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Structural Design According to Constructal Theory in Architecture

Aseel Abdulhaleem Latif[1] and Bahjat Rashad Shahin[1]

[1]Department of Architecture Engineering, College of Engineering, University of Baghdad, Iraq

Corresponding Email: aseel.latif@coeng.uobaghdad.edu.iq

Abstract. Constructal theory plays a major role in the conceptual design stage of the structural system in architecture. It provides a conceptual framework for predicting the form depending on natural systems to model those systems geometrically according to the constructal law that works in two directions: the first is towards predicting the general form of the structural system, and the second is the physical application of the law in the process of detailed design of the parts of the system. The aim of this paper is to determine the mechanism adopted in the structural design according to the constructal theory, assuming that the structural design according to the constructal theory achieves high structural efficiency. The paper depends in its theoretical framework on the clarification of the concepts of constructal theory, the mechanism of constructal law work, and then the verification of its compliance with the applicable rules to achieve high efficiency. The paper concludes a set of indicators that can be adopted in assessing the level of structural efficiency - at the level of form and material - of architecturally designed structures according to the constructal theory. The research concluded that constructal theory contributes significantly to research on the origins of living systems, and to employ them in the process of creating the architectural form on one hand, and enhancing the structural efficiency of the structural performance on the other hand.

Keywords: Constructal theory, Structural design, structural efficiency, Architectural form, material.

1. Introduction
Constructal theory provides a conceptual framework for predicting the form according to an evolutionary process concerned with form and aims at modelling natural or engineering systems. It depends mainly on generating the structure of the form on the principle of flow - the flow of energy or forces - according to the adopted system [1], and through a hierarchy that starts with the smallest structural mass and continues towards the largest mass by a process called "Constructs" (see figure 1). The form of the system and the structure of the internal flow are the result of continuous design processes and attempts in order to reach the best performance of the system.

2. Constructal theory
The theory relies on building its intellectual framework on natural systems, which present a tremendous variety in terms of forms. It is far from the idealism resulting from the geometric symmetry that we may see in some geometric shapes, such as the sphere that has the highest geometric symmetry possible. This restricts the process of flow within the system and thus the collapse of the system, while living systems have the advantage of being kinetic systems far from the concept of static equilibrium resulting from physical and geometric symmetry.[2]

The parts or components that make up the system, and the method of linking the parts ensures that the linear and angular momentum of all the forces generated is preserved, and then the continuation of the flow paths starting from the smaller structural parts to the larger parts. Working at the same time to reduce and balance the forces encountered, by all internal and external currents in light of the existing restrictions on the whole system. [3].

3. Constructal law
The constructal law of structural theory states that: if a system has the freedom to evolve and transform, it develops a flow structure in time to ensure easier access methods for the currents flowing through it. Adrian Bejan stated the law as follows: *"For a finite-size flow system to persist in time (to live) its configuration must change in time so that it provides greater and greater access to its currents"* [3].
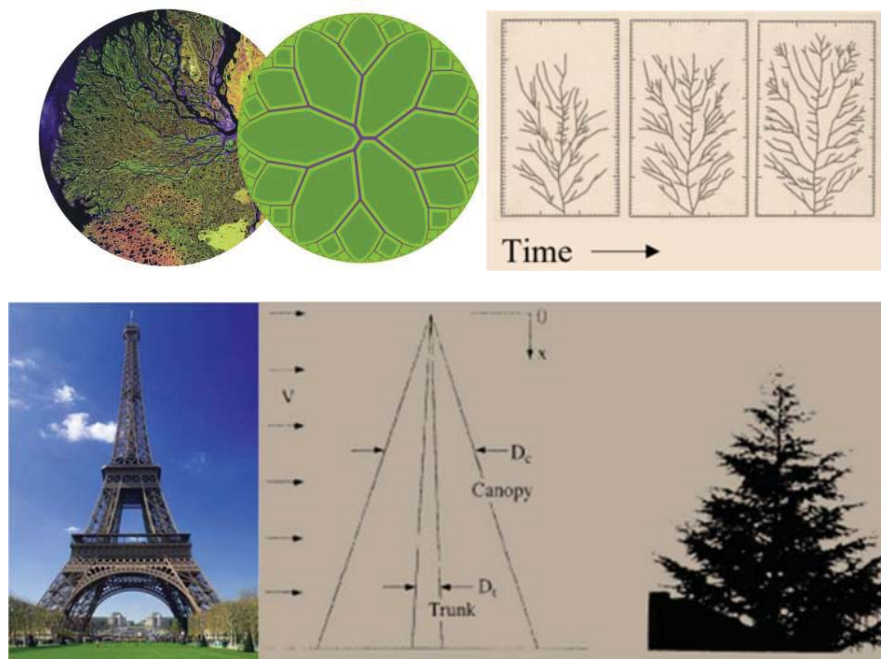

Figure 1. The process of creating a tree-shaped structure progresses from small to larger parts. Through a hierarchy that begins with the smallest building block, and continues towards the largest mass, a process called "Constructs" according to a wide range of variation in scale and shape [4].

The structural law explains how the form, structure, and geometry of a flow are generated. Its field of application aims to dissipate the flow processes to overcome the resistance generated by the effects of the forces exerting on the system, and then generate a level of anthropic and thermodynamics away from the concepts of equilibrium based on symmetry. In 1997, Adrian Bejan, when developing his theory, used physical intuition and mathematical thinking to derive "optimal paths" for the transfer of matter and energy between source and recipient, and based on Hess-Murray's law. He considered it as a basic model for Constructal Law.

The constructal law is used in two directions: the first direction is to predict and explain the occurrence of natural, rigid and dynamic flow formations, and the second direction is to apply the law as a physical principle in engineering design in order to obtain highly efficient design, starting from the small scale - micro and Nano scales– " The miniaturization revolution" for making tiny components that are invested in the process of form-finding.

In general, it can be said that the constructal law sets the rules of optimal structure and these rules are derived within different levels and scales, such as the tree structure, that increases in complexity with

the increase in its size and complexity. These multi-scale architectures based on the principle of generation depended on diversity in scale and shape [5].

According to the above-mentioned, a set of basic vocabulary on which structural theory is based can be summarized, as follows:

- The adoption of physical intuition based on natural systems and mathematical thinking -in terms of application- in accordance with the constructal law.
- Achieving balance for the whole system depends on the concepts of thermodynamics and anthropic, far from the balance based on symmetry.
- Adopting the form that ensures the continuous flow of forces and maintaining flow paths, starting from small structural parts to larger parts, and within different levels commensurate with the size of the system.

4. Applications of Constructal theory in structural systems

The structural systems known as "branching structure systems", or "umbel structures", are the most prominent examples that correspond to the general indications of Constructal theory. They are built according to the Constructal law of the theory, where the process of creating a branch form structure develops from small parts to the biggest.

The model depends on the branches of the internal nodes and the nodes (Bifurcations), and the branch is physically defined by its length (L), its diameter (D), the starting point (S) and the direction (I). The location of the nodes is governed by the angles between the axes of the parent branch and the sub branches (i = 1,2), where the angles play a large role in directing the flow paths within the system as well as the length ratios of those branches (Li / L0).

The proportions of the diameters between the parent branch and the smaller branch (Di / D0) is calculated according to Hess-Murray's law. With the increase in the secondary branches, the adopted directions change as well as the dimensions for both length and diameter - according to physical laws to ensure a better flow of forces - and defined by an angle that ensures the lowest permissible range of torsional forces. The direction of the branch is a function of the direction of the original branch (Ji), the angle of the nodes, and the angle of the bifurcation (qi) (see figure 2) [6].

The branching system displays a repetitive hierarchical organization, in which the parts are geometrically similar to the whole. It shows the self-similarity characteristic, which is a distinctive feature of fractal systems that show remarkable agreement with Constructal theory. Throughout the history of architecture, a variety of models are inspired by nature - and in which concepts of fractional engineering appear in their structural appearance - such as trees, cells, crystals, etc.

At present, contemporary computer technology has provided diverse possibilities for practicing a procedural generative approach based on mathematical relationships between variables in the modelling process.
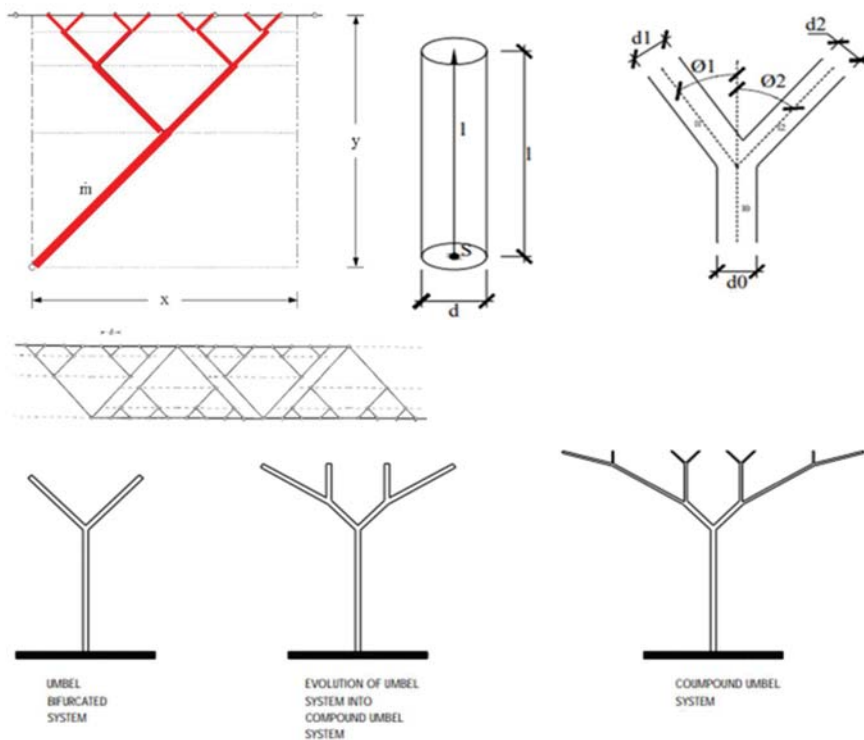
Figure 2. The branching structure systems depends on the branches of the internal nodes and the nodes (Bifurcations). [6].

It is possible to summarize the most prominent rules followed to reach such lightweight structures [6], which show a clear agreement with the basic vocabulary on which the constructal theory is based, and these rules are as follows:

- Avoiding bending stresses and rotational moments, and adopting minimum limits for them. According to the structural theory, this is achieved by maintaining short branch lengths relative to their diameter on one hand, and on the other hand adopting a certain range of angles between the primary branch and the secondary branch. That ensures an easy flow of currents - energy and forces - within the elements of the system.
- Adopting the shortest distances in the distribution and transmission of the impacted loads, controlling the pressure forces generated to achieve the required stability.
- Containing and integrating the compressive forces over long distances at the main support points by adopting self-stabilizing systems, for example pre-stressing systems.
- Adopting the structural elements with appropriate shapes to contain the compressive forces generated by the impacted loads, and ensure the required stability.
- Adopting short-circuiting of forces within the structural system can result in lightweight structures, allowing the use of simple foundations for construction.

5. Structural design and efficiency

The conceptual or planning design concepts dominate the structural efficiency assessment, which is the most important aspect of the entire design process to produce an efficient structure. Where the main task is to define the load paths in the structure -vertical loads in addition to the horizontal loads- to reach logical load paths and thereby achieving structural efficiency [7].

Structural performance is related to the concepts of balance, stability and strength at the initial design and implementation stage (ultimate limit state - ULS), and criteria for deflection and oscillation induced by wind and vibrations at the occupancy stage of the structure (serviceability limit state - SLS) [8]. As

well as the material cost which accounts for 60-70% of the total construction cost in some developing countries, and 25-30% in some developed countries. The amount of material consumption is an important indicator of the economy or material cost [9]. In this context, structures that achieve the required structural performance with less material consumption are more efficient.

In the context of the importance of having sufficient strength and rigidity for a structure, structural efficiency is defined as the ratio of the structural rigidity to the amount of material consumption [9], It is considered one of the basic criteria adopted in the evaluation of the structural system. It is measured based on the weight of the materials that must be provided to bear a certain amount of impacted loads.

$$Element\ Efficiency = Strength\ /\ Weight\quad [10]$$

The level of efficiency is governed by two factors: the type and the size of the internal forces produced when a certain load is impact, according to the form and the amount of materials that must be available to give the elements sufficient strength and rigidity. The shapes of the structural elements -especially the shapes of their longitudinal axes in relation to the pattern of the impacted load- determine the types of internal forces that occur within them and affect the size of these forces [10]. Recent developments in digital technology have led to a remarkable evolution in structural design, by moving from traditional manual calculations to design with the help of advanced computer programs.

Accordingly, the concepts of structural efficiency are related to a set of standards that can be adopted as indicators to assess the level of structural efficiency of the building, as shown in table 1.

Table 1. Standards and indicators adopted in evaluating the level of structural efficiency of the building

Indicators of assessing the level of structural efficiency of the building.	In terms of Form: the adopted form governs the type and size of the internal forces generated	Path of forces	Ensuring direct paths to the internal forces generated within the parts of the system.
		Type of forces	Ensuring the smallest internal forces within the structural elements.
		Distribution of forces	Ensuring a uniform distribution of forces within the parts of the system.
	In terms of the Material	Quantity of material	Adopting the lowest material consumption.
		Weight of material	Inversely proportional to the structural efficiency.

6. The Case studies

The research relied on the applied side on the analytical descriptive methodology for two selected case studies, according to the indicators that the research came out with to assess structural efficiency of the building, in order to verify the hypothesis of the research (see table 2).

The case studies are based on clear criteria that have been extracted from the content of the research to achieve its objectives, which are:
- The structural system used is consistent with the concepts of Constructal theory.
- The case studies emphasize one or more of the indicators covered by the research.
- They have distinctive intellectual, and formal characteristics.

The first case study: Stuttgart airport building, designed by Gerkan, Hamburg, Mag, and Partners in 1991. The designer used tree-like support structures to support the roof, which is divided into twelve sections.

Each area is supported by steel structures resembling trees. These columns collect the impedance loads that pass through the branches to travel through the stem to the foundation. Each pillar contains four connected tube columns -forming the trunk of the tree- and spreads across three different levels. They

are distributed in a manner that ensures the transfer of loads with the availability of minimum bending forces by controlling the dimensions and angles of those branches. (see figure 3).
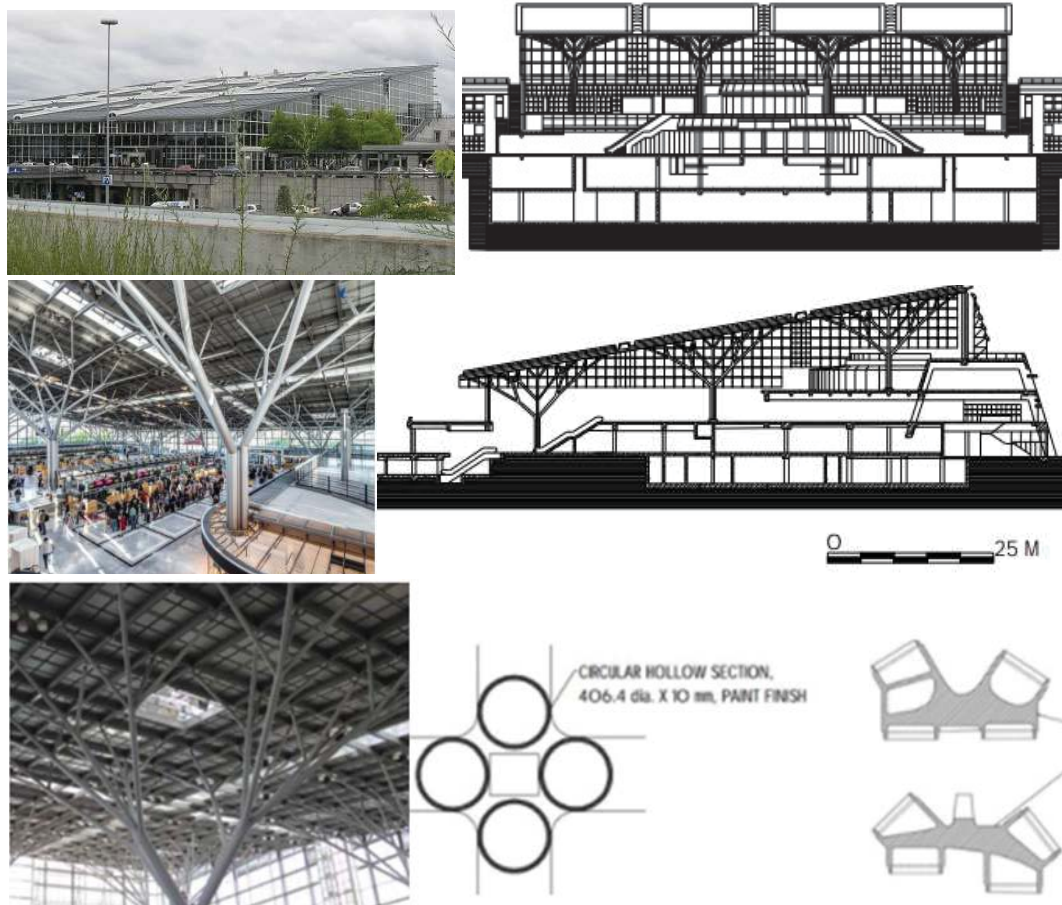

Figure 3. The Stuttgart Airport building, designed by Gerkan, Hamburg, Mag, and Partners in 1991, in Germany. Among the most prominent examples of "Umbel structures", or what are called "branching structure systems", depending on the tree model in their design.

The second case study: Performing arts centre in Abu Dhabi, designed by Zaha Hadid in 2007, (see figure 4). The structure of the building is inspired by the natural systems - the branches of the blood vessels - with the adoption of analytical studies to model the system and give it a hybrid general shape that mixes between the natural side and the physical mathematical side. The flow paths within the structure of the building's structural system are directed in a hierarchy from the part to the whole.

The form is divided to main paths that transfer loads to the main support points. The grid distribution of these paths appears in several levels and according to different measures, that ensure a homogeneous distribution of forces within the paths. As well as providing relatively short paths compared to the size of the system, to avoid the generation of bending forces within the elements.
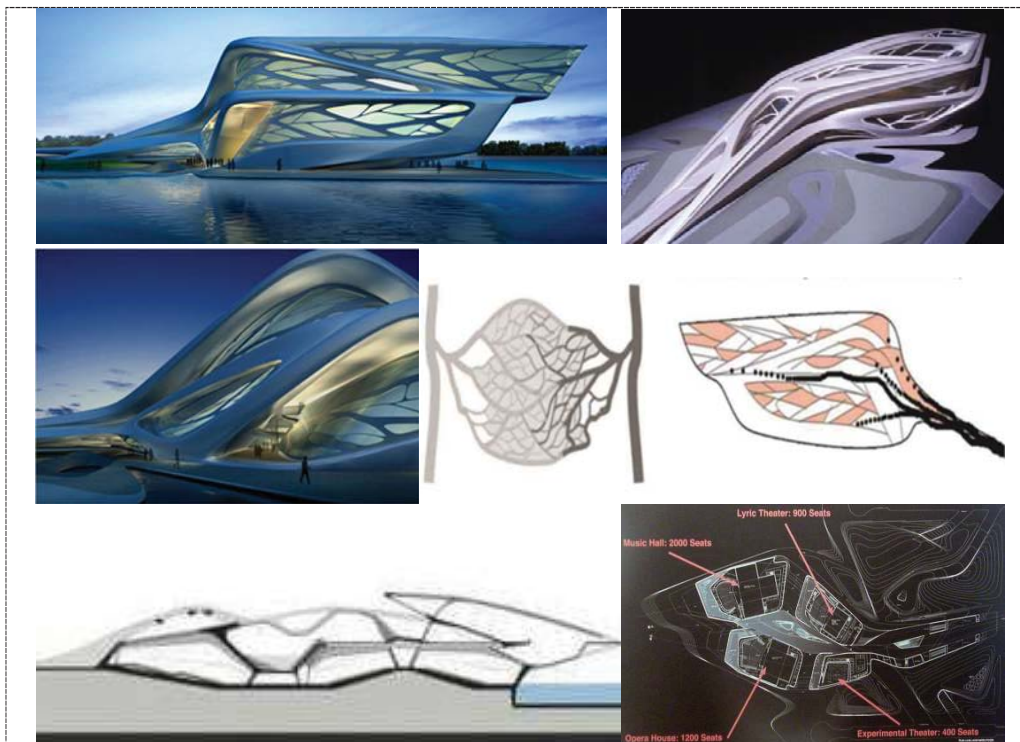
Figure 4. The "Performing Arts Centre" building in Abu Dhabi, designed by Zaha Hadid in 2007. The algorithms that are precisely branching have been applied to develop the energy building system. The paths of flow are directed in a hierarchy from the part to the whole.

Table 2. The characteristics of the projects selected for the analytical study according to the indicators that were extracted by the research within the theoretical framework, to assess the level of structural efficiency.

Selected Case study	Indicators of assessing the level of structural efficiency of the building	
	In terms of Form	In terms of Material
	Path of forces - Type of forces - Distribution of forces	Quantity of material - Weight of material
Stuttgart Airport building	− The use of tree-like support structures, branched into three different levels, ensure the availability of minimum bending forces by controlling the dimensions and angles of these branches. − Small spaces are adopted between loading points and support system, to avoid the generation of bending forces within the elements of the structure. − The main pillars are made of four interconnected tubular columns that act as one unit, and help to distribute forces uniformly within the support points.	− The branching used for all parts of the system - from tree-like branches to four-column support points - ensures that the bulk of the structural material is reduced. − Use of hollow steel in columns to reduce the weight of the structural material
Performing Arts Center	− Directing the flow paths in a hierarchical order from the part to the whole to form the system, and the shape is divided according to paths - main lines - for the flow of forces and their transfer to the main points of the structure. − The availability of relatively short paths compared to the size of the system to avoid the generation of bending forces within the elements of the structure. − The mesh distribution of these paths ensures a homogeneous distribution of forces.	− The division of the structure at the level of the general form ensures that the impacted loads are partitioned, so the mass of materials used is reduced. − The grid distribution of the flow paths within each part - at a detailed level - achieves the least amount of structural material used.

As a result of the analytical study of the two selected study cases, and according to the indicators that were extracted by the research to assess the level of structural efficiency of the building, and as shown in table 2, the research findings support the research hypothesis that structural design according to the structural theory achieves high structural efficiency.

7. Conclusions

Constructal theory is a new way of thinking -a philosophical method- from the cognitive point of view, proceeding from the simple to the complex -that is, from the part to the complex whole- and it gives an explanation of the evolution of natural systems.

Constructal theory contributes significantly to research on the origins of living systems, and then employing it in the process of creating the Architectural form -the model- on one hand, and enhancing the structural efficiency of the structural performance on the other hand.

The potential concepts in the conceptual or planning phases of the structural design - especially those associated with the concepts of thermo-mechanics - constitute an important aspect of producing an effective form to ensure high structural efficiency, and they have a major role in the decisions taken in the process of form-finding that affect the aesthetic and economic issues of Architectural Design .

Achieving high structural efficiency entails achieving a minimum level of material and resource inputs used. Thus, the economic aspect - cost - is an effective and influential factor in that relationship.

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