the ponds and the larger the number of people, the morphology satisfies the second objective of maximizing the shores. On the contrary, these small ponds fail to meet the objective of minimizing the surface. As for the morphological outcome of the first run of the experiment, the 200 mm rainfall, the maximum capacity value was 740,000 cubic metres. The preferred selected solution is the one that best satisfies the two objectives of the maximum volume and the maximum shore. And it falls into the first morphological category of scattered and small ponds. In the second run, that of 400 mm, the maximum capacity of the reservoir is 1400 km$^3$. The preferred selected solution for this run was the one with the same ranking values for all the objectives. The solution does not succeed in meeting the desired values of all the objectives. Morphologically, the solution exhibits the same features as the second morphological category: clustered and large ponds. The last run with the 600 mm rainfall, the selected solution represents the best for objective three, i.e. minimizing the water surfaces. On the other hand, the two other objectives are not satisfied - particularly the water volume. Regarding the morphology, the ponds are clustered and large which explains why the solution does not maximize the value of the shore. This case can be explained by the fact that the design restriction of the maximum pond depth and the maximum water surface areas inhibits the model from achieving the water capacity objective.

To conclude, the DS simulation informed the EM of the maximum carrying capacity. Its impact is generally more evident in the overall volume, area and depth. Regarding the detailed forms of the ponds, they were mainly determined by the EM and the morphological objectives. It is observed that achieving the system carrying capacity is related not only to climatic conditions but also to the morphological conditions and restrictions of the superblock.
4.7. SOLAR ENERGY
4.7.1. Dynamic Hypothesis and Causal Loop

The system behaviour is derived by employing the dynamic hypothesis which seeks to define the critical feedback loops that drive the system’s behaviour. The key factors influencing energy harvesting are irradiation rate (the power per unit area received from the sun), average consumption per capita, surface area available for solar panels and population. The system is described by five feedback loops. The population growth generates four feedback loops, three positive loops (reinforcing) and one negative loop (balancing). The positives increase the areas of the solar panels in both the domestic and farming solar panels and the area of the building footprint. On the other hand, a larger population generates negative loops to the land availability. Fig. 4.108 shows the initial dynamic hypothesis of the energy harvesting system in relation to irradiation rate.
4.7.2. Stock Flow Diagram

Based on the causal feedback loops, the energy harvesting system stock and flow diagram is shown in Fig. 4.110. The model was composed of four sub-models: a population growth sub-model, built area sub-model, domestic solar panels and a vertical farming sub-model. The population sub-model modelled the growth of the population, the growth equation uses average birth and death rate parameters – values from the statistics of the World Bank. (“Population growth (annual %) | Data.” n.d.) The growth is limited by the density which is generated by the built area sub-model. The built area is affected by the area per capita required and the average heights of the buildings.

In the domestic panel area, the sub-model modelled the increase in the area required to supply energy to the population, which is affected by the size of the population, irradiation rate value and the technical characteristics of the solar panel. The higher the irradiation rate the less the solar panel area needed. The fourth sub-model, the vertical farming solar panels, modelled the increase in the solar panel area required by the population and the calories joined by the vertical farming area required. The data of the consumption of calories and energy were subtracted from the farming area required and the energy required. The data of the consumption of calories and energy were subtracted from recent statistics and studies. Fig. 4.109 shows the model equation divided into 4 categories responding to the sub-models.

4.7.3. Validation

To validate the model, a structural validation test was conducted, followed by a behaviour validation test. The structural validation test compared the structure of the model against the structure of the real-world system to ensure that the model was structurally correct. By examining the simplified diagram of the model which describes the importance of the assumption, logic and features were employed to ensure whether all the important components were incorporated. Having done this test, a behaviour validation test was carried out. The test was used to evaluate parameters under extreme conditions. The model was run under two conditions to test the area of the domestic solar panels. The first condition used a constant value of the population over time and the second was population that grows over time. The results of the two simulations show that behaviour of a predicted pattern that can be verified. Fig. 4.112.

4.7.4. Simulation

The model is simulated and from the results of the energy required on various responses to different variables such as irradiation, areas requiring solar panels were generated. The relationship between the irradiation, density and the area of demand for panels is discussed.

Energy Run [1]: 2200 Kwh; population 38047; area per capita 25; Max Built Area 20%; Solar VF solar panels 107170.

Energy Run [2]: 1800 Kwh; population 38047; area per capita 25; Max Built Area 20%; Solar VF solar panels 22648; Domestic Solar panel 87799.

Energy Run [3]: 1400 Kwh; population 38047; area per capita 25; Solar VF solar panels 28614; Domestic Solar panel 107170.

Fig. 4.113 (A) shows the relationship between various parameters of the system and the total panels’ area. As can be observed that, the higher the value of the built footprint the higher the value of the total area of the solar panels. This can be explained by the fact that, the larger the population, the greater the demand for energy and consequently the larger the built footprint area needed for panels. The same trend can be observed in the vertical farming solar panels demand. The system shows that the population can continue growing throughout the simulation period and sufficient energy can be harvested to provide support to the system.

Domestic Solar panel 75472.

Due to the limited footprint area and limited energy harvesting, the population failed to grow beyond the size of 28047 after about 80 years.
4.7.5. SD Energy Conclusion

The model predicts the performance of the solar energy system harvesting for given irradiation rate values, solar panel specifications and quantities of urban parameters, such as the area needed per capita and building heights. The model output for every combination of the system parameters is analyzed in order to determine the effect of changes in variables on the system. The model is utilized to observe how the irradiation and density value affects the total energy harvesting, and it determines the quantitative morphological characteristics of the energy harvesting system.

The context of a self-sufficient superblock. To find the optimum system performance, changes can be assigned to the model parameters such as built area per capita, energy consumption per capita and building height. The model will be applied to decide the energy harvesting system parameters, given various constraints such as pane yield per square metre, climate and urban parameters. This gives the opportunity to foresee the system performance under various design strategies and system parameters, based on the configuration of the urban form. The limitation of this model that it is highly simplified and ignores many parameters that could affect the system performance.
The next step of the energy experiment is to explore the morphological relationship between solar energy harvesting, irradiation and urban skyline. The experiment utilizes a generic superblock with the size of 1000 by 1000 metres as the main component. The climatic and environmental data used in the experiment is driven by the average values from the data recorded at a latitude of 35 degrees (“World - Solar irradiation and PV power potential map | Data Catalog,” n.d.). The emphasis is placed on the overall block morphology as solar energy producer (harvesting), the whole superblock skyline performs as an energy device. To generate a skyline – landform – of an urban superblock that addresses this issue, the design model modifies the superblock surface in seeking the following objectives: 1) sufficient solar energy; 2) sufficient built area for a specific size of population; 3) Roof Area; and 4) increased block connectivity. The values of the first three objectives are exported from the simulated DS model in the first part of the experiment. In order to optimize the form of the skyline surface and building location towards to the solar energy harvesting objective, four fitness criteria were engaged in the operation of the GA. The four are: 1) Minimize distance between buildings; 2) meet the roof value area; 3) meet the built area value; and 4) maximize solar radiation on the surface Fig.4.114.

To achieve these objectives, a set of gene pools is employed in the algorithm to modify the superblock phenotype morphology by transforming: 1) the unit division of the superblock; 2) the built footprint proportion; and 3) building height. The genes control the size of the cells of the superblock surface and the proportion of the built area. The gene of the building height determines the skyline surface which is generated by connecting the highest point of each building with the primitive surface of the superblock. The more building generated, the more fluctuations in the surface. The numeric data of the genes were set to realistic values from previous knowledge, such as building height and built area proportion. Limiting the range of the domain determines the size of the search space and affects the time duration of the simulation. The genes were set as the following: 1) the grid between 20 and 60 units. 2) the built footprint 05-20%. 3) building height was set to 1- 50 floors.

The evolutionary solver parameters were set to 50 solutions and 100 generations (5000 solutions generated), the crossover, the mutation and the archive size parameters were set to the solver default settings. The run time for each simulated run lasted about 100 hours. From the evolutionary simulated outcome, a Pareto Front solutions were extracted and then clustered into three clusters. Of the preferred solutions, a nine solutions were selected from the three clusters for an initial evaluation of the solar energy harvesting. Then, the average solution of each cluster was chosen as the preferred one for further analysis and comparison. The experiment consists of three runs of the evolutionary solver for three different conditions of results from the SD simulations. They represent the generated outcome of the energy system for three input parameters of irradiation: , 100 kWh, 1800 kWh and 2400 kWh.
4.7.7. Analysis and Exploration of Design Solution

In this section, in-depth analysis studies were carried out for three runs of the energy system experiments, named Run-01, Run-02 and Run-03 representing 1000 Kwh, 1800 Kwh and 2400 Kwh average irradiation, respectively. Each run generates 5000 solutions; the solutions set along the Pareto optimal surface were selected and grouped into 3 clusters by applying the K-mean algorithm. Then, nine solutions were selected, including three that represent the average of each set. Based on the exploration of the chosen solutions, three solutions that showed the potential of satisfying design options were chosen for further study. The first one is the selection of nine solutions from Pareto optimal surface solutions. In the second part, from the nine solutions, three were selected for further analysis. The final part of the investigation was culling one satisfying solution and conducting further morphological research.

Part 1 of the analysis is presented in the figures as follows: 1) Run-01: Fig.4.115, Fig.4.116 and Fig.4.117; 2) Run-02: Fig.4.123, Fig.4.124 and Fig.4.125; 3) Run-03: Fig.4.131, Fig.4.132 and Fig.4.133. The analysis of each solution shows the plan of the system, the numerical data of the system related to spatial aspects and a diamond chart of the fitness criteria. The plan shows the generated skyline surface, including the values of the potentiality of energy harvesting in each point on the surfaces that visualised by colour-coded classification. The four fitness criteria, which are: level number, roof areas, built area and the percentage of the area receiving radiation, were extracted and their values are presented numerically and graphically by the diamond chart. The Pareto graph shows the representation Pareto optimal surface. The graph indicates the distribution of solutions along the Pareto surface. Location of each solution in the surface indicates its ranking value regarding fitness criteria. The graphs of the standard deviation show the standard deviation graphs of each fitness criteria. The graphs indicate the amount of variation in the solutions in each generation regarding each fitness criteria.

Part 2 of the analysis is presented in the figures as follows: 1) Run-01: Fig.4.118, Fig.4.119 and Fig.4.120; 2) Run-02: Fig.4.126, Fig.4.127, and Fig.4.128; 3) Run-03: Fig.4.134, Fig.4.135 and Fig.4.136. The graphs show the analysis and exploration of the Pareto optimal surface by applying the K-mean clustering method, which involves clustering the solution into three clusters represented by three colours red, blue, and green. The average solution of each cluster was selected for further morphological analysis, including Building distribution and the distance between them as shown in the Fig.4.121, Fig.4.129 and Fig.4.137.

Part 3 of the analysis is presented in the figures as follows: 1) Run-01: Fig.4.121 and Fig.4.122 a; 2) Run-02: Fig.4.122 b and Fig.4.130; 3) Run-03: Fig.4.137 and Fig.4.138. The images show the selected satisfying design solution. In the first set of images, the solution is presented in a plan, as a three-dimensional view showing the skyline surface and colour-coded value of its points indicating the potential of energy harvesting. The plan attached is numerical data of the spatial characteristics of the superblock. The second set of images shows morphological analyses including, distances between building, skyline patterns, open areas, solar analysis and area for built areas as shown in Fig.4.122, Fig.4.130 and Fig.4.138.
Fig. 4.115  Solar energy system, run 01, Pareto front.

Fig. 4.116  Solar energy system, run 01, standard deviation graphs.

DATA Input 1: Maximum number of levels
DATA Input 2: Roof area
DATA Input 3: Built area
DATA Input 4: Percentage of area receiving solar radiation
Fig. 4.120. Solar energy, run 02, selected solution.

Fig. 4.121. Solar energy, run 03, solution analysis.

distance of built

skyline

open agriculture

solar analysis

original terrain-built
Simulation results run 02

DATA Input 1: Maximum number of levels
DATA Input 2: Roof area
DATA Input 3: Built area
DATA Input 4: percentage of area receiving solar radiation

Solar Energy System 1800 Kwh

4.7.7.-2
4.7.8. SECOND RUN 1800K

Fig. 4.122 Solar energy system, run 02, 9 individuals/solutions.

Fig. 4.123 Solar energy system, run 02 Pareto front.

Fig. 4.124 Solar energy system, run 02, standard deviation graphs.

DATA Input 1: Maximum number of levels
DATA Input 2: Roof area
DATA Input 3: Built area
DATA Input 4: Percentage of area receiving solar radiation
Fig. 4.125  Solar energy, run 02, K-MEANS CLUSTERING.

Fig. 4.126  Solar energy, run 02, Means Value Deviation Graphs

Fig. 4.127  Solar energy, run 02, 3 selected individuals-solutions
Fig. 4.128 Solar energy, run 02, selected solution.

Fig. 4.129 Solar energy, run 02, solution analysis.
Simulation results run 03

DATA Input 1: Maximum number of levels
DATA Input 2: Roof area
DATA Input 3: Built area
DATA Input 4: Percentage of area receiving solar radiation

Solar Energy System 2400 Kwh
THIRD RUN 2400K

Fig. 4.130  Solar energy system, run 03, Pareto front.

Fig. 4.131  Solar energy system, run 03, standard deviation graphs.

Fig. 4.132  Solar energy system run 03, 9 individuals/solutions.

DATA Input 1: Maximum number of levels
DATA Input 2: Roof area
DATA Input 3: Built area
DATA Input 4: Percentage of area receiving solar radiation
The experiment explored a solar energy harvesting system in a superblock for different irradiation values: 1400 kWh, 1800 kWh and 2200 KWh. The system performance is affected by many variables including irradiation, building density, roof area available, efficiency of the solar panels and the rate of consumption. The SD simulation result shows the roof areas required to produce enough energy in order to meet the population demand. It can be seen from the result that the higher the radiation, the less roof required. In addition, the model simulated the population growth and the built area needed. The results show that, due to the limit of maximum area of roof, the harvested energy is limited as well. The combination of maximum roof area and irradiation value affected the population growth. In the runs of the 1400kWh and 1800 kWh, the population growth was limited because the energy production was not sufficient.

The morphological outcomes demonstrate that the building skyline rises gradually from the south to the north. It can be explained by the fact that the model maximizes the exposure to the south in order to harvest more energy. Therefore, the skyline silhouette is a result of the optimized solution of the solar energy harvesting. The results show variation in the maximum number of levels (building floors) that affects the number of the buildings of the superblocks. In the two selected solutions of the 2200 KWh run and 1800 kWh run, the heights of the building are 5 and 8 metres respectively. The pattern of the distribution is similar, which is chunks of clusters, allowing 70 to 85% of the surface to receive solar radiation. These two solutions succeed in achieving the objectives of roof area and built area required.

On the other hand, the selected solution of the 1200 kWh meets the rooms area objective, but the built area failed greatly. The built area was six times more than that required due to the fact that the maximum building height reaches 29 floors. This explains why the built area is too large, because achieving the targeted footprint of the roof of this height requires more built areas. Moreover, the relatively low value of the solar radiation resulted from the distribution pattern of the buildings. It can be seen in the solar radiation plan that there is a blue gradient color, which represents low radiation.

In conclusion, the integrated DS and EDM generate a skyline corresponding to the solar energy harvesting. The morphology of the building is determined by the generated skyline. SD simulated results inform the design model by the objective quantities required and the EDM generate solutions that satisfy the objectives. Due to the lack of morphological restrictions, the EDM allows for the generation of excessive built areas. Therefore, integrating SD output data in the EDM requires an elaborated definition of the morphological restrictions and conditions in order to meet the design objectives.
4.8.1. Introduction

This section presents the application of system dynamic modelling of the agriculture system in a superblock. It was constructed to simulate the production system and the cultivation area of six types of Mediterranean crops. To achieve this goal, the model is organised as follows:

1) dynamic hypothesis and causal loop diagram, 2) stock-flow diagram, 3) model validation, 4) simulation and analysis, and 5) conclusion. The experiment explores the system by using crops from Mediterranean agriculture which depends heavily on precipitation and climatic conditions. The three main aspects of Mediterranean agriculture are: (1) orchard farming, (2) viticulture, and (3) cereals and vegetable cultivation. It is distinguished by irregular topology and nearness to water bodies, among other factors. For that reason, six types of crops were chosen and analysed in relation to their yield, water required and sun need (see Fig.4.139). These become the parameters of land allocation for each crop in the superblock.

The model simulates the area required by each crop according to the share of the crop. The yield of each crop was calculated as a percentage of the sum of the total yield of all the crops. The model simulates the required crop production to support the population. The variable of the consumption per capita, driven by World Bank data, was set to 136 kg/capita (Alexandratos and Bruinsma, 2012).
4.8.2. Dynamic Hypothesis and Causal Loop Diagram

The key factors of the system that influence the agricultural production system are: 1) the yield per hectare in open field and in vertical farms, and 2) the size of the land area. The system can be described by three loops. The loops are affected by the population stock, when the population increases, buildings footprints, public space and vertical farm increase. These increases negatively affect open field farming and decrease its area. The yield per hectare in open field farming is a deciding factor in population increase and the area of vertical farming: the more production per hectare, the less area needed for urban farming. The population stops growing in one of two conditions: the first when there is insufficient production area to meet the demand of the overall population and second when there is no available land on which to build. Fig. 4.142 shows the Causal loop diagram - initial dynamic hypothesis - of the crop production system, which is based on standard assumptions of how the agricultural production system typically works, which is calculated in terms of crop yield, consumption per capita, and available land for agriculture.

Stock and Flow

The model consists of three sub-models: the population sub-model, the agriculture demand sub-model and agriculture sub-model. Fig. 4.143. The population sub-model represents the population size in the superblock, wherein the population growth is affected by the urban density parameters and the growth and death rates. Its density affects the built area footprint, and it is calculated by multiplying the area per capita required by population size and then divided by the average building heights. The maximum footprint area is determined by the urban variable of the maximum percentage for the urban system (in these experiments the value of 20% was applied to allow enough area for agriculture and water ponds). The agriculture demand calculated the total crops required to meet the demand of the population. According to the literature review, the crop consumption per capita is 136 kg/capita, this value was applied to the consumption/capita variable. It is obvious that the growth is linear, the larger the population, the larger the crop (WHO | 3. Global and regional food consumption patterns and trends, n.d.).

In the agriculture sub-model model, the initial field farming value represents the maximum potential of the land that can be used for agriculture. It was assumed that the initial area needed for agriculture was 75% of the superblock area. It was calculated as the difference between the block area, the water surface area and initial residential area. The Field Farming area changes over time by outflows of land uses for residential, public and vertical farming due to the growth of the population.

The area of vertical farming starts to increase and accumulates after the agricultural demand exceeds the maximum production of the field farming land. The system calculates the overall agricultural production to meet the demand over time. The total production is the sum of the field production and vertical farming production. The overall area of the agricultural land is divided into six different areas: one area for each crop. The distribution is calculated relatively: the percentage of the annual yield per hectare to the sum of the annual yield per hectare for all the crops. The land needed for
Fig. 4.143  System Dynamic Modelling Stock and Flow diagrams of Agriculture
4.8.3. Validation

To validate the model, a structural validation test was conducted followed by a behaviour validation test. The test compared the structure of the model against the structure of the real-world system to ensure that the model was structurally correct. By examining the simplified diagram of the model describing the important assumption, logic, and feature were used to ensure whether all the important components were incorporated. Having conducted this, a behaviour validation test was carried out, which was used to evaluate parameters under extreme conditions. The first part of the test was to examine the relationship between population growth and agricultural demand. Fig. 4.145 shows the behaviour pattern demonstrating an increase in demand when the population grows. The second part verifies the behaviour pattern of the relation between the built area and the agricultural land. The predicted pattern is that the increase in built area must cause a decrease in the quantity of agricultural land. This assumption was proved in the simulated results. Fig. 4.146.

4.8.4. System Simulation

The System Dynamics model was developed to address the implications of the agricultural production of different crops on the land use area and vertical farming areas in relation to population growth and climatic conditions. The model was simulated to predict the change in land use area and population growth for a period of 100 years. Three sets of the simulated results were extracted, representing the values of parameters in the 10th, 50th and the 100th year. Fig. 4.148 shows the simulated results every 10 years over 100 years and the following graphs represent the behaviour pattern for the three selected time periods.

The graph shows that the population grows over the 10 years and reaches the figure of about 11,000 people. The table and graph indicate that the agricultural area is sufficient to meet the demands of the population and there is no need to carry out vertical farming. It can also be seen that there is a slight decrease in the lands of all the crops, which can be explained by the need for more building land to meet the demand as a result of the population growth.

The graph shows that the population continues to grow at the same rate, reaching 21,052 people by the 50th year. It also continues to display the same behaviour pattern over the whole period (50 years), i.e., a growth in the population and decrease in the agricultural land. It is obvious from the graph that the open field agriculture production is not sufficient in meeting the demand and the system generates a vertical farm to bridge the shortage between the demand and the production. It can be observed that each crop decreases at the same rate, which can be explained due to the fact that the model decreases the land for building use from all the crop lands in relation to their sizes.

The simulated results show that the population ceased to grow in the year “90”. It can be explained by the shortage of land for building. In that year – 90- the entirety of the land allocated to building, which is 25% of the overall area, was used. The graph shows that the population levelled off at 41,141 people.

4.8.5. Agriculture System dynamics: Conclusion

In this experiment, a system dynamics model has been modelled to simulate: 1) the change of land use from agriculture to built land, 2) the total crop demand, and 3) the total crop production according to crop type. Simulated results show that the growing population caused a decline in the agricultural land available. Due to the fact that the density of building and the built area land is limited, the decrease in the agricultural land also became limited. The second observation was that field farming agriculture succeeded in meeting the demand of a population size up to 20,000. Above this figure, the results show the need for vertical farming to balance the insufficiency of the field farming production. Therefore, any change in consumption per capita which leads to change in the crop demands, affects the system behaviour. The data can be exported to the morphological model related to the land areas for each type of crop and the total production. Three sets of outputs were exported which represented the evolved system in the 10th, 50th and 100th year respectively.
Following the SD simulation, an evolutionary design model was developed to address the distribution of agricultural land over the superblock surface. The GA seeks to generate a landform that satisfies the agricultural production system objectives. An exploration is carried out by examining the relationship between agricultural crops, landform morphological characteristics, including slope, orientation, and size. Similar to the previous experiments, this experiment utilizes a generic superblock with the size of 1000 by 1000 metres as the main component. The climatic and environmental data used in the experiment is driven by the average values from the data recorded at latitude 35 degrees (“Average precipitation in depth (mm per year) | Data,” n.d.) (“World - Solar irradiation and PV power potential map | Data Catalog,” n.d.). The agriculture and crop data were driven by the recorded data of Mediterranean agriculture.

The objective is to generate a set of optimized solutions for the landform surface appropriate for an agriculture system. To achieve that, the following objectives were set: 1) sufficient orchard farming; 2) sufficient viniculture; 3) sufficient cereal; 4) sufficient vertical farming; and 5) maximizing water shore length. All of the first five values required to be satisfied for these objectives were imported from the outcome resulting from the DS simulations in the initial phase of the experiment. To accomplish this, four fitness criteria were introduced: 1) Maximize areas southern slopes for orchard agriculture; 2) Maximize flat area for cereal agriculture; 3) Minimize solar radiation on water surfaces and built areas; and 4) Meet the built area value from the DS. The transformation of the landform morphology is controlled by five genes: 1) Grid (cell size) ranging between 20 and 60 units; 2) built footprint proportion (05-20%); 3) water surface proportion (10-30%); 4) foothill proportion of the grid (5-20%); and 5) foothill average height (5 – 20 metres). The topography of the surface is determined by the number of cells selected and the foothill heights Fig.4.149.

The solver allows for the emergence of a variety of surface slopes that seeks to find viable solutions in obtaining suitable land for agriculture. The GA calculates the inclination of the slope and, accordingly, the type of agriculture assigned to the slope. Steeper slopes are more appropriate for orchard farming and gradual ones more appropriate for cereal and vegetation. Regarding the solver, the experiment is comprised of a generation size of 50 and a generation count of 50. This was determined by the simulation runtime though test runs of the experiment in order to balance between solution evaluation and total simulation time. From the evolutionary simulated outcome, Pareto Front solutions were extracted and then clustered into three clusters. For the preferred solutions, nine solutions were selected from the three clusters for an initial evaluation of solar energy harvesting. Then, the average solution of each cluster was chosen as the preferred one for further analysis and comparison. The experiment consists of three runs of the evolutionary solver for three different conditions of results from the SD simulations. They represent the generated outcome of the agricultural system for three input parameters of populations of 15000, 30000 and 45000.

Fig.4.148  Pseudocode, Water, evolutionary model/ process diagram
4.8.7. **Agriculture System Dynamic**

In this section, in-depth analysis studies were carried out for three runs of the agriculture system experiments, named RUN-01, RUN-02 and RUN-03 representing 1000 kWh, 1800 kWh and 2400 kWh average irradiation, respectively. Each run generates 2500 solutions; the solutions set along the Pareto optimal surface were selected and grouped into 3 clusters by applying the K-mean algorithm. Then, nine solutions were selected, including three that represent the average of each set. Based on the exploration of the chosen solutions, three solutions that showed the potential of satisfying design options were chosen for further study. The first one is the selection of nine solutions from Pareto optimal surface solutions. In the second part, from the nine solutions, three were selected for further analysis. The final part of the investigation was culling one satisfying solution and conducting further morphological research.

**Part 1 of the analysis is presented in the figures as follows:**
1) Run-01: Fig.4.150, Fig.4.151, and Fig.4.152;
2) Run-02: Fig.4.158, Fig.4.159, and Fig.4.160;
3) Run-03: Fig.4.164, Fig.4.167, and Fig.4.168.
The analysis of each solution shows the plan of the system, the numerical data of the system related to spatial aspects and a diamond chart of the fitness criteria. The plans show the generated terraced surfaces, indicating different types of crop production. It includes topographical lines showing the levels of the agricultural terraces.

The six fitness criteria were extracted, which include five agricultural crops types named tomatoes, wheat, olive orchard and vineyards and the sixth is the total area facing south. The fitness values are presented numerically and graphically by the diamond chart. The Pareto graph shows the representation of Pareto optimal surface. The graph indicates the distribution of solutions along the Pareto surface. The Location of each solution in the surface indicates its ranking value regarding fitness criteria. The graphs of the standard deviation show the standard deviation graphs of each fitness criteria. The graphs indicate the amount of variation in the solutions in each generation regarding each fitness criteria.

**Part 2 of the analysis is presented in the figures as follows:**
1) Run-01: Fig.4.153, Fig.4.154, and Fig.4.155;
2) Run-02: Fig.4.161, Fig.4.162, and Fig.4.163;
3) Run-03: Fig.4.169, Fig.4.170, and Fig.4.171.
The graphs show the analysis and exploration of the Pareto optimal surface by applying the K-mean clustering method, in which the solution is divided into three clusters represented by three colours red, blue, and green. The average solution of each cluster was selected for further morphological analysis, including terraces distribution and the water flow directions as shown in Fig.4.152, Fig.4.160, and Fig.4.168.

**Part 3 of the analysis is presented in the figures as follows:**
1) Run-01: Fig.4.156 and Fig.4.157;
2) Run-02: Fig.4.164 and Fig.4.165;
3) Run-03: Fig.4.172 and Fig.4.173. The images show the selected satisfying design solution. In the first set of images, the solution is presented in a plan, and a three-dimensional view showing the agricultural terraces surface, which are colour-coded indicating the type of crop. Numerical data is attached to the plan stating crop quantities and indicating the areas facing south. The second set of images show morphological analyses indicating the location distribution and surface area of the different crops, as shown in Fig.4.157, Fig.4.165 and Fig.4.173.
DATA Input 1: Total area of tomatoes
DATA Input 2: total area of wheat
DATA Input 3: total area of olive orchard
DATA Input 4: total area of barley
DATA Input 5: total area of vineyards
DATA Input 6: Total Area Facing south
Fig. 4.152 Agriculture system, run 01, K MEANS CLUSTERING.

Fig. 4.153 Agriculture system, run 01, Means Value Deviation Graphs.

Fig. 4.154 Agriculture system, run 01, 3 selected individuals-solutions.
crops type1
crops type2
crops type3
crops type4
crops type5
water

vineyard
olive trees
wheat
tomatoes
superblock

Fig.4.155 Agriculture system, run 01, selected solution.
Fig.4.156 Agriculture system, run 01, solution analysis.
4.8.7.-2  Agriculture system 20,000 Int. population

Simulation results run 02

DATA Input 1: Total area of tomatoes
DATA Input 2: Total area of wheat
DATA Input 3: Total area of olive orchard
DATA Input 4: Total area of barley
DATA Input 5: Total area of vineyards
DATA Input 6: Total area facing south
DATA Input 1: Total area of tomatoes
DATA Input 2: Total area of wheat
DATA Input 3: Total area of olive orchard
DATA Input 4: Total area of barley
DATA Input 5: Total area of vineyards
DATA Input 6: Total area facing south
Figs. 4.163-4.164  Agriculture system, run 02, selected solution.

- Vineyard
- Barley
- Wheat
- Olive trees
- Tomatoes
- Superblock

Crops type 1
Crops type 2
Crops type 3
Crops type 4
Crops type 5

Fig. 4.163  Agriculture system, run 02, selected solution.
Simulation results run 03

- DATA Input 1: Total area of tomatoes
- DATA Input 2: Total area of wheat
- DATA Input 3: Total area of olive orchard
- DATA Input 4: Total area of barley
- DATA Input 5: Total area of vineyards
- DATA Input 6: Total area facing south
THIRD RUN _40000

DATA Input 1: Total area of tomatoes
DATA Input 2: Total area of wheat
DATA Input 3: Total area of olive orchard
DATA Input 4: Total area of barley
DATA Input 5: Total area of vineyards
DATA Input 6: Total Area Facing south
crops type1
crops type2
crops type3
crops type4
crops type5

water

vineyard

barley

wheat

olive trees
tomatoes

superblock

Fig. 4.171 Agriculture system, run 03, selected solution.

Fig. 4.172 Agriculture system, run 03, solution analysis
The experiment explored the agricultural production system in a superblock for three different population sizes: 10000, 20000, and 40000. The system performance is affected by the many variables including population size, built area per capita, rate of agriculture consumption and initial agricultural land available. The model calculates the total consumption of the population and total agricultural production, and, if they are not balanced and the production fail to satisfy the consumption, the model calculates the area needed for vertical farms to supply the shortage.

The SD simulation result shows the areas of the different types of crops areas required for production in order to meet the population demand. It can be seen from the result that the larger the population, the lower areas for field agriculture. This can be explained by the fact that the built area needed for the increase in population is deducted from the initial agricultural area. The model simulated the built area which needed to be transformed from the initial agriculture area. The results show that only when the population exceeded the 40,000 people was there a shortage in production and a need for vertical farms.

The morphological outcomes resulted from the condition to allocate the agriculture just on the area facing south radiation. The second condition was to distribute the crops along 6 levels, according to crop types and their demand for water. The morphological outcomes can be categorized in two groups: the fragmented patches and the clustered patches. The results show that the clustered patches converged towards the objectives of generating the required areas when the population was small. For example, in the first run for the 10,000 population, the solution generating the required areas when the population was small.

The third run, which simulated the agricultural demand of 40,000 people, served to prove that fragmented patches can generate enough agricultural area to satisfy the demand. This can explained by the fact that fragmented patches create more land exposed to the south and hence more area for agriculture. In conclusion, the integrated DS and EDM generate a agricultural patches for different types of crops which are allocated according to solar radiation and water demand (i.e., the higher the patch, the less water required).

The morphological of the agricultural patches is determined by the orientation of landform crop type. The model evolves to optimise a landform for the design objectives. SD simulated results were exported to the design model as the objective of EDM.
5. INTEGRATED SYSTEM
This chapter discusses the integration of the three subsystems developed in the previous chapter: water, energy and agriculture. The conducted experiment produces a self-contained urban system integrating the three sub-systems and their interaction with each other. It also discusses the outcomes and its relationship to urban morphology subject to climatic and environmental conditions in relation to its productivity. Similarly, to the subsystem experiments in Chapter 4, the process consists of two stages: First, it starts with SD modelling and simulation of the three integrated systems. The sub-models are connected and dependent on each other, their collective interaction determines the overall behaviour of the system. In this case, as well, the population growth model is central to the system’s behaviour. The population growth is determined by the availability of resources which can be seen as the carrying capacity of the superblock. Accordingly that, if any system fails to satisfy the demand of the population, the population growth stabilizes. The model also inhibits population growth when the superblock reaches its maximum density which is a variable defined as Design Objective. The resulting simulations’ outcomes provide data related to the behaviour of the whole system and its sub-systems.

In the second part of the experiments, the outcome data from the SD informs the evolutionary model. The data is determined by the three subsystems and had been used as the objectives of the evolutionary solver. When coupling the SD model with the Evolutionary Model there are a series of aspects to be taken into consideration:

SYSTEM FLEXIBILITY: When adding more subsystems to the systems, the flexibility within each subsystem decreases. In this case, the introduction of the subsystem named agriculture reduces the outcome of subsystem energy. Therefore, when modelling the integrated system there needs to be a compromise between the subsystems. In the model developed for this research, all the areas in the landscape facing south are assigned to the subsystem agriculture; thus, the energy production is reduced to the skyline in the areas that are facing north. That means that in this case, a priority is given to agriculture production. Therefore, one important aspect in the integrated model is to calibrate the flexibility that each subsystem has within the overall system.

COUPLING SD WITH THE EVOLUTIONARY ALGORITHM: In the case of the three sub-systems independently, roughly half of the objectives are related to the morphology of the urban block, while the other half are related to the output data coming from the SD model. However, when coupling the three subsystems, the parameters coming from SD are more prominent in the setting of the objectives in the evolutionary algorithm.

A set of morphologies were generated in each run of the experiment that composed a datascape operating as a provider of ecological services of water, energy and agriculture production. Following the same selection process used in chapter 4, a Pareto from solutions was selected and clustered by the K-mean algorithm. The average solution of each cluster is selected for further morphological analysis. The solution with the three integrated subsystems is a multi-dimensional datascape that constitutes the urban tissue of the superblock. This multi-dimensional datascape is used as the spatial organizer and distributor of the urban systems. It acts in two ways: first it sets the spatial boundaries of the morphology of the inhabited spaces and second it provides a multi-dimensional datascape which informs the material development of the superblock.

The experiment concludes by showing the potential for further design development, departing from the multi-dimensional datascape coming from the model. The resulting multi-dimensional datascape constrains the space for further development as well as providing index data for the implementation of design algorithms. In this case the algorithms will be constrained by the spatial limitations coming from the model. In the model, the point cloud constitutes a metadata, meaning that which structures and spatially organizes other data, which, in this case is either numerical data or vectors related to water, energy and agriculture; yet this could be expanded further by integrating other systems. In this experiment, the multi-dimensional datascape is used to study the connectivity between high density areas, which, in this case, determines two distinctive qualities in the public realm. What is distinctive about this design methodology, is that in each design iteration it refines the qualities, materials and requirements needed in each point in space in the form of expected qualities or likelihoods, rather than in a deterministic approach which leaves the design open for further development.
5.2. Computational Design Model SDEDM

The unified computational design model is represented in the following diagram. On the right is the SD model and on the left is the evolutionary design model. The SD model is described as a stock-flow diagram of the system. In addition to the population growth system, it consists of three sub-systems: agriculture, water, and energy system. Each system is framed as "sector" which includes the system components. The interactions within the sectors are defined by connector symbols.

On the other hand, the evolutionary design model is represented as a model pseudo-code composed of two parts: the genetic algorithm and evolutionary solver. The evolutionary solver shows the diagram of genes affecting the three systems. The operations of the genes are displayed for each system as an array of geometric actions grouped into columns. On the right of the pseudo-code, is the evolutionary solver showing the phenotype output, and the fitness criteria of geometric and numeric inputs and outputs.
Fig. S.174  STELLA model integrated systems
5.3. Introduction

The following chapter builds on the models developed in the previous experiments, which simulated the three different systems and generated the urban morphology in relation to their behaviours. In this chapter, the experiment objective is to create a unified model of the integration of the three models and explore their morphological implications. Similar to the previous experiments, the design context will not be situated within a particular site, but the modelled systems will be related to the climatic region through rainfall, radiation and crop production measures. The experiment will focus on three scenarios representing the maximum population growth in each climatic region. The first has a maximum population of 10,000 in a climate condition of 1000 kWh irradiation and 200mm rainfall, and an initial population of 4000. The second scenario has a maximum population of 28,000 in a climate condition of 2200 kWh irradiation and 400mm rainfall, and an initial population of 10,000. The last scenario bears a maximum population of 40,000 in a climate condition of 1800 kWh irradiation and 600mm rainfall, and an initial population of 10,000. The focus of the experiment is to evolve an integrated system through the Systems Dynamic method and gendered morphology responding to its behaviour.

5.3.1. Dynamic System Model

This section presents the application of System Dynamic modelling of integrated systems in a superblock. It was conducted to simulate the behaviour of the systems and to calculate their production in terms of water collecting, solar energy harvesting and agriculture production. So as to achieve this goal, the model was organized as follows: 1) dynamic hypothesis and causal loop diagram, 2) stock-flow diagram, 3) model validation, 4) simulation and analysis, and 5) conclusion. The experiments made use of the models developed in chapter 4 for each system as a connected sub-model in one integrated model. Similar to the individual sub-models which simulate each system separately, the integrated model simulated all the outcomes of the three systems simultaneously in relation to the same variable and the same population in each run. It calculated the water volume, the surface needed for solar energy harvesting, crops according to their types, and vertical farming to compensate shortages in the field farming if in evidence. The same climatic and environmental data from the previous System Dynamic models were used in this experiment, including type of crops, solar irradiation, rainfalls, data related to consumption, and areas required per capita in urban contexts/ the urban context.

5.3.2. Dynamic Hypothesis and Causal Loop Diagram

The dynamic hypothesis, which drives the system’s behaviours, is represented by the causal loop diagram. The water, solar energy and agriculture are hypothesized to generate production according to a causal loop diagram. The generated system productions affected the population growth, and these dynamics resulted in the climatic and environmental consequences of the feedback structure. The causal loop diagram is shown in Fig.5.177. There are five principle feedback loops in the system, of which three are positive i.e. re-enforcing, and two are negative, i.e. goal-seeking. The positive ones increase the consumption of water and energy and the three negative ones limit the population growth and decrease the agricultural land areas.

5.3.3. Stock and Flow

The model consists of four main sub-models, each comprising a number of sub-models: the population sub-model, the agriculture sub-model, the water sub-model and the solar energy sub-model. All of these main sub-models represent the sub-systems of the superblock system. The population sub-model represents the population size in the superblock: the population growth is affected by a number of factors, namely urban density, water availability, and solar energy harvesting. In addition, there is the assumed variable of the death and growth rates.

The agriculture sub-model calculates the total crop yield in the superblock and the area required for each crop. The crop and field agricultural areas decline as a result of the population growth. The decreased quantities of crops are compensated for vertical farming production.

The solar energy harvesting system calculates the amount of energy consumption in relation to the population and the surface area required to produce energy to meet the demand. The production size is a result of the climatic factor of the irradiation and the surface of the solar panels available. The availability of area on the “solar” surface is determined by the population size and assumed density value within the superblock.
The water sub-model calculates the volume of water that the system can collect in the superblock. It is affected by the average rainfall rate of the region, the assumed water catchment area and the percentage of the water recycled. It also calculates the population’s total water consumption which is a result of the average consumption, rate and the population size.

The following three runs simulate the system over 100 years. The data was subtracted and analyzed for exportation to the morphological model as data for the design objectives.

5.3.4. Validation

To validate the model, a structural validation test was conducted, followed by a behaviour validation test. The test compared the structure of the model against the structure of the real-world system to ensure that the model was structurally correct. By examining the simplified diagram of the model describing the important assumptions, logic and feature were used to ensure whether or not all the important components were incorporated. Having conducted this, a behaviour validation test was carried out, which was used to evaluate parameters under extreme conditions. The first part of the test examined the relation between population growth and total solar consumption. Fig. 5.178 shows the behaviour pattern, demonstrating an increase in demand as the population grows. The second part verifies the behaviour pattern of the relation between the built area and the available area for agriculture. The predicted pattern is that the increase in built area must cause a decrease in the available area for agriculture. This assumption was proved in the simulated results.

5.3.5. System Simulations

The System Dynamics model was developed to address the implication of the three systems on the land use areas and production volumes in relation to environmental factors and population. The model was simulated to predict the changes in land use area with a population growth over a period of 100 years. Three runs were performed under three conditions: 1) 1000 kWh irradiation, and 200mm rainfall and an initial population of 4000. 2) 2200 kWh irradiation, and 400mm rainfall and an initial population of 10,000. 3) 1800 kWh irradiation, and 600mm rainfall and an initial population of 10,000.

Run 01: Fig. 5.180 shows the simulated systems which present the water volume in the reservoir, solar panel areas, the built area and the population growth. The graph demonstrates that the system allows the population to increase over the whole simulation period, which is 100 years. The population grew from 4000 to about 17000 in one hundred years. It also shows that the resources were sufficient when it came to supporting the population. Although the rainfall conditions were not favourable, nevertheless the system remained stable. This can be explained by the fact that the initial population was small and the resources were deemed to be sufficient in supporting it. Fig. 5.180 shows the change in the volume of the crops over time, and it can be observed that the crops were enough in supporting the population and that there was no need for vertical farming. The data that was extracted from the morphological model represents the values of the 70th year.

Run 02: Fig. 5.181 shows the simulated systems which present the water volume in the reservoir, solar panel areas, built area and the population growth. The graph demonstrates that the system allows the population to grow over the whole simulation period, which is 100 years. The population grew from 4000 to about 17000 in one hundred years. It also shows that the resources were sufficient when it came to supporting the population. Although the rainfall conditions were not favourable, nevertheless the system remained stable. This can be explained by the fact that the initial population was small and the resources were deemed to be sufficient in supporting it. Fig. 5.181 shows the change in the volume of the crops over time, and it can be observed that the crops were enough in supporting the population and that there was no need for vertical farming. The data that was extracted from the morphological model represents the values of the 70th year.

Run 03: Fig. 5.182 shows the simulated systems which present the water volume in the reservoir, solar panel areas, built areas and population growth. The graph shows the system allowed the population to grow until about 95 years and then the population levelled off. The population grew from 10,000 to about 41,000 in the 90th year. The cessation in the growth is related to the availability of land for building areas. The system proved its stability in supporting a population of more than 41,000. It is obvious from the graph that the water system started to decline after the year 75. It can thus be learnt that the water system could not support more population growth. It also shows that the other two resources were sufficient in supporting the population. This can be explained by the fact that there was a high rate of irradiation and an availability of sufficient land for agricultural production. Fig. 5.181 shows the change in the volume of the crops over time, and it can be deduced that the crops were sufficient when it came to supporting the population. Thus, there was no need for vertical farming. The data that was extracted from the morphological model represents the values of the 70th year.
proved that it could be stable in terms of supporting a population in excess of 41,000. Unlike the previous run, the graph shows that the water system was stable and could support the population. It can be explained by the fact that the rate of rainfall is the highest – higher than in Run-02. It also shows that the other two resources proved to be sufficient in supporting the population. This can be explained by the fact that there was a high rate of irradiation and availability of sufficient land for agricultural production. Fig. 5.180 shows the changes in the volume of crops over time and it can be seen that the crops were plentiful enough to support the population. Thus, there was no need for vertical farming, the data that was extracted from the morphological model represents the values of the 100th year.

5.3.6. Integrated System Dynamics conclusion

In this experiment, a unified system, which integrated three systems, had been modelled in chapter 4 to simulate the changes in land use, production and population growth. Simulated results show that the impacts of rainfall rate on the system was more significant than the irradiation rate. Therefore, the influence of the different climate conditions on the stability of the system were not at the same degree as their impacts. In this experiment, the evolved system was driven by the water sub-system. Similar to previous experiments, the first run shows that the impact of the initial population is crucial in the stability of the system over time. The resulting data for exportation was extracted from different years of the simulation output: the first two runs from the 70th year and the last run from the 100th year.
Having performed the SD simulation, the next step is to explore the morphologies that correspond to the systems simulated and their resulting outcomes. The experiment utilizes the same generic superblock that has been used thus far: the 1000 by 1000-metre model. The evolutionary model was constructed from the three models developed in chapter 4. Fig. 5.183 shows the pseudo-code of the model which presents the three parts of water, energy, and agriculture. The three sub-models operate in the same superblock and each generates the related morphology that derives from its system. The water system generates the landform with the ponds as reservoirs, the solar energy system generates the skyline surface, and the agriculture generates the terraced landform. As can be seen from the pseudocode, the genes act upon the generic geometry surface in the same manner as the basic models from the previous chapter.

The objectives set for the experiment are the accumulated objectives of the three systems operating simultaneously on the same superblock. The three boxes entitled “Input Data” on the diagram show the resulting outcomes exported from the simulated SD. They define the objectives of the evolutionary model along with the design objective including proximity between building sand land terraces facing south.

To achieve these objectives, a set of gene pools is employed in the algorithm to modify the superblock phenotype morphology by transforming: 1) the unit division of the superblock; 2) the built footprint proportion; 3) building height; 4) water surface proportion; 5) water depth; 6) foothill proportion of the grid; and 7) foothill average height. The genes control the sizes, heights, and divisions of all the surfaces of the superblock. The numeric data of the genes were set to realistic values from previous knowledge and a trial test, such as building height and built area proportion. In addition, test runs were executed to assess the simulation duration time. Limiting the range of the domain determines the size of the search space and affects the time duration of the simulation. The genes were set as the values were set in the separate systems of the prior experiments.

The evolutionary solver parameters were set to 50 solutions and 100 generations (5000 solutions generated). The crossover, mutation, and archive size parameters were set to the solver default settings. The run time for each simulated run lasted about 100 hours. From the evolutionary simulated outcome, Pareto front solutions were extracted and then clustered into three clusters. For the preferred solutions, a nine solution was selected from the three clusters for an initial evaluation of the solar energy harvesting. Then, the average solution of each cluster was chosen as the preferred one for further analysis and comparison. The experiment consists of three runs of the evolutionary solver for three different conditions of results from the SD simulations. They represent the generated outcome of the integrated system for three input parameters of population: 10,000, 28,000, and 40,000.

5.4. Integrated Systems - Evolutionary Design Model
5.5. Integrated Dynamic System

In this section, in-depth analysis studies were carried out for three runs of the integrated system experiments, named Run-01, Run-02 and Run-3 examining the system under the condition of the maximum population size of 10,000, 28,000, and 40,000, respectively. Each run generates 5000 solutions; the solutions set along the Pareto optimal surface were selected and grouped into 3 clusters by applying the K-mean algorithm. Then, eight solutions were selected, including three that represent the average of each set. Based on the exploration of the chosen solutions, one satisfying and preferred solution was culled for further morphological research.

For each run, the eight solutions analysis is presented in the figures as follows: 1) Run-01, Fig.5.183, Fig.5.184, Fig.5.185 and Fig.5.186; 2) Run-02, Fig.5.189, Fig.5.190, Fig.5.191, and Fig.5.192; 3) Run-03, Fig.5.195, Fig.5.196, Fig.5.197 and Fig.5.198. The analysis of each solution shows the plan of the system, the numerical data of the system related to spatial aspects and a diamond chart of the fitness criteria. The plans show the generated surfaces relating to the water landform (pond), the energy harvesting skyline, the agriculture terraces and building distribution. The numerical data attached to the plan shows three types of information: 1) generated results regarding quantities of crops agriculture crops, built area, water storages and area of solar panels; 2) The values of fitness criteria that show how the generated results meet the design objective; 3) A diamond chart displaying the fitness criteria value graphically.

Besides, the analysis shows the Pareto graph representing the Pareto optimal surface. The graph indicates the distribution of solutions along the Pareto surface. Location of each solution in the surface indicates its ranking value regarding fitness criteria. At the bottom of the Pareto graph is the fitness criteria standard deviation. These graphs indicate the amount of variation in the solutions in each generation regarding each fitness criteria. Fig.5.186, Fig.5.191 and Fig.5.198 show the analysis and exploration of the Pareto optimal surface by applying the K-mean clustering method, which clusters the solution into three clusters represented by three colours red, blue, and green. It also shows the mean value trending of each fitness objective through generations.

The final objective of the analysis was to select one satisfying design solution among all generated solutions. The selected prefer solution is presented in the figures as follows: 1) Run-01, Fig.5.187 and Fig.5.188. 2) Run-02, Fig.5.193 and Fig.5.194. 3) Run-03, Fig.5.199 and Fig.5.200. The images show the selected satisfying design solution. In the first set of images, the solution is presented in a plan and a three-dimensional view showing the surfaces of the four components of the superblock, including water ponds, energy skylines, agricultural terraces and buildings. The surfaces are colour-coded, indicating the type of production in relation to each system. Along with the plan are attached numerical data of the different production quantities and the areas. The second set of images show morphological analyses indicating distributions and morphology of the system surfaces, as shown in Fig.5.188, Fig.5.194 and Fig.5.200.
Fig. 5.183  Run 01-Selected solutions/Pareto front

Fig. 5.184  Run 01-pareto front and Standard deviation analygraphs
Fig. 5.191  Run 02 - Selected solutions

Fig. 5.192  Run 02 - Statistical analysis K-means clusters
5.5.3. Run 03-Population 40,000

Fig. 5.195 Run 03-Selected solutions

Fig. 5.196 Run 03-Pareto front and standard deviation graphs
The experiment explored the three systems in one integrated system and their implication on the overall behaviour and morphology of the superblock. The SD simulation aimed to define the conditions and the variable values of the carrying capacity and resources to support the population growth of the superblock. Similar to one system simulation, the resulting outcomes of the SD model showed the maximum population size in the superblock in each run. The dominant factor that continued to affect the limits of the system was water availability. As in the previous experiment of the water system, the run of the 200 mm annual rainfall could support more than about 11,000 people in the superblock. The other two runs displayed the same pattern. The distribution patterns of the morphological outcomes of the evolutionary model exhibit similar characteristics to the solution generated in the previous experiment, which were mainly divided into two categories: the scattered and the clustered spatial organisation of ponds, agriculture, and buildings. The morphological evaluation data of the generated solutions revealed the conflicts between the objectives of the three systems. The water and the agriculture compete for land surface: where the agriculture achieves the objective, and the water system fails. This observation can clearly be witnessed in the preferred solution of the first two runs. Moreover, it can be observed that lower irradiation of the energy system, eventually resulted in a larger built footprint. It can be explained by the need for a larger surface area for solar panels to harvest energy. For example, for a population of 10,000 and an irradiation of 1000 kWh need approximately the same area for 28000 people an 1800 kWh area. It can be interpreted from the results that the built area exceeded that required for 10,000 people, just by generating more solar surface to support the system. Another observation, is that the pattern that was developed towards average objective solutions, was the scattered one, interweaving the three morphologies of the three systems. It can be seen in the image of the third run, that the water and the agriculture are interlaced. This may well result from the fact that to maximize the area for agriculture requires more sun exposure. The concluded result from the agriculture in the previous chapter proved that scattered patches generated much more areas exposed to sun in the context of the proposed superblock. Another factor that contributed to preventing the generation of the successful solution, satisfying most of the objectives was the morphological constraint of the evolutionary model. For example, the maximum surface and depth of the water was limited by morphological constraints. The same was evidenced regarding the limits of maximum footprint and building heights. Therefore, a successful simulated system in DS that exhibit desired behaviours, still might fail to function properly due to morphological concerns.
In this following section, the experiment demonstrates the potential for further design development departing from the multi-dimensional datascape coming from the model. The resulted multi-dimensional datascape constrains the space for further development, as well as providing index data for the implementation of design algorithms. In this case the algorithms will be constrained by the spatial limitations coming from the model. In the model, the point cloud constitutes a metadata, meaning that which structures and spatially organizes other data which, in this case, is either numerical data or vectors related to water, energy and agriculture. Yet this could be expanded further by integrating other systems. In this experiment the multi-dimensional datascape is used to study the connectivity between high density areas, which in this case determines two distinctive qualities in the public realm. What is distinctive from this design methodology is that, in each design iteration, it refines the qualities, materials and requirements needed in each point in space in the form of expected qualities or likelihoods rather than in a deterministic approach which leaves the design open for further development.

5.6. Evolved Ecological Superblock
5.7. Datascape and Design Development

The design model generates data that is represented as three-dimensional surfaces, and numerical data representing the potential value of each point in the superblock. The data is organized in one combined datascape. The exploration of the data can be carried out in different scales and resolutions. It can be done on the scale of the whole superblock or selected, local areas of it. Moreover, the analysis can be limited to one individual system and a combination of two or more systems. The datascape informs the design process in two ways: firstly, by defining the boundaries and limitations of spatial and morphological possibilities; and secondly, by informing each point, in the three-dimensional space of the superblock, with information regarding spatial location, productivity potential and geometric properties in relation to the environment. The objectives of these data visualizations are to inform the design and the final morphology of the ecological superblock. The images in this section demonstrate the potential employment of the generated datascape in the design of the ecological superblock. The first six images Fig. 5.202 – Fig. 5.207, explore the datascape in the scale of the whole superblock. The datascape integrates all the data and information generated from the three models and simulated systems. Nevertheless, the second set Fig. 5.208 – Fig. 5.218, examines the potentiality of the design possibilities of a single system of two combined systems in the scale of the whole superblock and smaller scale by zooming in on a specific local area within the superblock. These analyses, investigations, and explorations of the datascape led to the initial manifestation of a design of the ecological superblock, as shown in Fig. 5.219.

Fig. 5.202 shows the integrated data related to water, energy, and agricultural systems. The data is represented in two ways: first, each set of data constitutes a separate surface and a three-dimensional numerical data distributed spatially. The surfaces - landform (water), skyline (Energy) and terraces (agriculture) - indicates the limitations and boundaries of the morphological manifestation of the superblock. On the other hand, the spatial numerical data inform the productivity potential and morphological properties in each point. This productivity is defined by the potential productivity of each point in relation to data, water, and energy. Agriculture. These points contain information regarding the morphological distribution of the systems and the inhabited buildings. At the bottom of the images one can observe the integration of the water and agricultural surfaces, the dotted areas represent the distribution of the agriculture and the opaque area is the water pond. At the top, there is the energy surface and its extracted numerical data. In the middle of the image, a three-dimensional numerical data section has been placed, informing the design of the inhabitable area, including connectivity network (red colour lines).

Fig. 5.203, Fig. 5.204 and Fig. 5.205 show further exploration of the datascape. The first shows another representation and visualization of the datascape divided into two sections that can come useful in term of facilitating and informing the design. The second image is a demonstration of the "exploded" numerical integrated datascape into metadata, including boundaries, sections, and landform morphology limitations (green surface). Fig. 5.206 shows the three-dimensional representation view and a section of the numerical data, combined with the surfaces in "wireframe mode" (lines and curves). Fig. 5.206 and Fig. 5.207 depict another two sections; the former is data regarding the water and agricultural terraces levels and the latter data represents the inhabitable area with close-ups in some specific areas, named Type01, Type02 and Type03.

Fig. 5.208 and Fig. 5.209 visualize and explore the data of the water systems combined with the agricultural terraces. The first image shows the pond distribution (green surfaces) and the distribution of the agricultural terraces, marked with vectors and circles. The vectors indicate the areas facing south and the circles show the steepness of the slopes. This information is also represented in the section at the bottom of the image. The second figure, it is a zoom in on a specific area that shows more details, including numerical data of levels, south facing vectors, steepness, and water bathymetry analysis.

Fig. 5.210, Fig. 5.211 and Fig. 5.212 combined the visualization of the energy and agriculture systems. The data provides three-dimensional prisms of the sun that allow six hours of sun exposure on the coldest day of the year. It also shows agricultural data and terraces distribution. The image in Fig. 5.210 includes the sun "fan" (prisms) section and the numerical value of the energy harvesting productivity. Fig. 5.211 presents a zoom in view of the layered data of energy and agriculture. The last image, Fig. 5.212, is the side view of the energy surfaces that indicate the boundaries of the productive area of energy harvesting.

Fig. 5.213, Fig. 5.214, Fig. 5.215 and Fig. 5.216 explore and visualize the agricultural system. The first image views the agricultural datascape, combined with the solar radiation; the data are displayed numerically. A connectivity analysis layer was added to the inhabitable areas (red colour lines). The analysis is viewed in the three-dimension section as well (lower part). The image in Fig. 5.215 highlights the hard and softscape distribution and examines locally (close-up) the datascape of the agricultural system. The last two images, Fig. 5.215 and Fig. 5.216, depict a colour-coded distribution of the agricultural terraces; the first shows the data on the plan and the second is displayed in a three-dimensional view. Analyses of urban network proximity, and connectivity and hard and softscape distribution are shown in Fig. 5.217 and Fig. 5.218. The first image shows the connectivity network (red colour) connecting clusters of hardscapes. The second image highlights the hard and softscape, layered with the network; the dark blue is the hardscape, and light blue is the softscape.

Following all these visualization, analyses, and exploration of the datascape, an initial morphological design manifestation emerges, as shown in Fig. 5.219. The importance of the emerged design is the datascape representing ecological processes expressed by mathematical relationships. The final morphology could develop according to the design preferences and material development determined by the requirements.
Fig. 5.202 shows the integrated data related to water, energy, and agricultural systems. The data is represented in two ways: first, each set of data constitutes a separate surface and three-dimensional numerical data distributed throughout the surfaces. The surface sets—landform (water), skyline (energy), and terraces (agriculture)—indicate the limitations and boundaries of the morphological manifestation of the superblock. On the other hand, the spatial numerical data inform the productivity potential and morphological properties in each point. The productivity is defined by the potential productivity of each point in relation to water, energy, and agriculture. These points contain information regarding the morphological distribution of the area, including inhabited buildings. At the bottom of the images one can observe the integration of the water and agricultural surfaces, the boundaries represent the distribution of the agriculture and the opaque area is the water ponds. At the top, there is the energy surface and the extracted numerical data. In the middle of the image, a three-dimensional numerical data section has been placed, informing the design of the inhabitable area, including connectivity network (red color lines).
Fig. 5.203, Fig. 5.204 and Fig. 5.205 show further exploration of the datascape. The first shows another representation and visualization of the datascape divided into two sections that can come useful in term of facilitating and informing the design. The second image is a demonstration of the “exploded” numerical integrated datascape into metadata, including boundaries, sections, and landform morphology limitations (green surface). Fig. 5.206 shows the three-dimensional representation view and a section of the numerical data, combined with the surfaces in “wireframe mode” (lines and curves). Fig. 5.206 and Fig. 5.207 depict another two sections; the former is data regarding the water and agricultural terraces levels and the later data represents the inhabitable area with close-ups in some specific areas.
Integrated Datascape

Fig. 5.204    Multi Dimensional Datadcape
Fig. 5.205  Perspective view _Datascape:
steepness of the agricultural terraces, south orientation angles data, urban networks connections, energy skyline of hard space
Fig. 5.206 shows the three-dimensional representation view and a section of the numerical data, combined with the surfaces in "wireframe mode" (lines and curves).
Fig. 5.207 depict another two sections; the former is data regarding the water and agricultural terraces levels and the latter data represents the inhabitable area with close-ups in some specific areas, namely Type01, Type02, and Type03.
Fig. 5.208 and Fig. 5.209 visualize and explore the data of the water systems combined with the agricultural terraces. The first image shows the pond distribution (green surfaces) and the distribution of the agricultural terraces, marked with vectors and circles. The vectors indicate the areas facing south and the circles show the steepness of the slopes. This information is also represented in the section at the bottom of the image. The second figure is a zoom-in on a specific area that shows more details, including numerical data of levels, south-facing vectors, steepness, and water bathymetry analysis.
Fig. 5.209 Top View: highlighted, water ponds.

Bathymetry Data.
Fig. 5.210, Fig. 5.211 and Fig. 5.212 combined the visualization of the energy and agriculture systems. The data provides three-dimensional prisms of the sun "fan" that allow six hours of sun exposure on the coldest day of the year. It also shows agricultural data and terraces distribution. The image in Fig. 5.210 includes the sun “fan” (prisms) section and the numerical value of the energy harvesting productivity. Fig. 5.211 presents a zoom-in view of the layered data of energy and agriculture. The last image, Fig. 5.212, is the side view of the energy surfaces that indicate the boundaries of the productive area of energy harvesting.
Fig. 5.211 Top View_Energy Datascape: Solar Fan, Energy Data, Hard and SoftScape data.
Fig. 5.212 Energy Surface Section
Fig. 5.213, Fig. 5.214, Fig. 5.215 and Fig. 5.216 explore and visualize the agricultural system. The first image views the agricultural datascape, combined with the solar radiation; the data are displayed numerically. A connectivity network analysis layer was added to the inhabitable areas (red colour lines). The analysis is viewed in the three-dimensional section as well (lower part). The image in Fig. 5.215 visualizes and examines locally (close-up) the datascape of the agricultural system. The last two images, Fig. 5.215 and Fig. 5.216, depict a colour-coded distribution of the agricultural terraces: the first shows the data on the plan and the second is displayed in a three-dimensional view.
Fig. 5.214 Perspective view_Ground Datascape:
Levels of the agricultural terraces, south orientation angles data, water bathymetry data.
Fig. 5.2.15  Inside the Datascape of Agriculture: Hardscape and Crops terraces Levels, Connections,
Fig. 5.216 Inside the Datascape of Agriculture:
Hardscape and Crops terraces Levels, Connections, South orientation, Steepness, Data.
Fig. 5.217    Inside the Datascape of Agriculture: Hardscape and Crops terraces Levels, Connections, South orientation, Steepness, Data.

Analyses of urban network proximity and connectivity and hard and softscape distribution are shown in Fig. 5.217 and Fig. 5.218. The first image shows the connectivity network (red colour) connecting clusters of hardscapes. The second image highlights the hard and softscape, layered with the network; the dark blue is the hardscape, and light blue is the softscape.
Fig. 5.218 Top view: Ground Datacape.

Hard and SoftScape, urban networks proximity data.
Based on these visualization, analyses, and exploration of the datascape, an initial morphological design manifestation emerges, as shown in Fig.5.219. The importance of the emerged design is the datascape representing ecological processes expressed by mathematical relationships. The final morphology could develop according to the design preferences and material development determined by the requirements.
5.8. Summary and Discussion

The research argued that the city in general and the superblock in particular are ecosystems whose performances and function depend on the flux of matter and energy through them. The superblock is seen as a fundamental ecological unit in the architecture of the city. It exhibits similar basic features and patterns to natural ecosystems, in relation to structure and function. As an ecosystem, the superblock consists of subsystems within a subsystems interacting together. Therefore, in terms of its design, the emphasis is placed on the obligatory relationship, interdependence and causal relationship. Ecologically, the evolution of these systems is constrained by physical and systemic laws as well as by environmental properties. Defining the relevant systems and their boundaries, relationships and interactions is crucial to the generation of the ecologically driven morphology of the superblock.

To address this notion, the research also employed principles from computational ecology utilizing basic ecological models including the Malthusian growth model of population. For the mass and energy conservation, biochemical and bioenergetic dynamic models were used. These models were constructed using the conceptual industrial dynamics methods developed by Forrester, which describe the flows of matter and energy in ecosystems. Within this ecological thoughts framework and the System Dynamic method, the systems and subsystems of the superblock were designed, modelled and simulated.

The experiments in chapter 4 demonstrate the productivity of the sub-systems and their impacts on the morphology of the superblock. SD models were developed to assess the behaviour and the productivity of each system separately in this phase. The simulation results show the different output values of solar energy, water and agriculture production. The results were presented graphically and numerically: the first allowed for the observation of the trends and threshold points of the system and the second provided the figures needed for further development. The model calculated the carrying capacity of each system to support the growing population. To perform assessment of the different system scenarios, only one variable connected to climate was changed in each run. The resulting values were exported to the morphological model (evolutionary model) to serve as objectives to be achieved. The morphological outcomes exhibited different patterns of configuration in response to different systems’ dynamics.

In the water experiment, the system describes the interaction between growing population and water collecting, storing and consuming. The DS simulation revealed two significant outcomes: the first that the water system inhibited the population growth in some cases. The volume of water available determined the carrying capacity and the ability of the population to grow. The second implication is the impact of the initial population on the stability of the system. Due to the fact that the system relies on the feedback loop of recycled water, the volume of the recycled water is critical for the system, which depends on the population size. Morphologically, the outcomes were driven not only by system dynamic behaviour but also by the design objectives. The solutions developed toward morphologies that could satisfy both. For example, small scattered ponds developed in response to maximize the waterfront as a design objective and water capacity volume as system objectives. Similar to a natural ecosystem, the experiment proved that finite resources are a limiting factor to the system growth. In addition, it demonstrates that the rate of consumption affects the stability and the system growth over time. This fact added another factor in the system design which is that of population behaviour.

Similar to the water experiment, the solar energy system experiment exhibited the same pattern of behaviour concerning the availability of the resource and its impacts on population growth. The interesting conclusion in this experiment was the demonstration of the effect of the environmental characteristics on the system stability and productivity. Due to the fact that the solar energy harvested through a surface that is defined as a skyline of the built area, the amount of energy was restricted to the area of this surface. The surface area represents an environmental physical restriction which is defined by the preferred population density. The concept of energy flow and production is limited to the area of the skyline surface availability. The impact of the system behaviour on the generated morphologies was significant: all of the solution developed a skyline that inclined to the south to maximize exposure to the sun.

The last experiment in chapter 4, explored the agricultural system in relation to the water availability. Although the system predicted the growing population and the agricultural production areas, the crop volume was determined by the land area available for field agriculture. The two systems affected each other indirectly: the growing population caused changes in the land use and, as a result, changes in the volume of crops. This pattern partly recalls the two-species mathematical model of Lotka-Volterra, which describes growth intensity in relation to resources. Morphologically, the design model generates a terraced landform resembling the traditional Mediterranean agriculture system where crops with less need for water were allocated to higher level terraces and vice versa. The model optimized the terraces and their areas to achieve the quantities required to support the population.

Chapter 5 builds on the experiments performed in chapter 4: the developed models so far have been utilized to compose one combined model. The experiment was designed to integrate the three systems of water, solar energy and agriculture (unified model, Fig.5.221). The SD results show that the systems competed with each other in obtaining land area, they interacted with each other and coevolved to keep the system stable. The continuing population growth was mainly determined by the rate of rainfall. The other two systems had only an indirect effect. The evolution of the combined system shows characteristics similar to subsystems of natural ecosystems, where they evolved through interaction to adapt to constraints and environmental conditions. Regarding the morphology, the results also show a pattern of distribution...
related to the optimised objective. For example, when the solar system optimised morphologies developed towered clustered forms and, when there was water, it generated scattered forms. Following the integrated experiment, another experiment was performed to improve the condition of the sun optimization for agriculture by introducing a new condition of six-hour exposure on the frostiest day of the year. When coupling the SD model with the Evolutionary Model, there is a series of aspects to be taken into consideration: (1) System Flexibility: When adding more subsystems to the systems, the flexibility in each subsystem decreases. Therefore, when modeling the integrated system there needs to be a compromise between the subsystems. (2) Coupling SD with the Evolutionary Algorithm: when coupling the three subsystems, the parameters coming from SD are more prominent in the setting of objectives in the evolutionary algorithm.

The solution, with the three integrated subsystems, is a multi-dimensional datascape which constitutes the urban tissue of the superblock. This multi-dimensional datascape is used as the spatial organizer and distributor of urban systems. It acts in two ways: first off, it sets the spatial boundaries of the morphology of the inhabited spaces and secondly, it provides a multi-dimensional datascape which informs the material development of the superblock. In this way, the SD models succeeded in describing, numerically and graphically, the superblock system’s behaviour, functions and production over time. The observation proved that there is a significant implication of these data on the morphological outcomes. The result suggested that changes to the spatial organization, orientation and distribution affected the functionality of the simulated system. For example, in terms of the water pond morphology, it was obvious that small scattered ponds succeeded in achieving the system goal. Another example: the solar panel surface developed as an inclined surface to the south which allowed for an increase in the productivity of the system.

Based on the holistic, systemic approach to the superblock design, architecturally and ecologically, the generated morphologies emerged from co-evolution of the subsystems along with the environmental conditions (water, solar and agriculture). The resulting multi-dimensional datascape constrains the space for further development as well as providing index data for the implementation of design algorithms. In this case, the algorithms will be constrained by the spatial limitations coming from the model. In the model, the point cloud constitutes a metadata, the meaning of which is that it structures and spatially organizes other data, which, in this case, is either numerical data or vectors related to water, energy and agriculture. This could be expanded further by integrating other systems. Unlike the repetitive urban settlement of Hilberseimer or the hyper structure of Soleri, in each design iteration it refines the qualities, materials and requirements needed in each point in space in the form of expected qualities or likelihoods, rather than in a deterministic approach which leaves the design open for further development.

The experiments proved that in each geographic patch there is a limit to the size of the population. Thus, additional population growth could be achieved by the expansion of the tissue. Due to the fact that the tissue performs according to the interactions with its close environment, the expansion cannot be carried out by scaling up or by uniform repetition.

In conclusion, the experiment conducted aimed to demonstrate the applicability of the ecosystem concept and its modeling methods in the design of the ecological superblock. The System Dynamic modelling approach allowed for the flexibility of aggregating systems and integrating them into one, unified system. In this context, the method applied succeeded in describing and simulating the behaviour of the ecological superblock. The integration of the System Dynamic and Evolutionary Design model in one integrated design model created the possibility of connecting the morphology to ecological processes such as urban metabolism. The developed design model was implemented in different climatic conditions and successfully simulated the systems and generated morphologies. The model is also mutable and can be adapted to different environmental, climatic and cultural conditions. The population habits of consumption can be varied and therefore could lead to the development of different solutions. Such cultural aspects could impact the systems’ behaviour and the morphological implications.
6.1. Introduction

The aim of the research is to develop a design method that integrates System Dynamic modelling into the design process of the ecological superblock. In Chapter 2, the research departs from a critical reflection on the work of Hilberseimer's "Decentralized City" and Soleri's "Arcology", who considered the city and the superblock to be an ecological system. This contextualizes the research within the larger scope leading to the focus on the investigation of ecology and its subfield, the ecosystem. This brings the study down to three dominant areas of research: ecology, computational ecology and urban design. The computational model employed in the research is a System Dynamic Model coupled with an Evolutionary Design Model. The SD model integrates different subsystems. For the scope of this research, water, energy and agriculture are selected. As discussed in Chapter 5, one important aspect to consider when it comes to the design of the integration of these subsystems is the system flexibility. This leads to considering the possibility that when adding more subsystems to the system, it reduces the space of possibilities within the subsystems. Another important aspect discussed in Chapter 5, is the data flow between the SD and the Evolutionary Design Model. One important finding in the development of the experiments in Chapter 5 is that the more subsystems are added, the more spatially constrained they become and therefore the outputs from the SD model become more prominent in the future of objectives for the evolutionary algorithm. The research output is a multi-dimensional datascape, meaning that it structures and spatially organizes other data. Furthermore, this could be expanded further by integrating other systems. What is distinctive about this design methodology is that each design iteration refines the qualities, materials and requirements needed in each point in space in the design model. This is either numerical data or vectors related to water, energy and agriculture. Furthermore, this could be expanded further by integrating other systems. What is distinctive about this design methodology is that each design iteration refines the qualities, materials and requirements needed in each point in space in the dataflow, as a design tool for addressing the complexity of the ecological superblock. In particular, there is the impact of the System Dynamics models on the ecological systems simulations and analysis in the urban context. Unlike the existing method of analysing and designing isolated systems, the design model allows for the simulation of an integrated urban system. This can be seen as a significant improvement for the application of System Dynamics in design.

This chapter reflects on: 1) the ecological approach of Hilberseimer and Soleri to design; and 2) computational ecology in design. In addition, it contextualizes the research within the larger scope. It also addresses the central contribution, limitations and future research.

Critical Reflection

In the first half of the twentieth century, there was a surge of interest in the idea of the city as a productive system. The seminal work of Hilberseimer and Soleri showed two antipodal yet complementary approaches. Hilberseimer adopted a holistic design approach towards the integration of agriculture into the city. His dynamic organizational model was developed by collecting empirical data and layering the implications of environmental dynamics for form. He presented his model by utilizing the diagram as a tool for representation of an urban model, advancing his ideas of employing the model as a dynamic organizational tool. His urban model is based on the definition of ecology, which deals with the relation of organisms to their environments, whereby the landscape is seen as an integrated whole. All the components of the landscape, non-living and living beings, are engaged in natural cooperation and comprehensive symbiosis. Considering the landscape as an organism places the emphasis on the mutual relationship between the parts and the whole. The part affects the whole and vice versa. This notion places the emphasis on the interaction between its parts and their implications for the system's ability to adapt to different conditions over time. His main contribution - the idea of the settlement unit - was in the field of regional and urban planning, whilst architecture is reduced to its footprint and outer volume. Although the model integrated agriculture and industry into the city, nature remains outside the city. The proposed settlement units were placed in nature with clear delineation between the outer and inner environment (Fig.6.222). In addition, he did not consider the dynamic interrelationship between the different systems or how these evolve over time.

Soleri, on the contrary, expanded upon the traditional definition of ecology and the relationship between the natural world and man-made nature. For him, architecture and ecology are two parts of the same entity. Soleri proposed Arcology (combining architecture and ecology), which is a city as an integrated "organism", interacting with the natural cycles of the planet while taking full advantage of solar energy. Arcology draws design principles from ecology, noting that higher life forms (such as bees, ants, apes), live in organized, dense settlements, while lower life forms (corals, fungi and so on) are spread out.
He also introduced the idea of miniaturization as the process of bringing people and things into close proximity, in order to create the conditions needed to facilitate a greater level of interaction. It can be observed from his thirty arcologies that he considered the city to be a hyper structure that has its own interior nature, isolated from the outer environment. The Arcology surrounded by nature, performs as a self-contained system, capable of regulating the artificial conditions inside the structure (Fig.6.223.) However, his idea of creating self-contained systems of man-made nature against the natural world might prove redundant, taking into consideration that at least 70% of the Earth’s surface is currently managed by humans.

The Ecological Superblock, proposed in this research, introduces Paolo Soleri’s idea of self-contained systems into Ludwig Hilberseimer’s concept of the settlement unit. By doing so, it allows one to continuously assess the performance of the dynamic complex systems of the Superblock and their implications for form. In this case, there is no distinction between city and nature. In the Superblock, the city, at the same time, nature and therefore sustains all the environmental dynamics necessary for its own survival. The computational model proposed in this research synchronizes ecological, morphological and metabolic parameters by coupling a Dynamic System Model with an Evolutionary Design Model. In this way, the research adopts a dynamic system approach and allows for the understanding of how these system dynamics evolve over time, overcoming some of the limitations of the Hilberseimer Model.

The research proposes energy and material fluxes as drivers of urban morphology. This point of departure is underpinned by the expanded definition of ecosystem by Eugene Odum (1971). The author understands ecosystem as, “a unit that includes all the organisms, i.e., the community in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity and material cycles, i.e., exchange of materials between living and non-living, within the system”. Based on Odum’s definition, cities can be considered as ecological systems of flows of materials and energy. The understanding and assessments of these flows can be conducted employing a Metabolic approach. This approach understands city as a result of flows of water, materials and nutrients in terms of mass fluxes. Although urban metabolism is widely used and proved to be a productive way to conceptualize how an urban area functions, and assessments of these flows can be conducted employing a Metabolic approach. This approach understands city as a result of flows of water, materials and nutrients in terms of mass fluxes. The understanding and assessments of these flows can be conducted employing a Metabolic approach. This approach understands city as a result of flows of water, materials and nutrients in terms of mass fluxes. The understanding and assessments of these flows can be conducted employing a Metabolic approach. This approach understands city as a result of flows of water, materials and nutrients in terms of mass fluxes. However, increasing the number of subsystems adds more systems, the designer needs to decide on the interrelationships between them and adjust the fitness criteria accordingly. The experiments in Chapter 4 demonstrate the capability of the model in generating design proposals of separate systems within various climatic conditions. Chapter 4 employed the developed method in carrying out three separate experiments of the three systems. Each experiment was performed in various climatic conditions, exploring the limitations, impacts and effects on the system’s behaviour. In this phase of the research, the unified integrated model of System Dynamic model and the Evolutionary model was capable of simulating metabolic processes of a separate system and affecting the generation of the morphological solution.

Chapter 5 focused on the integration of the three systems studied separately in Chapter 4. The integrated system evolves as a result of the interaction of the three subsystems over time. The model calculates the integrated system and simulates its development over time. Understanding the behaviour of the system allows the design to export the simulated results of the most relevant scenarios to the Evolutionary model. The morphology is determined by the objectives and limited resources imported from the System Dynamic model. The experiments proved the ability of the integrated model to aggregate more than one subsystems. However, increasing the number of subsystems increased the complexity of the optimisation process.

Chapter 5 reflects on two aspects: 1) The ecological approach of Hilberseimer and Soleri towards Urban System Dynamic Principles, introduced by Sir Arthur George Tansley in 1935, which is the “ecosystem”. System Dynamics principles were initially developed and introduced by Dr. Jay Forrester, in the sixties of the last century, as a modelling and simulation method for industrial management, based on System Theory and Feedback Control Theory. SD has been used for a wide spectrum of applications, including modelling and simulating of social, economic, physical, chemical, biological, and ecological complex systems. Contrary to traditional analytical approaches that focus on the system as a whole and on the interconnectedness between components and processes, the SD method is defined as a collection of parts that continuously interact over time that lead to the emergence of new properties. Although, SD was widely applied in the field of ecological systems (including water, agriculture and energy), it has not been utilized in architectural design in general or in the superblock.

The System Dynamic Principles are introduced in the System Dynamic Model, considering the interrelation and evolution form such as: urban system stability and resilience, flexibility of the system, stress analysis of the system. These types of discussions are very relevant considering the current environmental challenges of climate and nature emergency that cities are facing today. The challenge of developing this model is to couple the System Dynamic with the Evolutionary Design Model. The research adopted the idea of creating self-contained systems of man-produced nature against the natural world with the aid of evolutionary computation. This logic offers an alternative approach to optimization. On the contrary, evolutionary computation does not offer a solution but a solution space. The analyses of the different solution spaces offered by the model gives rise to new discussions related to urban
over time between the three sub-systems. The central focus of the research lies in the system of dynamic modelling of cities as ecosystems in an attempt to model and simulate the behaviour and development of a superblock’s systems over time. The selected systems of the research study are water, solar energy and agriculture. The formation, which is a development of these systems, is based on the understanding of the characteristics of ecological systems and their complex dynamics, as described in Chapter 2. Ecological Systems Dynamics are represented by stock and flow over time extracted and implemented in the domain of Urban System Modelling.

Through the implementation of System Dynamic Modelling in design, the focus is shifted from the concept of form to the concept of dynamic processes and the development of the design problem over time. The SD model describes the behaviour of the system that emerges from the interaction of the system components between themselves and with the environment. The modelling process starts by defining the components, feedback loops and dynamic hypothesis becomes the foundation of the definition of the design problem. Following this, a mathematical description of the model is applied, and test runs are executed. Having validated and verified the model, a number of iterations are performed to model the system’s evolution within different scenarios. SD models are used to predict resources availability and critical thresholds for the stability of the system regarding water, energy, population and agriculture. The simulated results become the key variables in the design model and determine the development of the morphology, which is generated by the Evolutionary model. The model explores the carrying capacity of the systems and the factors limiting growth or leading to the collapse of the systems (Chapter 3).

6.2. Research Contribution

The main contribution of the research lies in two primary fields: Computational Design Modelling of cities and Computational Ecological Modelling in design. The first focuses on the design of ecological superblock driven by the ecological and metabolic processes of urban systems. The morphology of the superblock develops and emerges as a response to the dynamics of the ecological systems and their interaction between themselves. The systems develop and evolve over time in response to inner and outer factors in relation to their structure and function. The former factors are the environmental and climatic conditions, such as rainfall rate, sun irradiation rate and topographical conditions. The second set of factors are the internal conditions, such as resources consumption rate, initial population size, density and morphological parameters. The process involved the application of Evolutionary and Ecological Modelling methods to describe and simulate the systems in order to generate morphologies of the superblock. This method requires synthesising multidisciplinary knowledge including ecology, Complex System Theory, mathematics and computation. Although the model was constructed to simulate three systems, it can be extended by including more systems such as social, urban and economic systems. Moreover, the existing systems can include additional parameters which might increase the complexity of the system. Therefore, the significance of the model in its mutability and its ability to be adapted, is developed and further expanded.

The second field was the development of integrated computational design model incorporating two models: System Dynamics Model and Evolutionary Design Model (SDEDM). The integration required utilizing STELLA, a visual programming language for System Dynamics Modelling and Grasshopper, a visual programming language and environment that runs within Rhinoceros 3D. STELLA computed and simulated the systems and Grasshopper was coupled with the open source evolutionary solver Wallacei to evolve solutions. The System Dynamics generated outputs for different scenarios representing different internal and external factors. The output represents the parameter values of the system for specific behaviour under specific conditions. The chosen outputs are exported to the evolutionary design model, which are applied as objectives to be achieved by the morphological outputs. Then, the evolutionary solver is used to generate a set of solutions – morphologies – that seek to achieve multi-objective optimised solutions. The development of a unified computational design model, capable of generating morphologies in response to dynamic systems, is contributed to the synthesis of the two fields: Computational Design Modelling and Computational Ecology.

6.3. Limitations

The level of practicality of the model is limited to three systems and only a few factors of each system have been considered. The systems used in the model need further development to satisfy more design objectives. This requires more elaboration and expansion of the System Dynamic model in order to provide better understanding of the dynamics of the whole model. Moreover, developing the model requires integrating further systems and wider knowledge of discipline outside the design domain. The System Dynamic simulated results used in the design model are to some extent, at basic level, due to the fact that the systems only focus on a small number of factors.

Another challenging issue is the need for at least basic knowledge of ecology, Ecological Modelling and System Theory. The multi-disciplinary approach of the proposed design might also prove complicated and uncontrollable for the majority of designers. Moreover, when it comes to real-world problems, the number of such variables is enormous, and, furthermore, there is no way of quantifying all of them for computational simulation or scientifically assessing their importance. The computational platform might prove to be challenging as utilising the model requires knowledge of System Dynamics software and skills in Ecological Modelling, which are unfamiliar to most designers. The extended model to more systems leads to an increase in the complexity and the evolutionary solver might require much more time that could be considered practical. For example, one test run of the three integrated system lasts more than 50 hours which requires an extensive modification to the algorithm to cut the simulation time.
6.4. Further Research

The research undertaken for this thesis has highlighted that some pathways of further research would be beneficial. One direction for further development is related to the potentiality of overcoming the research limitations mentioned earlier. In this regard, further research studies can be carried out in five directions: First, expanding the number of ecological systems, because the design model has only focused on three environmental systems. Thus, it is essential to examine and test more systems that reflect real-life urban problems, including economic, political, cultural, and technological systems. This can be achieved by 1) expanding and aggregating sub-systems into the System Dynamic model, and 2) increasing the data related to ecological parameters. The research employed basic data regarding the system; therefore, the systems were modelled as a basic abstract of the real systems. Consequently, further research studies could be carried out to establish the critical data needed to be employed in the modelling processes.

Another pathway topic for further research is the examination of the model under different climatic and environmental conditions. Because the study’s experiments were confined to the Mediterranean region, a system impact on the urban system could differ in scale and density from one climatic region to another. For example, the water system has a tremendous effect on the arid climate but a marginal impact on the subarctic region. For that reason, research studies are needed to implement the model in different contexts. Further investigations into the environmental system’s structure, behaviour, and its impact on urban patterns should be undertaken.

In this context, further research can be based on drawing comparisons between several different climate regions. The design experiments should examine similar population sizes, superblock sizes and cultural aspects such as consumption habits and spatial requirements per capita. This setup is essential in terms of drawing comparisons between the generated urban morphologies concerning climatic conditions. Therefore, the emphasis will be laid on the climatic data, which can pose a challenge because of the climatic system’s complexity. It will require a thorough analysis and data collection of the relevant climatic data before the design experiments.

The third pathway is related to urban scale and population growth; the design experiments were confined by the size of the superblock (one square kilometre). Therefore, to examine the possibility of urban growth, research studies regarding the development of the model to address urban expansion were conducted. Theoretically, the model can handle any size, but a change in the level of organisation requires adaptation and modification of the model. The model can be tested in different ecological organisational levels, from the lowest level of a single building to a superblock to a city and to a region, which is the highest level.

This direction of research can be developed into two sub-directions. The first may require a further understanding of spatial population distribution; a fundamental topic in the science of ecology. Developing and employing such a model in urban design and architecture necessitates integrating principles derived from the science of ecology. Thus, the ecological superblock’s design model can be expanded to include the ecological spatial distribution model, which can be seen as the primary research question of future work. The second sub-direction is related to the urban fabric’s organisational level; in this regard, the model would undergo significant modifications concerning the parameters and data needed to simulate and generate the morphology. For example, a single building’s morphology generation and its material manifestation are considerably different from the urban patch in block or superblock scale. Consequently, the research focus would be on the changing parameters and data between the different organisation levels and their impacts on the design model’s structure.

The fourth pathway is related to the recent development of network and communication technology and its impact on cultural behaviour. The communication and media technologies are becoming pervasive into all aspects of life, integrating this ubiquitous technology with the system dynamics of urban systems is necessary for a city’s performance. Developing the model in this direction requires the integration of computer and social behaviour sciences.

It can be achieved by introducing information and communication technologies and the ICT application in the design model. In this case, further research will focus on the implication of these emerging technologies on the physical urban infrastructure. The research may require an extensive exploration and understanding of the dynamic interaction between the ICT and the city on different scales. Moreover, these technologies have a fundamental impact on societal behaviour, including production, consumption, and communication. Based on this understanding, further research will be concerned with real-time data relating to responsive systems and metabolic processes employed in the design. Therefore, the primary question of such research may be the dynamic relationship between ICT and urban morphology.

The last pathway is in the computational domain and the development of one integrated computational environment. The developed design model is a combination of two separated models working in a different computational environment. The unified model might pose difficulties for users and designers who are usually unfamiliar with these software applications. Developing the model in one computational interface might facilitate the use of the developed model by different users, including designers, planners, and policymakers. This type of research is computationally inclined and can be based on the models developed in this research.

Further research in this direction involves developing an integrated computational platform which combines System Dynamic modelling and Generative Design modelling. Moreover, the need for powerful computational hardware to run such models requires the development of a tool that can run on a personal computer or laptop. Conducting this research also requires establishing a theoretical and conceptual background of the platform and its computational flow. It will be followed by the development and coding the interface that can facilitate utilizing the combined design model by designers and non-familiar users with computational skills.
The evolutionary model files for the simulations presented in chapters 4 and 5 are presented in high resolution in the following pages. Subsequently, two of the awarded papers’ work is presented as a catalogue of material: first the GS4Q Paper Publication, secondly the Innovate UK, Singapore Urban Bridge Awarded mission.
7.1.1. Appendix GH Models
7.1.2. Energy system evolutionary model
7.1.3. Agriculture system evolutionary model
7.1.4. Integrated system evolutionary model
7.2. APENDIX -INTEGRATED SYSTEM MATHEMATICAL EQUATION

<table>
<thead>
<tr>
<th>Population Growth</th>
<th>carrying_capacity_density = land_area/(Total_built_Footprint+public_spaces)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;footprint_build_area,(%)&quot; = .25</td>
</tr>
<tr>
<td></td>
<td>Fractional_death_rate = 0.01</td>
</tr>
<tr>
<td></td>
<td>land_area = superblock_area*&quot;footprint_build_area,(%)&quot;</td>
</tr>
<tr>
<td></td>
<td>public_spaces(t) = public_spaces(t-(dt)) + (Flow_19)*(dt) [NON-NEGATIVE]</td>
</tr>
<tr>
<td></td>
<td>INIT public_spaces = 0</td>
</tr>
<tr>
<td></td>
<td>INFLOWS:</td>
</tr>
<tr>
<td></td>
<td>superblock_population(t) = superblock_population(t-(dt)) + (population_rate_growth - Death)*(dt) [NON-NEGATIVE]</td>
</tr>
<tr>
<td></td>
<td>INIT superblock_population = 4000</td>
</tr>
<tr>
<td></td>
<td>population_rate_growth = IF carrying_capacity_density &gt; 1 THEN Fractional_birth_rate<em>superblock_population ELSE Fractional_death_rate</em>superblock_population [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>OUTFLOWS:</td>
</tr>
<tr>
<td></td>
<td>Death = superblock_population*Fractional_death_rate [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>water_% = .25</td>
</tr>
<tr>
<td></td>
<td>water_surface = water_%*superblock</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agriculture demand</th>
<th>agricultural_demand = superblock_population*vegetable_consumption_per_capita</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average_floor_VF = 5</td>
</tr>
<tr>
<td></td>
<td>eden_Vertical_Farm = 4854/(44*44)*37</td>
</tr>
<tr>
<td></td>
<td>population_growth_1 = population_rate_growth-Death</td>
</tr>
<tr>
<td></td>
<td>public_space_per_capita_1 = 5</td>
</tr>
<tr>
<td></td>
<td>Residential_average_number_of_floors_2 = 8</td>
</tr>
<tr>
<td></td>
<td>&quot;surpass_-fail&quot; = total_superblock_yield*agricultural_demand</td>
</tr>
<tr>
<td></td>
<td>vegetable_consumption_per_capita = 0.136</td>
</tr>
<tr>
<td></td>
<td>vertical_farm_required = IF &quot;surpass_-fail&quot;&lt;0 THEN &quot;surpass_-fail&quot;*-1/eden_Vertical_Farm/average_floor_VF ELSE 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water System</th>
<th>Average_annual_rainfall_rate_1 = .2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>carrying_capacity_factor = IF (Domestic_water_demand_1+Evaporation)&gt;Water_inflow THEN 0 ELSE 1</td>
</tr>
<tr>
<td></td>
<td>Catchment_area = 1000000</td>
</tr>
<tr>
<td></td>
<td>Catchment runoff_percent_1 = .8</td>
</tr>
<tr>
<td></td>
<td>Domestic_water_demand_1 = superblock_population* Initial_average_domestic_water_demand_per_capita_1</td>
</tr>
<tr>
<td></td>
<td>industrial = 0</td>
</tr>
<tr>
<td></td>
<td>Initial_average_domestic_water_demand_per_capita_1 = 25</td>
</tr>
<tr>
<td></td>
<td>regional_reservoir(t) = regional_reservoir(t-(dt)) + (outflow_to_regional_reservoir)*(dt) [NON-NEGATIVE]</td>
</tr>
<tr>
<td></td>
<td>INIT regional_reservoir = 0</td>
</tr>
<tr>
<td></td>
<td>outflow_to_regional_reservoir = IF Water_in_reservoir_1&gt;=2000000 THEN Water_inflow -Domestic_water_demand_1 ELSE 0 [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>reservoir_surface_area = 500000</td>
</tr>
<tr>
<td></td>
<td>&quot;self-sufficiency&quot; = Water_in_reservoir_1/Domestic_water_demand_1</td>
</tr>
<tr>
<td></td>
<td>Water_in_reservoir_1(t) = Water_in_reservoir_1(t-(dt)) + (Precipitation_inflow_1 + &quot;Recycled_water_([grey_water])&quot; + Reigonal_Water_Source - water_Extraction - Seepage - Evaporation - outflow_to_regional_reservoir)*(dt) [NON-NEGATIVE]</td>
</tr>
<tr>
<td></td>
<td>INIT Water_in_reservoir_1 = 0</td>
</tr>
<tr>
<td></td>
<td>INFLOWS:</td>
</tr>
<tr>
<td></td>
<td>Precipitation_inflow_1 = Catchment runoff_percent_1<em>Catchment_area</em>Average_annual_rainfall_rate_1 [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>&quot;Recycled_water_([grey_water])&quot; = Domestic_water_demand_1*fracion_of_recycling [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>Reigonal_Water_Source = 0 [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>OUTFLOWS:</td>
</tr>
<tr>
<td></td>
<td>water_Extraction = Domestic_water_demand_1+industrial [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>Seepage = (5/1000)<em>reservoir_surface_area</em>365*0 [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>Evaporation = reservoir_surface_area*(10/1000)*12 [UNIFLOW]</td>
</tr>
<tr>
<td></td>
<td>outflow_to_regional_reservoir = IF Water_in_reservoir_1&gt;=2000000 THEN Water_inflow -Domestic_water_demand_1 ELSE 0 [UNIFLOW]</td>
</tr>
</tbody>
</table>
|              | Water_inflow = "Recycled_water_([grey_water])"+Precipitation_inflow_1
Agriculture System

\[ \text{barley}(t) = \text{barley}(t - \Delta t) + (\text{Flow}_2 - \text{Flow}_{14}) \times \Delta t \quad \text{[NON-NEGATIVE]} \]
\[ \text{INIT} \text{barley} = 0 \]

**INFLOWS:**
\[ \text{Flow}_2 = \begin{cases} 0 & \text{IF} \ \text{barley} > 0 \\ \text{siperblock} \times (\text{barley}_\text{yield}_{\text{per hec}}/\text{sum}_\text{of_total_crops}) & \text{UNIFLOW} \end{cases} \]

**OUTFLOWS:**
\[ \text{Flow}_{14} = \text{Converter}_3 \times (\text{barley}_\text{yield}_{\text{per hec}}/\text{sum}_\text{of_total_crops}) \quad \text{[UNIFLOW]} \]

\[ \text{barley}_\text{yield}_{\text{per hec}} = 6 \]

\[ \text{citrus}_\text{orchard}(t) = \text{citrus}_\text{orchard}(t - \Delta t) + (\text{Flow}_4 - \text{Flow}_{16}) \times \Delta t \quad \text{[NON-NEGATIVE]} \]
\[ \text{INIT} \text{citrus}_\text{orchard} = 0 \]

**INFLOWS:**
\[ \text{Flow}_4 = \begin{cases} 0 & \text{IF} \ \text{citrus}_\text{orchard} > 0 \\ \text{siperblock} \times (\text{citrus}_\text{yield}_{\text{per hec}}/\text{sum}_\text{of_total_crops}) & \text{UNIFLOW} \end{cases} \]

**OUTFLOWS:**
\[ \text{Flow}_{16} = \text{Converter}_3 \times (\text{citrus}_\text{yield}_{\text{per hec}}/\text{sum}_\text{of_total_crops}) \quad \text{[UNIFLOW]} \]

\[ \text{citrus}_\text{yield}_{\text{per hec}} = 50 \]

\[ \text{Converter}_3 = \text{population}_\text{rate}_\text{growth} \times \text{Residential}_\text{area}/\text{Residential}_\text{average}_\text{number}_\text{of_floors} \]

\[ \text{olive}_\text{orchards}(t) = \text{olive}_\text{orchards}(t - \Delta t) + (\text{Flow}_3 - \text{Flow}_{15}) \times \Delta t \quad \text{[NON-NEGATIVE]} \]
\[ \text{INIT} \text{olive}_\text{orchards} = 0 \]

**INFLOWS:**
\[ \text{Flow}_3 = \begin{cases} 0 & \text{IF} \ \text{olive}_\text{orchards} > 0 \\ \text{siperblock} \times (\text{Energy}_\text{Demand}_\text{farming}_{squer\_meter}/\text{Energy}_\text{Yield}_{squer\_meter}) \times \text{Superblock}_\text{population} & \text{UNIFLOW} \end{cases} \]

\[ \text{Energy}_\text{Demand}_\text{farming}_{squer\_meter} = 3500/72000 \]

\[ \text{Energy}_\text{Yield}_{squer\_meter} = \text{annual_average_irradiation} \times \text{solar_panel}_\text{yield} \]

\[ \text{Energy}_\text{Demand}_\text{farming}_{squer\_meter} = 3500/72000 \]

\[ \text{annual_average_irradiation} = 1 \]

\[ \text{Energy}_\text{Demand} = \text{Energy}_\text{per capita} \times \text{superblock}_\text{population} \]

\[ \text{Area}_\text{per}_\text{2000\_cal}_\text{per\_day} = 4.8 \]

\[ \text{domestic}_\text{panels}_\text{area}(t) = \text{domestic}_\text{panels}_\text{area}(t - \Delta t) + (\text{Increase}_\text{domestic}_\text{panels}) \times \Delta t \quad \text{[NON-NEGATIVE]} \]
\[ \text{INIT} \text{domestic}_\text{panels}_\text{area} = 20000 \]

**INFLOWS:**
\[ \text{Increase}_\text{domestic}_\text{panels} = \text{IF} \ \text{superblock}_\text{population} = 10000 \ \text{THEN} \ \text{superblock}_\text{population} \times \text{panel}_\text{meter}/\text{per capita} \ \text{ELSE} \ \text{superblock}_\text{population} \times \text{panel}_\text{meter}/\text{per capita} \quad \text{[UNIFLOW]} \]

\[ \text{Energy}_\text{Demand}_\text{farming}_{squer\_meter} = 3500/72000 \]

\[ \text{Energy}_\text{per capita} = 1 \]

\[ \text{Energy}_\text{Yield}_{squer\_meter} = \text{annual_average_irradiation} \times \text{Solar Panel Area} \]

\[ \text{Performance Ratio} = 0.75 \]

\[ \text{population}_\text{increase} = \text{population}_\text{rate}_\text{growth} \times \text{Death} \]

\[ \text{Solar Panel Area}_\text{Farming}(t) = \text{Solar Panel Area}_\text{Farming}(t - \Delta t) + (\text{Flow}_\text{increase}_\text{Farming}_\text{panels}) \times \Delta t \quad \text{[NON-NEGATIVE]} \]
\[ \text{INIT} \text{Solar Panel Area}_\text{Farming} = 1555 \]

**INFLOWS:**
\[ \text{Flow}_\text{increase}_\text{Farming}_\text{panels} = \text{increase}_\text{Farming}_\text{area}_{low\_4} \times \text{Energy}_\text{Demand}_\text{farming}_{squer\_meter}/\text{Energy}_\text{Yield}_{squer\_meter} \quad \text{[UNIFLOW]} \]

\[ \text{Total Energy Farming} = \text{Energy}_\text{Demand}_\text{farming}_{squer\_meter} \times \text{Urban Farming Area} \]

\[ \text{Urban Farming Area}(t) = \text{Urban Farming Area}(t - \Delta t) + (\text{increase}_\text{Farming}_\text{area}_{low\_4}) \times \Delta t \quad \text{[NON-NEGATIVE]} \]
\[ \text{INIT} \text{Urban Farming Area} = 10000 \times 4.8 \]

**INFLOWS:**
\[ \text{increase}_\text{Farming}_\text{area}_{low\_4} = \text{IF} \ \text{superblock}_\text{population} = 10000 \ \text{THEN} \ \text{superblock}_\text{population} \times \text{Area}_\text{per}_\text{2000\_cal}_\text{per\_day} \quad \text{[UNIFLOW]} \]
NOTIFICATION OF ACCEPTANCE

Dear Aiman Tabony and Enriqueta Llabres-Valls

Paper ID: 32
Paper Title: The agrarian city in the age of planetary scale computation: Dynamic System Model and Parametric Design Model for the introduction of vertical farming in high dense urban environments in Singapore

Congratulations! The review processes for 2019 Conference on Game Set and Match 4 Qatar 2019 (GSM4Q 2019) has been completed. Based on the recommendations of the reviewers and the Technical Program Committees, we are pleased to inform you that your paper identified above has been accepted for publication and oral presentation. Kindly find reviewers comment in the email.

You are cordially invited to present the paper orally at GSMIV 2019 to be held between February 06-07, 2019 in Qatar. For the most updated information on the conference, please check the conference website at https://www.hyqil.org/ The Conference schedule will be available on the website. Please e-mail gsm4q@hyqil.org for any queries concerning GSM4Q 2019.

Finally, we would like to further extend our congratulations to you and we are looking forward to meeting you in Qatar!

Regards

Kas Oosterhuis
Qatar University
Abstract

Current conditions related to food security lead to study alternative forms of food production in cities such as vertical urban farming in high dense urban environments. This paper discusses the development of the Innovate UK award-winning project consisting of a dynamic system model that generates a large dataset of artificial environments linked to a multi objective optimization model of urban massing for one square kilometer of development along the coastline of Singapore. The scope of the model is to reach the highest level of self-sufficiency in relation to food consumption.

The model operates as a dynamic system constituted of different subsystems including transport, water, agriculture and energy. These systems dynamically interact among each other and with their environment, which is considered the primary source of energy and the main provider of hydrological resources. A large dataset of artificial environments is created employing a Dynamic System Modelling Software; this includes different scenarios of environmental stress such as sea level rise, population growth or changes on the demand side. Such dataset of artificial environments serves as an input for the multi-objective optimization model that employs genetic algorithms to produce a large data set of urban massing including the distribution of a range of food production technologies in relation to pre-established conditions for vertical urban agriculture and compatibility with other urban programs. Connectivity, solar radiation and visual cones are the fitness criteria against which the model has been tested. This paper assesses whether artificial environments further away from the pareto front produce populations of urban design solutions that responds to environmental extreme conditions and environmental shocks.

Keywords: vertical farming, dynamic system modeling, evolutionary algorithms, relational urban model.
EVALUATION PROCESS

GENERATIONS PROCESS
Innovation in Urban Infrastructure: UK mission to Singapore

Research on Relational Urban model and interface developed based on the methodology discussed and developed throughout the investigation for this thesis.

Current urban systems rely on food and energy sources located far away from the centers of consumption. This disconnection between production and consumption results in a model with large energy and CO2 footprint, it exacerbates inequalities among urban population to access to fresh food, clean water and energy and reduces the competitive field resulting in low quality products at a higher cost. One way to tackle this problem is to decentralize the production of food and energy by allowing this production to be closer to the urban fabric at a lower scale.

Lower scale production of food and energy in high dense urban environments faces two main problems:

1. How could it be implemented in the urban fabric, facilitating access to natural light and water and
2. How to compete with economies of scale.

In order to address the first issue, the proposal introduces a digital model that is able to optimize the location of urban built area in relation to the location of urban agricultural fields in high rise and high dense environments. It does so by taking access to natural light as a major constraint and producing an estimated timeline of how the city would grow vertically in relation to population growth.

The model operates as a dynamic system constituted of different subsystems including water, agriculture and energy. These systems dynamically interact within themselves and with their environment which is considered the primary source of the energy and hydrological resources (water and sunlight).

The model is employing the following softwares: Stella (Dynamic System Modelling) and Rhinoceros/Grasshopper/Python Script (A Parametric design software for architecture). It computes and measures the different variables and parameters according to the local condition of light, water and climate and that in turn become the inputs for the distribution of urban massing. The model is able to generate multiple multi objective urban design solutions.
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