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Algorithmic Synergy and Architectural Form Generation Mechanisms

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ABSTRACT

Today, the architecture field is witnessing a noticeable evolution regarding the used tools that the designer should invest in a peculiar way that is made available in architecture through the concept of synergy generally and algorithmic synergy specifically. The synergy is meant to study and analyze the cooperative behavior of complex systems and self-organizing systems that leads to different outputs referred to by the synergy as the (whole), which is bigger than the sum of parts and in architecture, it's translated as the architectural form. This point resulted in a need of a specific study regarding the concept of synergy that focuses on the cooperative, synergistic relations within the trilogy of (form, structure, and material) and clarifies the role of technological evolution of design tools through algorithmic synergy in formulating that relation, thus resulted in the research's problem which came in the following statement (The lack of clear knowledge of the algorithmic synergy and its mechanisms in generating and discovering the architectural form digitally) and to solve this problem and Achieving the research goal which is represented in (Clarifying the knowledge regarding the role of algorithmic synergy and its mechanisms in generating and discovering the architectural form digitally), the research clarifies the concept of "Synergy" in general and "Algorithmic Synergy" precisely in order to get the epitome of vocabulary on the theoretical part and moving on to the practical application on elected projects samples moving on to the conclusions and recommendations that shows having the architecture a self-organizing synergy system connects the designer and the developed digital tool that is provided by algorithmic synergy, plays a vital role in reaching the digitally synergized whole that represented by the architectural form.

Keywords: Synergy, Algorithmic Synergy, Self-Organization, Form Generation

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التآزر الخوارزمي وآليات توليد الشكل المعماري

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الخلاصة

تشهد العمارة اليوم تطورا ملحوظا في الأدوات المستخدمة والتي يجب على المصمم استثمارها بطريقة مميزة يوفرها للعمارة مفهوم التآزر بصورة عامة والتآزر الخوارزمي بصورة. يُعنى التآزر بدراسة وتحليل السلوك التعاوني للأنظمة المعقدة والأنظمة ذاتية التنظيم والمؤدي الى نتاج مختلف أشار له التآزر بعنوان الكل الأكبر من مجموع الأجزاء والذي يقابله في العمارة الشكل المعماري، من هنا ظهرت الحاجة الى وجود دراسة مختصة لمفهوم التآزر المهتم بالعلاقات التعاونية المتآزرة ضمن ثلاثية (الشكل والهيكل والمادة) وتوضيح دور التطور التكنولوجي الرقمي لأدوات التصميم متمثلا بالتآزر الخوارزمي في بلورة تلك العلاقة، لذلك جاءت مشكلة البحث بالصيغة التالية (عدم وضوح المعرفة حول دور التآزر الخوارزمي وآلياته في توليد واستكشاف الشكل المعماري رقميا) ولغرض حل تلك المشكلة وتحقيق هدف البحث المتمثل بـ (بتوضيح المعرفة حول دور التآزر الخوارزمي وآلياته في توليد واستكشاف الشكل المعماري رقميا)، اهتم البحث بتوضيح مفهوم التآزر بصورة عامة والتآزر الخوارزمي بصورة خاصة بغية استخلاص مفردات الاطار النظري والانتقال الى التطبيق العملي على عينات المشاريع المنتخبة وصولا الى الاستنتاجات والتوصيات التي بينت امتلاك العمارة نظاما تآزرياً ذاتي التنظيم يجمع المصمم والاداة الرقمية المتطورة والذي يوفره التآزر الخوارزمي الذي له دور رئيسي في الوصول الكل المتآزر رقميا متمثلا بالشكل المعماري.

الكلمات الرئيسية: التآزر، التآزر الخوارزمي، التنظيم الذاتي، توليد الشكل

1. INTRODUCTION

In its search of achieving perfection and elevating the different goals of society and individuals, architecture has synergized with many sciences and knowledge fields to give the designer the ability to find unique, innovative solutions and achieving goals and utopian ambitions of designers in order to create a unique and special architectural output in any stage of the design process. The concept of synergy in architecture first surfaced in the most basic form referring the whole behavior that describes the behavior of structural systems that cannot be predicted through the individual behavior of these systems' elements, afterward came a number of studies that went on to clarify the concept briefly or implicitly through a number of conceptions that all of them had a common element of looking at architecture as one of the complex systems that its elements interact to reach an output (architectural form) shown by the different and bigger whole which is greater than the sum of parts. And with the technological development and the digital control of relations that connect the elements of architecture with each other that gave birth to new readings in architectural output and the mechanisms of its emergence and finding, came the need to study the concept of synergy and its application in architecture and its role in generating architectural form, as the research takes the concept of synergy in general and the algorithmic synergy specifically to create a group of vocabulary that connects algorithmic synergy and its mechanisms with the operations of generating architectural form. So, the following came into view:

- **The research problem is set in the following statement:** (The lack of clear knowledge of the algorithmic synergy and its mechanics in generating and discovering the architectural form digitally)
- **The research goal:** Clarifying the knowledge regarding the role of algorithmic synergy and its mechanisms in generating and discovering the architectural form digitally.
- **And the hypothesis is as follows:** The mechanisms of algorithmic synergy that is a result of the designer's realization of the tool's logic and behavior in the design process plays a big role in enabling the designer to generate, discover, and analyze contemporary forms.
- **The research follows the following methodology:** constructing the theoretical framework of the main conception of the research that is the algorithmic synergy and its connections in

architectural form generating mechanisms to conclude main vocabulary (variables) for practical application purposes, followed by conclusions and recommendations.

2. PART ONE: THE GENERAL THEORETICAL SHOWCASE

2.1 General look on the Synergy concept

2.1.1 The linguistic and idiomatic definition of the synergy concept

- According to Al-Moheet Dictionary: The word (Ta'Azar) (Arabic for Synergy) root is (Azara) (Synergized) means surrounding, and power, and synergy: Equality, adjacency, and cooperation, and synergizing: covering and empowering, and it is said; a synergetic victory meaning a very grand one **(Al-Fayrouzabadi, 2005).**
- Synergy or Synergism is a term taken from the Greek word Synergos meaning (to work together). It refers to the activity that two or more effects or separated elements that work together create a bigger effect than that predicted through knowing the separated effects of these singular elements on their own **(Berrett, 2007)**. Synergetics is defined as the science of static and dynamic group activities in multi-element closed and open systems with the existence of interactions between the system units **(Zhang, 1991)**. The synergy focuses on the self-organizing operations and the phenomena that lead to great changes in the types and functions of those systems that are a result of the cooperation of its subsystems **(Haken, 1979)**, where synergy takes steps towards overlapping and synthesizing the natural and human sciences **(Knyazeva, 1999)**.

According to the previous points, the synergy is a (method) focused on discovering and studying the connection resulted from the cross-pollination of two or more elements in a process where the whole (which is the result of the common cooperative effects and self-organizing ones between the connected parts that leading to forming unique and expressive structures) bigger than the singular effect of those parts.

2.2 Architecture and synergy

Architecture, in its wider definition and meaning, is the synergy of art and science **(Lankhorst, et al., 2017)**. The history of architecture interconnects with the history of mathematics, philosophy, and engineering on different levels, the designers used a set of concepts and terminologies from these fields to help them in their specific speeches **(Nawari and Kuenstle, 2015)**. Architect (Buckrninster Fuller) says that our language and concepts aren't enough to understand the world in all of its dimensions, and so, to imagine a harmonized future, new concepts and representations must be generating that will producing artifacts that have the ability to affect the human behavior and singular human habits **(Lama, et al., 2011)**, one of these concepts is the Synergetics, that is described as the arrangements that are cross beneficial for all parts and elements or a combined entity that has a value which is bigger than the sum of the parts **(Weingardt, 2006)**. And Fuller sees that the synergy is a whole system behavior that is unexpected and unpredictable just by knowing the behavior of the separate parts that form it, so it's a discovering strategy that starts with the whole **(Fuller, 1979)**. Architecture followed the generic sequential development of the trilogy (Form – Structure – and Material) **(Oxman & Oxman, 2010)** that work with each other in a way that cannot predict the whole behavior of this trilogy through analyzing any of them separately **(Weinstock, 2010)**. Today, contemporary architecture witnesses a move away from determined forms and plans in the ways of design, towards more complex scenarios. This means design problems that cannot be solved through a series of linear steps of logical thinking. This transformation requires developing new ways to design and process different fields collectively **(Kasimati and Panagoulia, 2013),** which is represented through the exchange of information, connections, and the capabilities of digital design, where the newly created software abilities have

been transforming design and finding form into the digital realm, where it's looked at the design and development process as a non-linear process that could be reformed and changed at any stage and in any direction **(Bentscheff and Gengnagel, 2010).**

In addition to structural synergy between architecture and structure, and the material synergy between architecture and material and under the use of the newly brought digital software, architecture is developing within the trilogy (Form – Structure – Material) in a non-linear way relying on a goal set by the designer or the nature of the project or other affecting elements that affect the design process. Form (is a verb, not a noun (**Werner, 2011**)) relates to the evolution of digital technology that relates to its generating and finding processes that was made for architecture by the concept of (Algorithmic Synergy) which the research discusses, and as shown below.

2.2.1 Algorithmic synergy

The design strategies are built from different tools and decisions that are based on the used technology and the designers' skills or architects. Added to that, the personal experiences and visual/cognitive perception and physical interactivity in space. And this means that these strategies come encoded with cognitive and physical data **(Werner, 2011)**. With the advancement of digital technology and the variety of human needs and functional requirement linked to multiple goals and targets, came the need of the existence of a relationship between the designer and the digital tool that enables them to find and discover different forms and simulate different phenomena in ways that differ from the ordinary ways. This paragraph clarifies the synergetic relation between the designer and the tool according to a synergetic approach based on a common language between them, which is the programming language or the algorithmic language.

First: The tool in architecture

Through the past few years, the hand drawing method was replaced with the computer aided design to help the designer form the creative processes that they wouldn't be able to invent without the help of these tools **(Sobejano, 2011)** which in turn evolved with the introduction of parametric features that enable Changes. The parametric tools started to put the spotlight on the logic of renewal or generating that through it, discovering complex forms became possible. The insertion of programming languages was for decades. Its popularity sparked lately in architecture, which raised interest in the computational approach in design, like the generative design. The generative design is defined by generating forms that are determined with algorithms, the insertion and use of programming languages lead to the development of the used algorithms as part of the design process to produce unique designs and achieving change in the design itself. The generative systems provide a synergy between the creativity and intuition of a designer and the computer abilities **(Fernandes, 2013)** which could lead to creating a connection between the professionals of different fields **(Knyazeva, 1999)**, and allows the interaction with the design solution space that could bypass the restrictions put on human and time (**Fernandes, 2013)**.

Second: Programming language (language or behavior of tool)

Many academic researches and advanced practices focused on the attempt to get rid of the restrictions forced by applications and software and discovering new ways to process this software from inside to find solutions and undiscovered forms through programming **(Tedeschi, 2014)**. It is considered a formal method to express ideas through three mechanisms: (Elements or primitive expressions, methods or mechanisms of combining and methods or mechanisms of abstraction) **(Abelson, et al., 1996)**. Programming provides a common world of conversation as a result of interactivity processes between designers and computers, and as a result, the abilities of humans

and machines is widened, programming languages that are used in the generative design process are divided into two types **(Champion and Chien, 2010),** as shown in **Fig.1**:

a) **Visual Programming Language – VPL:** Which allows describing the program in a two-dimensional representation, which is made of unique elements (Also called Iconic components **(Leitão and Proença, 2014)**).
b) **Textual Programming Language – TPL:** In which, the software is described using a linear order of letters **(Leitão, et al., 2012)**

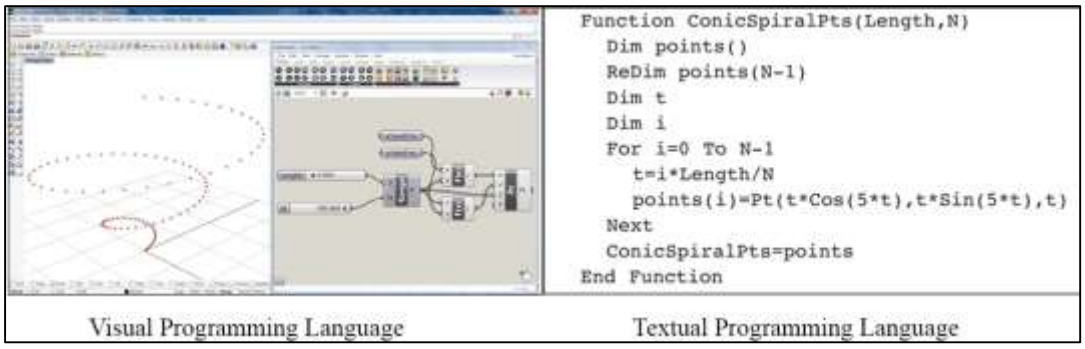


Figure 1. The programming language used by designers **(Leitão, et al., 2012)**.

The programming language enables the designer to know the behavior of the tool used in the design process and gives them the ability to translate their ideas and their different information into a digital language that can be understood by the tool to produce a unique synergetic dialogue that combines the behavior of the tool and behavior of the designer to compose an inventive Whole embodied in the final form in a synergetic digital environment.

Third: Digital (computational) synergetic design

The design process that makes use of the abilities of computing and computerization and works on combining the new digital technologies or emerged through the organized process of production based on interactivity between form and information is defined as the Computational Design **(Rossi and Buratti, 2018).** The computational design, by its branches and names such as (Generative design, bio morphogenetic, parametric design, and algorithmic design) was the stage that produced a revolution in the computer's role in the form-finding process, the computational design is all about using the power of algorithms in coding through computers to discover the ability to reiterate forms and solve problems unlimitedly, and do very complex geometrical math **(Fathi, et al., 2016).** By counting on two synergetic approaches: From one side, the computational design focuses especially on the tools of design and graphic representation which demands to build a new system with a computational nature that takes into account the design priorities, and on the side hand, computational design interprets design as a practice of horizontal interaction that works according to the basic components of the design itself **(Rossi and Buratti, 2018).**

The computational design term represents the synergetic mechanism that combines creativity and designer's thoughts and the computing ability that the tool (Computer) is used for in a digital environment to find the form and create as many alternatives as possible, through the designer's description of the variables of the design process using a number of elements specialized in computational design in specific digital representations that will be clarified later on.

a) Elements of synergetic computational Digital Design

In the context of digital thinking, the ways and tools of computational design can be explained through its relationship with a number of main elements that work on its organization and these are **(Rossi and Buratti, 2018)**:

- **Algorithms:** This type of modeling process depends on programming languages that are used to express a group of instructions in a certain shape that can be executed using a computer through a process of predetermined steps that is the algorithm **(Tedeschi, 2014)**. The algorithm includes a group of processes like inference, induction, abstraction, generalizing, and organized logic (**Terzidis**, **2004**). And through them, different geometrical forms are produced, and that can be done by writing these steps and translating them into the specific program language, and keeping in mind a group of qualities including:
  1. An algorithm is a group of correctly predetermined **instructions**.
  2. The algorithm depends on a group of clear and determined **inputs**.
  3. The algorithm generates **outputs** that are well defined **(Tedeschi, 2014).**
- **Parameters:** Parameters refer to a database that, through it, it's possible to edit a certain status of all elements or information that belongs to that state **(Rossi and Buratti, 2018).** and it may represent the values or rules or group of parameters that define the functional efficiency or even algorithms or any other part of the design **(Tedeschi, 2014)**, **(Alfaris, 2009).**
- **Objects:** Any system is usually made of objects or things that are part of or, physical or abstract variables inside the system **(Alfaris, 2009)**, in programming, objects are defined as abstract entities prepared to achieve something specific, and also it can be reused in many other applications of different contexts and environments **(Rossi and Buratti, 2018).**

b) Methods (a mechanism) of synergetic computational Digital Design

The form of mathematical design is represented by the type of programming language used in three methods on different abstract levels **(Celani and Vaz, 2012),** as follows:

- **Iconic representation:** On a more realistic way, parametric representations can be described as Iconic representations, for example, some programs like CAD software allows specified parametric relations between graphic entities visually in a direct way on the screen as in programs like MicroStation and later versions of AutoCAD **(Celani and Vaz, 2012).**
- **Analogue representation**: This one uses active Visual Programming Languages to discover forms through the generating in the representation process. Icons are used to represent and process entities in an indirect way through environments. It allows describing visual relations between entities without the need to write code or specific encode as in Generative Component's Symbolic Diagram and Grasshopper language (software), that represents node-based algorithmic editor. It represents singular components connected in different ways depending on a Visual Programming Language to create programs **(Melendez, 2019).**
- **Symbolic representation:** This uses text-based textual programming languages to represent architectural form using text and numbers to describe and execute operations on graphic entities, and the likes of this type are all scripting languages of CAD, Rhino Script, AutoLisp, VBA **(Celani and Vaz, 2012).**

As was previously noted, in mathematical design, in a synergetic way programming fields (Behavior of tool) and design (Designer's mind) are merged to define architecture, it can be stated that the methods or mechanics of architectural form representation; is done through either Analogue representation which utilizes Visual programming languages, or the Symbolic one which utilizes textual programming languages. Both of them depend on generative design to generate and discover architectural form using algorithms, parameters as well as objects according

to the vision of the designer taking into consideration that textual programming languages proved more freedom in dealing with the tools and enables the designer to develop and build his own tools depending on the nature of his information or need or according to a certain target or goal.

Fourth: Self-organized generative algorithmic synergy

The generative design is looked at as cooperation between human beings and computers **(Cogdell, 2018).** It's described as being a design methodology that depends on rules and algorithms to generate form. The algorithms and rules are usually derived from computational tools like processing programming language, Rhino, and Grasshopper and other scripting platforms in a repetitive process that depends on exchanging comments between the designer and the design system that is transformed through a computer into a series of outputs with the ability to edit it according to feedback. The Italian architect (Celestino Soddu) defines the generative design as a morphogenetic process done through organized algorithms as non-linear systems to produce unlimited results, unique and not repeatable like nature **(Agkathidis, 2015).**

Generative design ties strongly with the digital formation which is described as a self-organizing process as seen in the growth in living creatures that architects can benefit, be inspired, and learn from it **(Hensel, 2006)**,**(Agkathidis, 2015)** because it provides a diverse knowledge that helps designers finding architectural solutions through simulating life in nature **(Al-khafaji and Mahmoud, 2019).** Also, the developed methods of generative design in architecture use the idea of self-organization, which is also called self-arrangement, based on certain concepts such as (cellular automata - Fractal - agents and crowd theory (swarm intelligence) - evolutionary systems) that are through which the form is generated **(Petruševski, 2012)**. As **(Labelle, et al., 2010)** see that self-organizing processes, if analyzed could lead to an understanding of how forms are generated, in computers field, lately noticed an increase in scientists' interest regarding self-organizing systems, in an attempt to use these systems to create new methods of the problem solving **(Narahara, 2008)** where the textual parametric software's user interface allows the discovery of new qualities of a self-organizing process in the architectural context **(Labelle, et al., 2010)** where self-organizing behavior is done through what's called (Stigmergy - One of swarm intelligence phenomena in nature) which has an important feature where structure is formed through dialogue which depends on the density of available symbols and not on the variety of meaning **(Dron, 2007)**. Stigmergy is considered an important technology in behavioral formation because it provides a method to merge architectural forms in a generative process that depends on creating feedback between agents or digital software that creates them **(Snooke, 2014).**

The previous paragraph shows that Algorithmic Synergy shown in Fig. 2 is based on the communication between the designer and tool (computer) in an active interaction and self-organized dialogue where the programming language is the common language of interactivity which allows the designer to translate design information and simulate self-organizing natural phenomena to generate, evaluate, and develop different architectural forms.

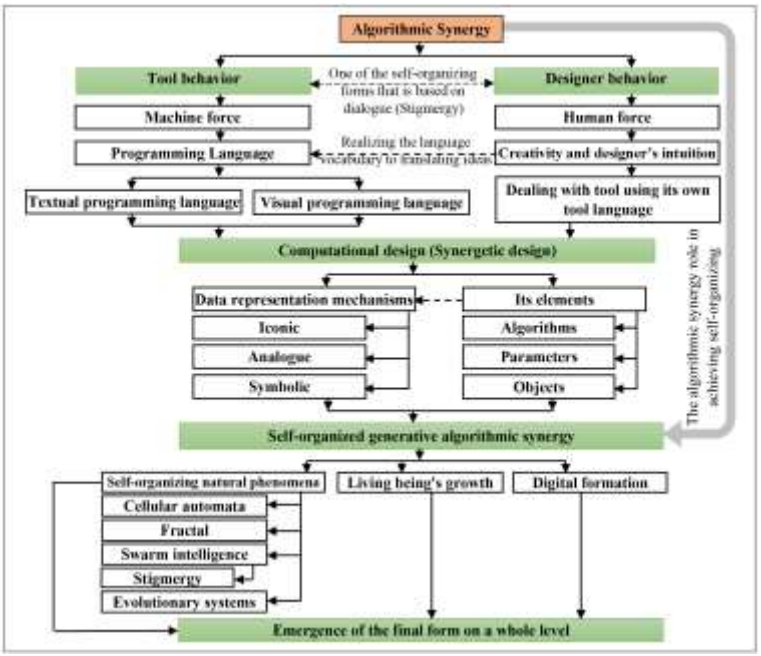


Figure 2. Algorithmic Synergy in Architecture / Source: Researchers.

2.2.2 Literature Review

Table 1. Literature Review / Source: Researchers.

a) Kostas Terzidis – 2006 (Algorithmic Architecture)	
Brief Description	This study described synergy as being a keyword used to refer to the process that could be achieved through the logic of mutual contributions: the human mind and the ability of the machine, by using algorithmic strategies within integrative, dialogical relation between the human mind and the machine **(PP. 27, 46)**. It includes a group of concepts like Variables – operations (Logical and mathematical) – Repetition - Fractions – Cellular Automation – and Hybridization **(PP. 67 to 97)**.
Study analysis	This study tries to reach the whole behavior that describes the design process as a result of an integral synergetic relation between the designer and the computer tool where the algorithmic language (Programming language) is used as a tool of communication between the designer and the digital tool in order to achieve the designer's or design's goals and targets that represented in architectural forms.
b) Kostas Terzidis – 2011 (Algorithmic Form)	
Brief Description	This study discussed the method or the way of using a computer for architecture within two main terms: Computerisation and computational thinking, and it seemed that the dominant method for using computers in architecture is computerization **(PP. 94)** which exposes the design process to the effects or (Whorfian) hypothesis **(p. 98)** that states that different languages allow transferring different types of messages **(Hunt & Agnoli, 1991)** and because the tool as described by the study itself, is used to describe the synergetic interaction between designers and computers, the study suggested an alternative which is the algorithmic design that is based on the computational thinking that makes the designer use a group of algorithmic operations like shape grammars, mathematical models, topological properties, genetic systems, mappings, and morphisms, to discover unfamiliar properties and form behaviors **(PP. 95, 100)**.
Study analysis	The study referred to the synergy concept in its description of the tools that are used as a method to describe the effects that are a result of synergetic interaction between the designers and the computers, where those effects represent the architectural output (form) that is reached through collective thinking and reciprocal relation between the designer and the tools and dealing with the tool using the language of the tool itself by prioritizing computational thinking over Computerisation because it depends on

	strategies or algorithmic operations that uses a mechanism to discover unknown areas of form behavior and expanding the boundaries of the human mind.
c) Christina Doumpioti – 2011 (Responsive and Autonomous Material Interface)	
Brief Description	This study indicated that the developments of the material are an opportunity to reconsider architecture as a part of its environment by taking into account the characteristics of the material based on interactions between the components of the material system itself and between the system and its environment. In this reaction self-organization of the material generates systems in which the components communicate with each other through proximity, bonding and geometrical configuration between the materials that lead to the emergence of various characteristics and properties **(P. 319)** that can be used as Inputs (parameters) in the design process to generates flexible and non-linear architectural systems and achieving the artificial self-systems where the form is generated as a part of a synergistic relationship between material thresholds and design goals **(P. 321).** In this process, the computational generating tools and associative modeling gain an integrated role in design by creating feedback between generation and analysis in search of coherent compositions within a multiple parameter range Uses **(P. 322)**.
Study analysis	The study mentioned the role of computational simulation of self-organized interactions and the various properties of the material in generating systems and architectural forms based on a synergistic relationship between the material and the design goals that generating in turn feedback between the generation and analysis processes in search of various and innovative forms that in turn achieve the desired aim or goal.
d) Yasha J. Grobman ،Eran Neuman and Aaron Sprecher – (2012 Performalism: form and performance in digital architecture)	
Brief Description	The study noted that the rise of computers and the generative operations and form-finding using computer languages depends on three dimensions of performance, these are an empirical dimension shown through physical data like the force, heat and the amount of light, and the cognitive dimension which is related to functions and logical operations and focuses on the method that is translated to a specific space and vice versa, and the perceptual dimension that relates to the concept of inactive emotional realization and focuses on the way that could be translated into space and vice versa **(Grobman, 2012)**. This information is considered as a condition for evaluating and checking the synergy between form and performance through three mechanisms. These are memorization that indicates the ability of architecture to include specific information regarding a subject or phenomena or an essence of something specific and adding the form over essence, and association: the interconnection between the cultural standard and political and community standards to search for perfect examples and finding forms, and connection: Architecture is an open-source, the products of architecture are no longer independent, it depends on different knowledge dimensions. The architectural formation that is imagined has a certain degree of performance that depends on the symbiotic relationship with other fields of different human activities **(Sprecher, 2012).**
Study analysis	The amount of information that is provided through interpreting functional needs of the design and other needs that have effects on the performance is what design can be used to evaluates and checks on the existence of synergy between form and performance (Function), because performance in this operation is a generative element of form by using computer language that The algorithmic synergy allows for the designer to work with it through three main –previously mentioned- notions of memorization, association and connection, they work on add something new to the knowledge and information and work on creating symbiotic relations between form and other human-based activities.
e) Esther Rivas Adrover – 2015 (Syntegration – A chapter from (Deployable structure))	
Brief Description	This study focuses on nature's role in achieving the synergetic integration with architecture because nature has been alive for billions of years and that helped develop many structural systems especially Deployable ones that could be learned from living systems like the growth of leaves or the beetle's wing opening that could be transferred to architecture through generative technologies **(P. 127-151)** that includes the principles of Deployable ones that is inspired by the art of Origami (Paper folding art) and other systems inspired by biological systems especially Biomimetics which forming in animals and plants, these principles are developed using generative technologies to make many structural systems **(P. 17)**.

Study analysis	In this study, architecture is connected each and every form of life on earth through using the term synergetic integration that is connected to different specialties and invested in simulating systems and life forms in nature using generative technologies considering it the first step in synergetic integration that the architecture could deal with to reach ideas and concepts embodies on forms with real meanings.
f) Nawari O. Nawari & Michael Kuenstle – 2015 (Building Information Modeling: Framework for Structural Design)	
Brief Description	In the context of synergy, the study proposed a new framework that represents synergy (SAS - Structure and Architecture Synergy) which provides a useful language for understanding the structure in relation to its close relationship to architecture, allowing the integration of structural decision-making at an early stage of the design thinking process**.** The framework in a collaborative work environment using building information modeling (BIM) tools combines the following vocabulary: structural melody which introduces a structural design language that clarifies the relationships between systems and details and aims to provide the basic vocabulary and grammar for expressing design ideas **(P. 5- 11-13).** And structural poetry aimed at learning from the natural growth process by designing self-assembling systems **(P. 23)**. The third stage, which includes structural analysis, which aims to analyze the structural elements of the generated model through a set of tools provided by modeling that relate to the balance of forces, reactions, shear force, bending moment and other concepts that enhance the stability of the structure **(P. 28).**
Study analysis	It is noted from the above that the study provided a framework or methodology based on the concept of synergy between architecture and structure through the interaction between structural concepts and architecture in three stages through which the elements of the structural system and the various relationships are employed in generating the final architectural form and by relying on the process of self-assembly of living cells in an environment Collaborative work provided by digital BIM technology.
g) Laurie Bouchard – 2016 (Arboreal Synergy: A philosophical Exploration of Biomimetic Architecture)	
Brief Description	This study turns an eye to simulating or mimicking nature to achieve ecological-technological synergy, which is the state that the relation between technological power and the natural life becomes comfortable for both rather than being as competing, it's more cooperative. It could be achieved through mimicking nature through three levels, on a bio-functional level, on form level, or on a material level which could make the best use of natural resources, this study focused on form-finding ("Frei Otto" architectural method) that depending on formation and self-organization processes that are available in the natural world and could help develop synergetic architecture in the future **(P. 2-15).**
Study analysis	This study deals with synergy as an approach that drives architecture towards using advanced technology that is represented by computational technologies to discover the form and generate it through simulation and nature mimicking process on the level of form and vital processes by simulating the processes of formation and self-organizing that exist in nature to generate cooperative structures that is synergetic on the technological-ecological level.
h) Arta Jakupi & Berat Istogu – 2017 (Modular Architecture as a Synergy of Chaos and Order: Case Study Prishtina	
Brief Description	As a solution to the problem addressed by the study regarding random construction of vernacular architecture, the study proposed applying the concept of modular architecture through synergy between two opposite sides: order and chaos as a strategy that can be used to respond to the needs of residents **(P. 71)**. Modular architecture, as covered by the study, has taken a synergy strategy to solve a specific problem by generating a compound form or a hybrid object according to a specific mathematical rule and a stable algorithm can be accessed from (order and chaos) that can provide through it the functional flexibility, population needs, and aesthetic demands while taking into account future expansion, cost and sustainability **(P. 79-80).**
Study analysis	The synergy in opposite sides such as order and chaos can create a wide range of solutions embodied in modular architecture and addressed by the study to solve the problem of random architecture due to its functional flexibility and aesthetic diversity in the units or parts that are collected in a specific compound according to a specific algorithm.

2.2.3 **Extracting theoretical framework vocabulary**

This paragraph is set to extract the most important vocabulary (Main and secondary) that are mentioned in previous knowledge that the study has discussed to form the theoretical part regarding the algorithmic synergy and form generation mechanics, as shown in **Table 2.**

Table 2. The Theoretical framework regarding algorithmic synergy and form generation mechanics/ source: researchers.

Main Vocabulary	Secondary Vocabulary	Indicators and Possible Values (Variables)	
Algorithmic Synergy Mechanisms	Coding (Digital Conversation)	Programming Language	
	Information Exchange		
	Collective Thinking		
	Mechanisms of expression and formation of concepts	Primitive Expressions	
		Collecting Mechanisms	
		Abstraction Mechanisms	
	Processing (Algorithmic Operations)	Deduction	Finding (Conclusion)
		Induction	
		Repetition	Repeating of program
			Repeating of forms
		Generalization	
		Operations	Mathematical
			Logical
		Hybridization	
		Shape grammar	
		Mappings	
		Morphism	
	Analogue computational representation	Acting in visual symbolic charts	
		node-based algorithmic editor	
		Visual Programming Language Grasshopper	
	Symbolic computational representation	Digital and textual representation of architectural form	
		Textual Programming Language (scripting)	
		Merging with visual programming languages	
		Processing written programs	Conditioning
			Specifying
			Reconfiguration
	memorization	Simulating a certain phenomenon	
		Adding form to the essence	
	association	Standards and values	Social
			Political
			Cultural

		(input parameters)	Restrictions and Conditions	
	Connection (multi-dimensional sources)	an empirical dimension	Physical Data	Force
				Heat
				Light
		Cognitive dimension	Translating functions and logical operations into spaces and vice versa	
		perceptual dimension	Translating emotional perception associated with the senses into space and vice versa.	
	Feedback			
	Structural analysis	Modeling tools based on a balance of forces and reactions	Shear forces	
			Bending forces	
	Combining order and chaos			
Self-organized generative algorithmic synergy	Simulation of self-organizing natural phenomena	Digital formation		
		living being's growth		
		Cellular automata		
		Fractal		
		Agents and crowd theory (swarm intelligence)	stigmergy	Self-organized dialogue between designer and tool
		Evolutionary systems		
	Simulation of self-organization of material in nature	Proximity		
		bonding		
		geometrical configuration		
Goals of using algorithmic synergy mechanisms to digitally generate the architectural form	Explore complex forms			
	Create constructive communication between specialists from different scientific disciplines			
	Explore new ways of processing programs from inside in order to find unexplored solutions and forms.			
	Unlimited repetition of forms, problem-solving and highly complex engineering calculations			
	Understand how forms are generated by studying self-organizing processes in an architectural context			
	Utilizing self-organizing systems to devise ways to solve problems			
	Promoting sustainability			
	Generate flexible, non-linear architectural systems			
	Design process integration			
	Merging the structural decision-making process at an early stage in the design thinking process			
	Providing functional flexibility, population needs and aesthetic demands, taking cost into account.			

3. PART TWO: A PRACTICAL STUDY

After discussing the knowledge regarding synergy concept in architecture in the first part of the study in general and algorithmic synergy and mechanisms of form generation especially, the second part of the study which is the practical study will apply the vocabulary of the theoretical framework on a group of selected project samples represented by:

- Multiple Natures – Fibrous Tower – 2011
- The King Abdullah Petroleum Studies and Research Center (KAPSARC) – 2017
- V&A docks Museum in Dundee – 2018

3.1 Criteria for selecting elected samples

1. The selected samples should include an achieving of the algorithmic synergy or the processes that connect to it.

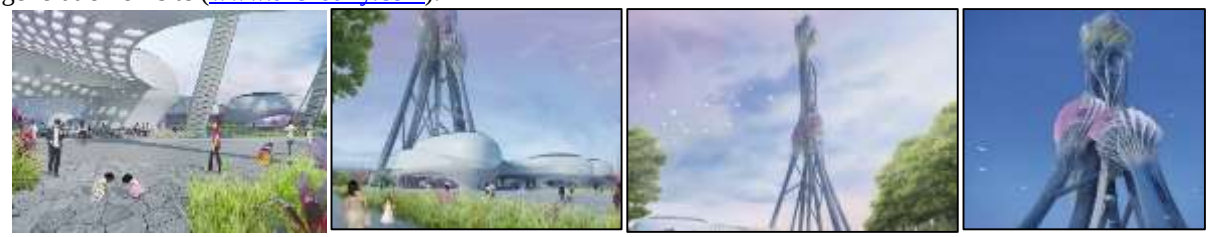
2. These samples should refer to the innovative product (different from the sum of the parts according to the synergistic logic), which can be distinguished according to the fact that the elected samples gained prizes in an international competition according to specific evaluations.
3. Using advanced digital technology (programming language) to find and generate the form.
4. The implicit referring to the integrated relationship provided by advanced digital technology, (programming language), between different engineering disciplines.

3.2 Description of elected samples

This paragraph includes giving a general description of the elected research samples according to a group of available information about these samples, and it's being used to verify and check the hypotheses of the research as shown below.

3.2.1 Multiple natures –fibrous tower - 2011

Table 3. The first sample measurement form / Source: Researchers.

Sample Code	Category	Location	Designer
A	Watchtower, Taichung city museum, park	Taichung, Taiwan	Soma Architecture
Defining Description			
This suggestion depends strongly on the architectural forms that learn from nature and uses the main principles of animal and plant structures (www.designboom.com). The design develops using the self-organizing system through swarm intelligence method which is a processing system that uses algorithms akin to natural biological processes and applied on digital examples (www.archdaily.com) where the structure and final form was generated using Crowding Gene Algorithms (Crowding GA) **(Schinegger, et al., 2012)** that works on organizing the building façade (www.designboom.com) while taking into consideration the wind weight taken from eight different directions and the final direction of evaluation is the worst direction. The generative process is done through applying a special variable that plans the population group into another: Where a married couple of people are selected and transformed and intersect leading to the production of two children, then defining each child efficiency would be compared to the original child if the child shows a better result and efficiency it will be elected to be part of the next generative process. Otherwise, the original child would be selected, and the final tower structure is chosen like that, which represents the synergetic merge of ideas and building after calculating and comparing more than 2,500,000 alternative solutions **(Schinegger, et al., 2012)**. The tower is designed as a zero-carbon building and also is designed to operate as a self-contained system and provides 100% of its energy from renewable energy generation on-site (www.archdaily.com).			
			

3.2.2 The King Abdullah Petroleum Studies and Research Center (KAPSARC) – 2017

Table 4. The second sample measurement form/ Source: Researchers.

Sample Code	Category	Location	Designer
B	Petroleum Studies and Research Center	Riyadh, Saudi Arabia	Zaha Hadid Architects&Arup
Defining Description			

One of the newly completed buildings, which consists of multiple buildings, the main one includes the Research Center, which is the largest one, the library, the information technology center, and a prayer hall. Each building consists of a group of irregular hexagonal cells, Each cell contains an irregular polygon court or a closed central foyer with a Polygonal roof opening **(Eilouti, 2019)**, These cells were generated through a rhombus based grid that was processed in various ways using analogy and metaphor for the design development and derived from the concept of a living cell or energy which It is represented as a leaf cell, a petrol molecule, honeycomb unit, and water molecule, as it also appears that it is inspired by sand crystals that symbolize the desert and the charcoal pieces that symbolize the origin of petroleum, these concepts were digitally represented as a hexagonal parametric cell that is repeated and regulated based on the concept of a primitive cell that is repeated to form living organisms that generates in turn a mix of modular and random units in the interface design and outdoor spaces (Landscape) **(Eilouti, 2018), (Eilouti, 2019)**. The KAPSARC represents the combination of deconstruction architecture and fractal engineering based on nature to generate a system that appears to be random from the surface but hides beneath it a well-organized structure. Also in order to enhance the local culture, a number of Islamic ornamations were reproduced in an abstract and contemporary way **(Eilouti, 2018)**. The custom parametric scripting tools also helped to design an integrated work path between the different specializations that allowed the transformation of those surfaces into rational engineering forms of steel that can be manufactured and installed and it is more clearly and more cost-effective. Also These tools helped in ensuring optimal structural performance and helped in the creation of the 3D BIM model for structural analysis (www.arup.com). Also, the construction, lighting, natural ventilation, intelligent control and interactive systems also reflect The Continuous reaction between the natural cells of living organisms and their environment **(Eilouti, 2018)** , as (Zaha Hadid) proposed an approach to achieving sustainability not only with the technology used in the building envelope but also through comprehensive thinking in form as well **(Kang, 2015)**, KAPSARC was awarded LEED Platinum certified by the American Green Building Council and was chosen as the best building in the Kingdom in the Honeywell Smart Building Awards program based on criteria that include sustainability, safety and productivity (www.archdaily.com).

3.2.3 V&A docks Museum in Dundee – 2018

Table 5. The Third sample measurement form/ source: Researchers.

Sample Code	Category	Location	Designer
C	**Museum**	**Dundee, Scotland**	**Kengo Kuma Associates & ARUP**
Defining Description			
In 2010 an international competition was announced to introduce a new building for V&A Dundee. The challenge facing architects was to suggest an inspiring home for the first design museum in Scotland - a waterfront building that would reconnect Dundee with the Tay River and its maritime history. Of the 120 architectural ideas presented, six were chosen in the shortlist, which ended with the selection of the concept submitted by Kengo Kuma and Associates according to thousands of questionnaires and comments submitted by members of the public (www. Architectmagazine.com). The goal of the architect in the design of the building was to capture the essence of the cliffs around the rugged Scottish coast, as it seems, according to him, as if the land and water had a long conversation and finally created this amazing form that looks like the front of the ship in a dynamic model that grows upward which was generated according to Parametric approach through algorithms that are written			

specifically for the purposes of splitting and meshing so that the structural model can be generated within hours instead of weeks. The 3D model also showed the response of the generated form to the forces and stresses with the ability to modify it skillfully while keeping the original idea by analyzing a set of models generated until reaching the optimum design **(Butler, et al., 2019)** which is two Inverted pyramids separate on the ground floor and then twist to connect in the upper floor of the galleries which leads to the presence of an open corridor in the center of the museum that reconnected the city to the river and works to simulate the royal memorial arch that was built nearby in 1844. Also the generated form was covered by dramatic lines from Precast concrete that creating in turn patterns of shadows which change in different times of day (www.architectmagazine.com). In order to enhance sustainability and through tests made using computational modeling it was found that the most suitable form of renewable energy for the building is geothermal energy through wells and heat pumps operating below the outer plaza and around the building, and in addition to natural ventilation and the high level of control systems the building obtained a BREEAM rating Excellent for the effectiveness of his energy strategy **(Butler, et al., 2019)**.

3.3 Applying and Measuring Variables Using Analytic Descriptive Method

This paragraph discusses the descriptive measurement where the research adopted the qualitative scale based on the descriptive analytical approach to test the amount of verification for each vocabulary or variable by referring to it in the table and giving it value (0) for not achieving that variable and value (1) for achieving it. This method aims to know how involved the mechanisms of algorithmic synergy vocabulary and their role in generating and discovering a digital form in the overall design process. This measurement process is carried out in a frequency table that includes the vocabulary under test and elected samples, repetition values, and the percentage of each vocabulary in a sample using (Excel 2016) software, as shown below.

Table 6. Applying and measuring variables using analytic descriptive method / Source: Researchers.

Main Vocabulary	Secondary Vocabulary	Indicators and Possible Values (Variables)	Samples of elected projects			number of times a Vocabulary is repeated	Vocabulary verification ratio in samples		Vocabulary Coding
			A	B	C		Possible values	Secondary Vocabulary values	
Algorithmic	Coding (Digital Conversation)	Programming Language	1	1	1	3	100%	100%	X1
	Information Exchange		1	1	1	3	100%	100%	X2

	Collective Thinking			1	1	1	3	100%	100%	X3
	Mechanisms of expression and formation of concepts	Primitive Expressions		1	1	1	3	100%	100%	X4
		Collecting Mechanisms		1	1	1	3	100%		
		Abstraction Mechanisms		1	1	1	3	100%		
	Processing (Algorithmic Operations)	Deduction / Induction	Finding (Conclusion)	1	1	1	3	100%	56.66%	X5
		Repetition	Repeating of program	1	1	0	2	66.66%		
			Repeating of forms	1	1	1	3	100%		
		Generalization		0	0	0	0	0%		
		Operations	Mathematical	1	1	1	3	100%		
			Logical	1	1	1	3	100%		
		Hybridization		0	0	0	0	0%		
		Shape grammar		0	0	0	0	0%		
		Mappings		0	0	0	0	0%		
		Morphism		1	1	1	3	100%		
	Analogue computational representation	Acting in visual symbolic charts		0	0	0	0	0%	0%	X6
		node-based algorithmic editor		0	0	0	0	0%		
		Visual Programming Language Grasshopper		0	0	0	0	0%		
	Symbolic computational representation	Digital and textual representation of architectural form		1	1	1	3	100%	66.66%	X7
		Textual Programming Language (scripting)		1	1	1	3	100%		
		Merging with visual programming languages		0	0	0	0	0%		
		Processing written programs	Conditioning	1	1	0	2	66.66%		
			Specifying	1	1	0	2	66.66%		
			Reconfiguration	1	1	0	2	66.66%		
	memorization	Simulating a certain phenomenon		1	1	1	3	100%	100%	X8
		Adding form to the essence		1	1	1	3	100%		
	association	Standards and values (input parameters)	Social	1	1	1	3	100%	75%	X9
			Political	0	0	0	0	0%		
			Cultural	1	1	1	3	100%		
			Restrictions and Conditions	1	1	1	3	100%		
	Connection (multi-dimensional sources)	an empirical dimension	Physical Data: Force	1	1	1	3	100%	33.33%	X10
			Physical Data: Heat	0	0	0	0	0%		
			Physical Data: Light	0	1	0	1	33.33%		
		Cognitive dimension	Translating functions and logical operations into spaces and vice versa	0	0	0	0	0%		
		perceptual dimension	Translating emotional perception associated with the senses into space and vice versa.	0	0	0	0	0%		
	Feedback			1	1	1	3	100%	100%	X11
	Structural analysis	Modeling tools based on a balance of	Shear forces	1	1	1	3	100%	100%	X12
			Bending forces	1	1	1	3	100%		

		forces and reactions								
	Combining order and chaos			0	1	0	1	33.33%	33.33%	X13
	main vocabulary verification ratios in each sample			67.5%	70%	55%				
Self-organized generative algorithmic synergy (Y)	Simulation of self-organizing natural phenomena	Digital formation		1	1	1	3	100%	55.55%	Y1
		living being's growth		1	1	0	2	66.66%		
		Cellular automata		0	0	0	0	0%		
		Fractal		0	1	0	1	33.33%		
		Agents and crowd theory (swarm intelligence)	Stigmergy	Self-organized dialogue between designer and tool	1	1	1	3	100%	
		Evolutionary systems			1	0	0	1	33.33%	
	Simulation of self-organization of material in nature	Proximity			0	0	0	0	0%	0%	Y2
		bonding			0	0	0	0	0%		
		geometrical configuration			0	0	0	0	0%		
	main vocabulary verification ratios in each sample				44.4%	44.4%	22.22%			
Goals of using algorithmic synergy mechanisms to digitally generate the architectural form (Z)	Explore complex forms				1	1	1	3	100%	100%	Z1
	Create constructive communication between specialists from different scientific disciplines				1	1	1	3	100%	100%	Z2
	Explore new ways of processing programs from inside in order to find unexplored solutions and forms.				1	1	1	3	100%	100%	Z3
	Unlimited repetition of forms, problem-solving and highly complex engineering calculations				1	1	1	3	100%	100%	Z4
	Understand how forms are generated by studying self-organizing processes in an architectural context				1	1	0	2	66.66%	66.66%	Z5
	Utilizing self-organizing systems to devise ways to solve problems				1	1	0	2	66.66%	66.66%	Z6
	Promoting sustainability				1	1	1	3	100%	100%	Z7
	Generate flexible, non-linear architectural systems				1	1	1	3	100%	100%	Z8
	design process integration				1	1	1	3	100%	100%	Z9
	merging the structural decision-making process at an early stage in the design thinking process				1	1	1	3	100%	100%	Z10
	Providing functional flexibility, population needs and aesthetic demands, taking cost into account.				1	1	1	3	100%	100%	Z11
	main vocabulary verification ratios in each sample				100%	100%	81.81%			

3.4 Analyzing Results

The application side results, as shown in **Fig. 3** has shown the following:

- The selected samples have been used **algorithmic synergy mechanisms (X)** for the purpose of generation and discovering architectural form, as these samples adopted a set of mechanisms that showed the results of the application using them in varying ratio that depended in the first

place on the digital conversation (Coding) using a programming language and information exchange, and collective thinking that combines the designer and tool in order to express and form thoughts using a symbolic computational representation of data that combines different algorithmic processes that connects the standards, values, as well as simulating multi-dimensional sources with the ability to edit the form continuously using feedback.

- The selected samples have invested algorithmic synergy mechanisms in simulating natural self-organizing phenomena by means of **Self-organized generative algorithmic synergy (Y)** based on a simulation of the self-organizing processes of living systems in a self-organized dialogue (stigmagery) between designer and the digital tool.
- The use of the selected samples for the algorithmic synergy and its mechanisms in the purpose generating and exploring the architectural form involves a set of designer-specific goals that have been addressed by the **Goals of using algorithmic synergy mechanisms to digitally generate the architectural form (Z)** ranged from exploring new ways to solve problems facing the designer to meet the desires and needs and taking into account aesthetic aspects and creating constructive communication between different engineering disciplines in order to explore complex architectural forms and work to enhance sustainability and energy saving.

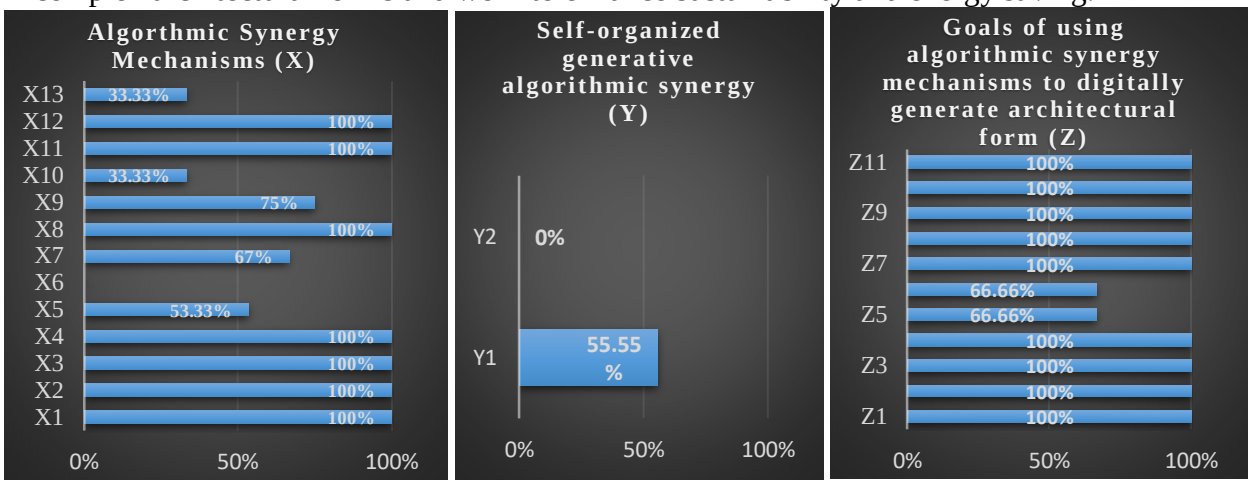


Figure 3. Results of the practical application of the main and secondary of the theoretical framework vocabulary terms on the selected projects samples/source: researchers.

The results have shown that the following hypothesis is correct: (The mechanisms of algorithmic synergy that is a result of the designer's realization of the tool's logic and behavior in the design process plays a big role in enabling the designer to generate, discover, and analyze contemporary forms.) based on different methods and expression mechanisms that have been adequately addressed by the vocabulary of the theoretical framework.

4. CONCLUSIONS

The constructing of the knowledge and theoretical framework and doing the practical study on a group of elected project samples lead the study to a group of conclusions that all focus on using the mechanisms of algorithmic synergy in generating and discovering architectural form as follows:

4.1 General conclusions of the study

1. The synergy represents an approach based on studying and analyzing cooperation behavior (Or interactivity) of elements or units within complex systems and self-organizing systems both natural and man-made, which leads to evolutionary changes regarding forming and emerging structures and types that represent the bigger whole than the sum of these units and elements when behaving separately, because it represents the sum of these behaviors in addition to the behavior and specifications earned as a result of interacting synergistically.
2. In algorithmic synergy, the designer and tool represent a self-organizing (stigmergy) system of architecture that allows it to develop in a non-linear elastic way within the trilogy (Form-structure, and material) to generate and discover form as a response to a specific need or a target**.**
3. The algorithmic synergy makes the tool a partner in discovering design because it represents a cooperative behavior that combines the behavior of the designer and the behavior of the digital tool which is represented in programming languages of both types (visual and textual) in a design process that the designer gets rid of the restrictions put on by some tools and pre-made programs and moves into dealing with forms in a direct way by writing steps and designing their own tools to design different forms and within the knowledge available, using three steps (Input, algorithmic process (operations), output) .
4. The algorithmic synergy in general and Self-organized generative algorithmic synergy, in particular, brings new methods undiscovered that connects architecture with nature through simulating the self-organizing synergetic phenomena and on different levels that cannot be realized using traditional tools, it offers the feature of simulating the algorithm of generative and formation or self-generation processes that happen in nature and work on understanding and analyzing internal mechanisms of the behavior of these systems that represent a source for generating architectural form.
5. Algorithmic synergy offers an alternative to the metaphor of a form through the idea of digital metaphor which means simulate of algorithms of software and algorithms of sciences and other knowledge fields instead of forms to become a method to generate a wide range of forms that makes the designer in front of unlimited discoveries of unlimited solutions.
6. In algorithmic synergy, the designer is moved from editing forms directly to editing text indirectly, where the architectural processing, varied elements, and material are all textual data that has been coded by a programming language that has been predetermined and can be edit at any time.

4.2 Practical study conclusions

1. Adopting the digital conversation between the designer and the tool to code inputs of elected projects through the computational coding used by the textual programming language that is the method the designer expresses and translates his ideas, this mechanism provided the possibility to algorithmic simulation for physical data that is connected within the trilogy of (Form – Structure – Material) that in its own became the design input of the integral synergetic design process, these inputs may be structural data, material data, or simulating a specific

phenomenon, or an idea, or rules and regulation, etc.. that the designer works on coding using the scripting language to generate an architectural form.

2. The algorithmic translation of digital formation of living beings and self-organization of material in nature became the main resource of the Self-organized generative algorithmic synergy that works on simulating self-organizing process steps that are used by these phenomena to generate and discover forms through one of the self-organizing methods based on dialogue (Digital dialogue) done between the designer and tool named (Stigmergy) and leading to dynamic generation of structures and forms that depend on generation dense signals (or symbols) provided by designer and used in the digital design programs could be read from the tool.
3. Symbolic computational representation gives the designer the ability to write and process other working programs (algorithms) from previous projects or from other fields of science and knowledge through conditioning the programs taken with the nature of the project and its requirements, and specifying it to solve the problems then reforming it (digitally representing it) to fit the requirements and generate the architectural form.

5. RECOMMENDATIONS

1. Guiding the designer towards learning and using a programming language (tool behavior) gradually through learning the terms and vocabulary of the language (using Python programming language) then moving on to digital platforms that support visual programming (using Grasshopper language) then scripting by using Algorithmic Synergy Mechanisms as the main mechanism to generate and discover forms and work on designing algorithms specified for the problems.
2. The natural phenomena that describe the self-organizing systems earned importance because of its ability to condition itself to face the changes and respond to specific needs, so the research recommends focusing on algorithmic simulation of natural self-organization phenomena in discovering different forms and work on studying and analyzing the synergetic behavior of those phenomena and systems and modify them according to needs.
3. Towards an ecologically synergetic architecture, the study recommends using algorithmic synergy mechanisms to code the environmental variables as inputs of the design process to generate and discover sustainable structures.
4. Applying the mechanisms of algorithmic synergy and related concepts in generating and exploring the architectural form based on simulating criteria and values related to local architecture in a contemporary way.

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