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"Methodology Comparative Analysis" in the Solar Decathlon Competition: A Proposed Housing Model based on a Prefabricated Structural System

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Abstract: The construction sector, by direct or indirect actions, consumes more than 40% of the global energy produced and is responsible for 30% of CO_2 emissions. It is a need of the construction industry to transform its practices and processes by proposing systems of lower demand to the environment. In this sense, closed prefabrication and industrialization as a constructive process could be the key to seek savings and efficiency from its origin to the end of life of buildings. In this context, this article presents a methodological proposal of quantitative, qualitative and comparative analysis of the structural systems of eight prototypes presented in the "Solar Decathlon" contest in its North-American and Latin-American editions (both of them in 2015) and the European edition (in 2014). This methodology deduces the characteristics of a structural system of lower environmental demand and the characteristics of these constructive processes, in favor of a new paradigm of sustainability and to be applied in innovative systems of new housing models.

Keywords: solar; prototype; system structure; construction; prefabrication; industrialization; sustainability; environmental; architecture; competition

1. Introduction

The construction industry is responsible, through the construction and the conditions that predispose for the operation of the buildings, for around 40% of the global energy use [1,2], 25% of the world water consumption and 30% of the emissions of greenhouse gases [3]. In this sense, it is essential to motivate interest and increase the consideration of designers, architects, builders and other actors involved in the industry, to reduce the environmental impact for which this activity is responsible [4,5].

On the one hand, based on the fact that the construction is still based on artisanal work with little precision, no repetitiveness in operations, no systematic control of finished quality, rationalization and guarantee of supplies; and on the other, that there is a great dispersion and waste of materials and construction systems that coexist in the market and are part of the building works [6], it is consequent that actions that allow to close the material cycles as a condition of sustainability and good practices to cushion the impact of this activity are made difficult [7].

In this sense, prefabrication and industrialization, as a constructive process, could be the key to seek savings and efficiency from origin and conception based on design and manufacturing, namely the efficiency and savings due to the speed of the construction, the saving and efficiency in the useful life of the building by the incorporated technique and, inclusively, saving and efficiency in the end of life of the building [8].

However, prefabricated and industrialized systems often face the inertias related to traditional ways of building and the technical ignorance that this constructive process entails [9]. Likewise, some other problems faced by architects in general when designing and constructively defining prefabricated or industrialized solutions are the absence of reference manuals, the lack of knowledge of design limitations and the restrictions of the industry and the methods or materials; the consequences of this ignorance are errors of definition in the project and construction that in turn generate increase in terms and costs or even abandonment of the type of construction systems chosen [10–12].

Therefore, to reinforce the use of this type of constructive processes, it is fundamental, firstly, to understand the industrial context and the need to modify constructive habits. Also, it is important to highlight and promote the environmental benefits of these practices and take into account the satisfaction and possibility of participation in the process of the end user.

In this sense, it is well known that, in the search for architectural models and sustainable constructive innovations, competitions are a meeting point in which knowledge applied to society's sustainability is generated and disseminated [13]. Based on this, the Solar Decathlon (SD) was chosen as the case study competition for the development of this research.

The Solar Decathlon it is the most important sustainable habitat competition for university students in the world. It is a research project of a competitive, international and institutional nature which constitutes a commitment to the future for sustainability, encompassing architecture and technologies for solar use and home automation, where the design and development of a self-sustaining and energetically autonomous dwelling is competed, using as much energy as possible and in the most efficient way [14,15]. In this competition, colleges and universities from all over the world participate, in collaboration with institutions and private companies, with the objective of designing and building a full-scale housing prototype with the maximum level of self-sufficiency, energetically autonomous, with an optimal cost and operation [16,17]. With a fundamental difference from other competitions, the projects are constructed, their consumption is measured and, finally, they are evaluated in a competitive way compared to other solutions, in theory, equally valid [18].

During the 15-day competition period in the "solar city" site, the prototypes (1:1 scale) are exhibited and evaluated in ten contests (hence the name decathlon). These are: Architecture, Energy Efficiency, Engineering and Construction, Comfort, Marketing and Communication, Electrical Energy Balance, House Functioning, Innovation, Urban Design and Affordability and Sustainability [19].

It is important to note that in the "Engineering and Construction" contest, the objective is to evaluate the design and implementation of the construction and engineering system at the competition site. The teams must therefore demonstrate the prototype's viability, adequate integration and maximum structural functionality alongside the adequate design of the electrical and solar energy production systems [20].

This contest has now expanded internationally, with six editions of the competition worldwide (Table 1) [21], where each one makes public the technical information of the contest projects, which is a source of immense value since these prototypes represent the biggest innovations in the design and construction industry. Different projects of different editions of the contest have been the object of study of several research articles, books and theses of undergraduate and postgraduate studies [22].

Table 1. Timeline of editions of the Solar Decathlon competition.

Solar Decathlon	Country	Year
US	Washington D.C.	2002
	Washington D.C.	2005
	Washington D.C.	2007
	Washington D.C.	2009
	Washington D.C.	2011
	Irvine, California	2013
	Irvine, California	**2015—Case Study •**
	Denver, Colorado	2017
Africa	Ben Guerir, Morocco	2019
China	Datong	2013
	Dezhou	2018
Europe	Madrid, Spain	2010
	Madrid, Spain	2012
	Paris–Versailles, France	**2014—Case Study •**
	Szentendre–Budapest, Hungary	2019
	Wuppertal, Germany	2021—Edition In Progress
Latin America and Caribbean	**Santiago de Cali, Colombia**	**2015—Case Study •**
	Santiago de Cali, Colombia	2019—Edition In Progress
Middle East	Dubai, United Arab Emirates	2018
	Dubai, United Arab Emirates	2020—Edition In Progress

The • is used to indicate that the edition has been chosen as a case study.

In this regard, it is worth noting the large amount of detailed information presented by each team, with a considerable number of plans and reports from different authors, so it is very important to review and take as reference different methodologies used to analyze and compare this documentation [23–25], where files are proposed and used that through graphics analyze the SD prototypes and their constructive details.

Derived from what is mentioned above, it is considered that the suitability of this article lies in the need to lay the foundations for a change in the more widespread and conventional construction models in Latin–Mediterranean countries, where the use of construction systems based on industrialization and prefabricated architecture are still underdeveloped and are sometimes contaminated by the weaknesses of traditional construction.

Thus, the main objective of this article will be to develop an evaluation methodology for construction systems focused on industrialization, through which we can objectify the overall quality of these systems. While it can be understood that many construction systems can have the prefabricated label, not all meet the highest expectations, if we focus on sustainability and efficient resource management.

Based on this, the second objective will be to put into crisis the evaluation methodology used by the prestigious Solar Decathlon contest, the source of our case studies, to score the "Engineering and Construction" test. As this is a subjective methodology, the materiality of the system, its weight or resources to be used in its assembly or its adaptability are not quantitatively differentiated.

Therefore, in this article, an original objective evaluation methodology will be developed and exposed, applying it to the prototypes with the highest score in the "Engineering and Construction" test of several editions of the competition. This methodology could be used as an evaluation tool for future labels or protocols, intended to "reward" construction systems with low impact on the environment.

To achieve this objective, the proposed methodology is described below.

2. Methodology

In order to achieve the proposed objectives, it is first necessary to define the prototype case study of the editions of Solar Decathlon competition held until now (Table 1) that, for purposes related to the development of this research, in the proposed methodology, are considered.

The three structural solutions of the prototypes best rated by the jury in the "Engineering/Engineering and Construction" contest of the editions Solar Decathlon North America 2015 (SDEE.UU.2015) and Solar Decathlon Europe 2014 (SDEU 2014) are considered. Likewise, the 2015 edition of the Latin America and Caribbean Solar Decathlon (SDLAC2015) considered two prototypes that, due to their structural system as a solution to the problems of their location, contribute great value to the development of this research.

For example, there is the Kuxtal (Mexico) proposal that aims to satisfy the needs of progressivity, perfectibility, heritage and self-construction in Mexico, or the Aura Project (Spain), which is based on a study of the Latin–Mediterranean tradition and the reformulation of all its concepts, through a fragmented and shared residential substrate that uses as a repetitive tridimensional module of self-construction that accumulates all the minimum housing requirements [26].

Consequently, the editions of the Solar Decathlon competition held in North America, Europe and Latin America between 2014 and 2015 are used as case studies for this research. This permits a global vision of the direction being taken in research focused on construction in western culture. Furthermore, taking into consideration that all these editions are linked in the context of time and space and the research is carried out by members of the Kuxtal (Mexico) and Aura (Spain) teams participating in the Solar Decathlon Latin America and Caribbean 2015 (SDLAC15), there is an alignment with the Latin–Mediterranean link in which construction is contemplated from a similar cultural perspective.

Having said this, there are two stages of analysis in the methodology (Figure 1):

- Firstly, there is the descriptive–qualitative–comparative analysis, where each of the case study prototypes (Table 2) is described and studied based on a series of criteria/parameters that analyze their constructive and structural characteristics. In this part, it is necessary to review the aspects that were weighted in the tests of each of the SD versions mentioned above, to subsequently recover those that assessed the characteristics of the structural system and its relationship to the living spaces that emerge from it, in order to later include other parameters of own contribution that are considered fundamental for the intended analysis. This being said, the parameters with which the comparative analysis is performed are: concept, typology, materiality, weight, area, possibility of assembly/disassembly, modularizable nature, prefabrication, industrialization, efficacy in placing, savings and quickness in construction, LCA consideration, flexibility, adaptability, perfectibility, accessibility and availability of materials, use of indigenous material, waste management during construction, recycling possibility of elements and reuse possibility of elements.
- Secondly, a quantitative–comparative evaluation is proposed (valued from 1 to 4, with 1 being the lowest rating and 4 the highest weighting) of the principal parameters and qualities of the prefabricated and industrialized structural systems with respect to the conventional structural systems, recovered from the qualitative analysis; this is in order to obtain a qualification that would allow a comparison between prototypes, an easy understanding of the main parameters and the results of the quantitative analysis of these in the prototypes in the competition.

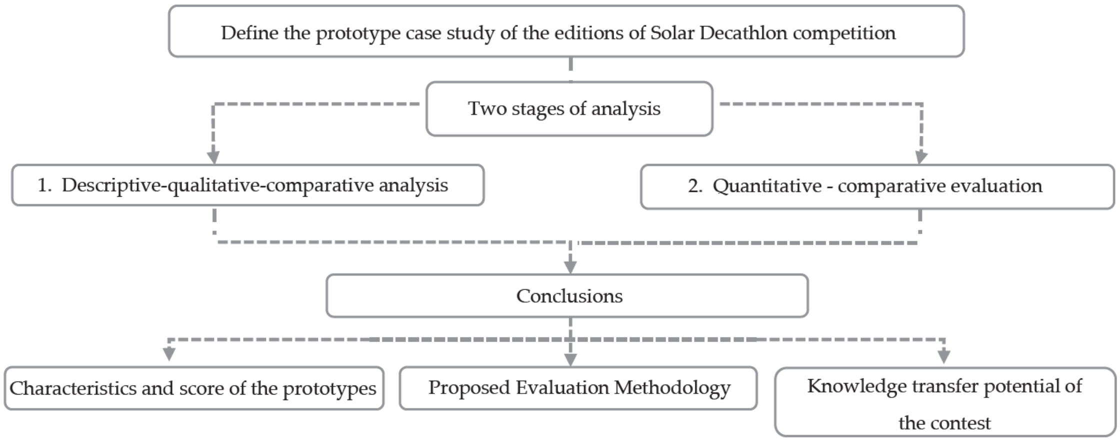

Figure 1. Methodology followed for research development.

Table 2. Case Study.

Solar Decathlon	Team	Test score of "Engineering and Construction"
U.S. 2015	SU + RE House—Stevens Institute of Technology	93/100
	Casa del Sol—University of California, Irvine, Chapman University and Irvine Valley College	92/100
	Nexushaus—University of Texas at Austin and Technical University of Munich	91/100
Europe 2014	CASA—National Autonomous University of Mexico and the Research Center in Industrial Design and the School of Engineering and the School of Arts (Mexico)	80/80
	Renaihouse—University of Chiba (Japan).	76/80
	Casa Fénix— Technical University Federico Santa María - Valparaíso (Chile) and University Rochelle - Espace Bois de l'IUT (France).	72/80
Latin America and Caribbean 2015	Aura Project—University of Sevilla and University Santiago de Cali (Spain–Colombia).	85/100
	Kuxtal— Monterrey Institute of Technology and Higher Education, Querétero Campus (Mexico)	80/100

In the presented table below, the teams of the case study prototypes, the edition of the contest in which they competed and the score obtained are compiled.

Next, these parameters are listed and the proposed rubric is exposed to determine the weightings of the prototypes.

A. Materiality

This refers to the materials that were used in the structural system. For the weighting of this parameter, the "Red List" developed by the International Living Future Institute is considered. This list is composed of materials that should be gradually withdrawn from production due to health problems, with the intention of eliminating the worst materials and practices, encouraging manufacturers and distributors to commercialize truly responsible materials for the environment and the people who inhabit it [27] (Table 3).

Table 3. Materiality assessment rubric.

A. Materiality			
1	**2**	**3**	**4**
If three or more of the materials used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) belong to the LBC Red List.	If two of the materials used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) belong to the LBC Red List.	If one of the materials used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) belong to the LBC Red List.	If none of the materials used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) belong to the LBC Red List.

B. Possibility of assembly/disassembly and efficiency in the placement (savings and quickness in the construction).

This evaluates the possibility of the structure to be assembled and disassembled, through the union of its different elements, giving to them the quality of being reused in the same structure or in another, even with different location, as a result of the correct choice of the connections between the elements that compose the substructures and the structural system. Likewise, the time required and the strategy of placing and building components (Table 4) are considered.

Table 4. Possibility of assembly/disassembly and efficiency in the placement (savings and quickness in the construction) assessment rubric.

B. Possibility of assembly/disassembly and efficiency in the placement (savings and quickness in the construction)			
1	**2**	**3**	**4**
If none of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) can be assembled and disassembled, making it impossible to reuse them in the same structure or in another.	If some of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) can be assembled and disassembled, allowing partial reuse in the same structure or in another.	If all the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) can be assembled and disassembled, allowing their reuse in the same structure or in another.	If all the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) can be assembled and disassembled, allowing their reuse in the same structure or in another, and if the strategy of placing and construction is based on prefabricated modules that are assembled at the site.

C. Modularizable nature.

This refers to the capacity of the structural system to be the result of the union of several modules that interact with each other. Each module must be independent of the rest of the modules and at the same time interact with the others to form a composite structural system (Table 5).

Table 5. Modularizable nature assessment rubric.

C. Modularizable nature			
1	**2**	**3**	**4**
If the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is not made up of separate modules or components that interact with each other.	If the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is based on modules or components that interact with each other, formed by elements of standard dimensions, and by joining these modules they result in the structural system.	If the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is based on modules or components that interact with each other, formed by elements of standard dimensions, and by joining these modules they result in the structural system, in addition to making it possible to replace any of these modules with another.	If the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is based on modules or components that interact with each other, formed by elements of standard dimensions, and by joining these modules they result in the structural system, in addition to making it possible to replace any of these modules with another and/or add more modules without affecting the rest of the system.

D. Prefabrication/industrialization:

Here, prefabrication is understood as the production of constructive elements and/or systems in the factory or workshop, that is to say, prior to the execution of the work (out of place), that will be incorporated later, through a set of operations known as placement. On the other hand, industrialization is the application to the production of buildings in organizational processes (techniques of production engineering), aiming for increasing the productivity of the sector, such as through continuity of production, standardization of products, mechanization, research and experimentation (Table 6).

Table 6. Prefabrication/industrialization assessment rubric.

D. Prefabrication/industrialization			
1	**2**	**3**	**4**
If none of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are prefabricated or industrialized.	If all the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are prefabricated.	If some elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are prefabricated and also industrialized (in case of mixed systems).	If all the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are industrialized.

E. Weight

This parameter considers a weight range that takes into account the heaviest and lightest system of the prototypes analyzed, with the intention of closely comparing the heaviness of the structural systems of the case studies and their relationship with the proposed materials and systems. From this range, "quarters of weight ranges" (difference between the highest weight and the lowest weight divided by four) were assigned for the weights (from 1 to 4 points) of each prototype. To obtain this quantitative data, it was necessary to dismantle and quantify each of the elements that make up the structural system of each prototype, to later relate it to the weight of each material and thus obtain the weight (Table 7).

Table 7. Weight assessment rubric.

E. Weight			
1	**2**	**3**	**4**
If the weight of the structural system (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is between 12,826.40 kg to 17,101.87 kg (last quarter of the weight range of the analyzed prototypes).	If the weight of the structural system (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is between 8,550.94 kg to 12,826.40 kg (third quarter of the weight range of the analyzed prototypes).	If the weight of the structural system (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is between 4,275.47 kg to 8,550.94 kg (second quarter of the weight range of the analyzed prototypes).	If the weight of the structural system (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is between 0.0 kg to 4,275.47 kg (first quarter of the weight range of the analyzed prototypes).

F. Flexibility and adaptability

Here, the flexibility and adaptability of the structural system is considered and scored, i.e., the ability of its modules or elements to change their initial configuration and adapt to the different phenomena and complexities of living. Likewise, maximum weighting is granted if, in addition to these qualities, the system considers perfectibility, understood as the capacity of the system to accept different assemblies of other elements to seek to gradually improve it (Table 8).

Table 8. Flexibility and adaptability assessment rubric.

F. Flexibility and adaptability			
1	**2**	**3**	**4**
If none of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is flexible to encourage reconfiguration of living spaces.	If some of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are flexible, that is to say, they allow different configurations of the living spaces.	If all of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are flexible and encourage the total or partial adaptability of the prototype.	If all of the elements used in the structural resolution (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) are flexible and the structural system also accepts other assemblies of elements or components that encourage the perfectibility of living space.

G. Accessibility and availability of the proposed materials

This parameter weights the choice of materials for the structural resolution of the prototype from a sustainable point of view. Aspects such as if the materials are indigenous, easy to access and transfer to the site of placement and the availability of the material are considered (Table 9).

Subsequently, based on the results obtained in the descriptive–qualitative–comparative and quantitative–comparative analyses, a discussion is carried out.

Table 9. Accessibility and availability of the proposed materials assessment rubric.

G. Accessibility and availability of proposed materials			
1	2	3	4
If the raw material with which the elements used in the structural resolution were made (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is not indigenous nor easy to access nor has a short transfer to the location of the prototype.	If the raw material with which the elements used in the structural resolution were made (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is not indigenous, but it is easily accessible and has a short transfer to the place of prototype site.	If the raw material with which the elements used in the structural resolution were made (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is indigenous and easily accessible and has a short transfer to the prototype site.	If the raw material with which the elements used in the structural resolution were made (primary structure, secondary structure and auxiliary structure of wall, floor and ceiling support) is indigenous and easily accessible and has a short transfer to the prototype site; besides that, its availability (supply) in the local market is greater than the demand.

3. Comparative Analysis of the Case Study Prototypes

3.1. Descriptive–Qualitative–Comparative Analysis of Structural System

Tables 10 and 11 expound the principal parameters that, to a greater or lesser extent, characterized all the prototypes in the competition. It is also inferred that these are parameters that prefabricated and industrialized structural systems must have, because they are qualities and characteristics that do not consider the solutions projected with conventional materials at present. In these tables the structural systems of the study cases are exposed comparatively according to these parameters.

Table 10. Descriptive–qualitative–comparative analysis.

	Concept	Typology	Materiality
SU + RE House (SD U.S. 2015) (SU)	Structure resistant to floods and storms, structural integrity in coastal environment, sustainable and durable.	Mixed structure (combination of Balloon Frame and Steel Frame).	Main structure based on: Laminated Veneer Lumber (LVL) beams (floor framing), Trus Joist I-Joist (TJI) for the floor, wooden columns, LVL beams (covered framing, TJI joists for roof). Porch: steel columns, steel beams.
Casa del Sol (SD U.S. 2015) (CS)	Modular structure, earthquake-proof, easy to assemble and transport.	Mixed structure (combination of Balloon Frame and Steel Frame).	Main structure based on: steel beams, metallic profiles. Substructure: wooden joists. Auxiliary structure: wooden elements.
Nexushaus (SD U.S. 2015) [NH]	Modular structure, easy transportation and assembly of components, sustainable.	Structure based on frames of Balloon Framing style with corner elements and steel columns.	For main structure: 2″ × 10″ beams for wood framing; pillars and beams steel Bantam cold formed.
CASA (SD EU 2014) [CA]	Modular structure, easy to assemble and transport, self-building, which seeks to optimize the occupation area.	Structure "Space Frame" type, made of steel and wooden frames for interior solutions.	For main structure: tubular steel of different diameters, OC steel columns; profiles, angles, and steel connections. For substructure of interior solutions: plywood frames
Renaihouse (SD EU 2014) [RE]	Prefabricated structure, which seeks high performance in an earthquake, optimized construction times and easy portability.	Frame structure of wood based on three cores (urban seeds).	For main structure: structure of 120 × 120 mm wooden pillars, 9 mm thick plywood For substructure of interior solutions: 9 mm thick plywood
Casa Fénix (SD EU 2014) [FE]	Light structure, of easy progressive modulation and fast assembly.	Wooden structure whose basic component is the "column panel".	The skeleton or main structure is formed by: ground footing, wooden footing, "column panel" components (structure) and the wall at the same time, floor beams, roof beams.
Aura Project (SD LAC 2015) [AU]	Grid structure with dry joints, which reduces assembly times and the generation of waste; based on three modules.	Steel grid divided in three modules with dry joints.	For main structure: tubular steel, steel angle, corrugated sheet, wood–steel composite profile
Kuxtal (SD LAC 2015) [KX]	Lightweight structure, self-built (assisted construction), modular and sustainable.	Structural system "Steel Framing" style.	Primary structure: IR expanded steel beams and OR steel profiles (HSS) for columns and roof structure beams. Secondary structure: C′formed-purlin profiles. Parapet Substructure: bracings, interior and enclosure walls.

Table 11. Descriptive–qualitative–comparative analysis.

	(SU)	(CS)	(NH)	(CA)	(RE)	(FE)	(AU)	(KX)
Possibility of assembly/disassembly	•	•	•	•	•	•	•	•
Modularizable nature	•	•	•	•	•	•	•	
Prefabrication	•	•	•	•	•	•	•	•
Industrialization	•	•	•	•	•		•	•
Efficacy in placing	•	•	•	•	•	•	•	
Savings and quickness in construction	•	•	•	•	•		•	
LCA consideration			•	•	•		•	•
Flexibility			•	•	•	•	•	•
Adaptability		•		•	•	•	•	•
Perfectibility						•		
Accessibility and availability of materials	•	•	•	•	•	•	•	•
Use of indigenous materials						•		
Waste management during construction				•	•	•	•	•
Recycling possibility of elements	•	•	•	•	•	•	•	•
Reuse possibility of elements	•	•	•	•	•	•	•	•

• is used to indicate the use of this item.

SU + RE House (SU)—Flood- and storm-proof design, minimal use of energy-intensive materials, high-efficiency safe system, fully integrated into the coastal setting, sustainable and durable (Figure 2). Mixed structure combining "Balloon Frame" and "Steel Frame" (mainly for the portico and external elements).

Figure 2. SU + RE House. SD U.S. 2015.

Casa del Sol (CS) – Modular system, earthquake-proof, transportable and easy to assemble. Mixed structure: mainly steel for the main structure and wood for the substructure and auxiliary structure to support finishes (Figure 3).

Figure 3. Casa del Sol. SD U.S. 2015.

Nexushaus (NH)—Modular project, easy transportation and assembly of sustainable components (Figure 4). "Balloon Frame" structure with some steel corner posts and beams.

Figure 4. Nexushaus. SD U.S. 2015.

CASA (CA)—Construction system design following basic concepts such as: modularity, light weight, flexibility, self-build, easy assembly and disassembly, transportability, compatibility with other systems and optimal usage of space. Steel "Space Frame" structure combined with wooden frames for interior solutions and finishes (Figure 5).

Figure 5. CASA. SD Europe 2014.

Renaihouse (RE)—Construction system design based on prefabrication, transportability, high resistance to earthquakes, light weight, and optimal construction times (Figure 6). Wooden lattice structure. Based on three hubs known as "Urban Seeds".

Figure 6. Renaihouse. SD Europe 2014.

Casa Fénix (FE)—Construction system design following basic concepts such as progressive modulation, flexible construction times, quick and easy assembly of components. Lightweight (Figure 7). Wooden structure whose basic component is "panel and column".

Figure 7. Casa Fénix. SD Europe 2014.

Aura Project (AU)—Based on concepts of assisted self-build and housing perfectibility, whereby the house is improved upon as the family grows (Figure 8). The structural system consists of a three-dimensional mesh on which the prototype is divided into three transportable modules. A metal, wooden and Guadua bamboo structure was developed.

Figure 8. Aura Project. SD LAC 2015.

Kuxtal (KX)—Dynamic, evolutionary, economical, innovative, passive and efficient construction system based on concepts such as self-construction, recycling and modulation. Industrially manufactured elements are used for easy transport and assembly (Figure 9). Simple, lightweight and easy-to-build structural system based on easily acquired commercial steel profiles to produce a self-constructible, modular, sustainable system. "Steel Framing" structural system, interiors and finishes.

Figure 9. Kuxtal. SD LAC 2015.

3.2. Quantitative–Comparative Evaluation

The scores obtained in each parameter evaluated are graphed below, and these results are discussed:

A. Materiality

Starting from the fact that all the structural systems studied are composed of wood, steel or mixed elements and because in this parameter the materials that were used in the structural system are evaluated, taking as reference the "Red List" developed by the International Living Future Institute, all the prototypes obtained the maximum score (4 points), because in this list these materials are not considered.

B. Possibility of assembly/disassembly (joints) and efficiency in placement

Similarly, almost all the prototypes analyzed meet the characteristic of enabling their assembly and disassembly, through the use of the relevant unions between its different components. Kuxtal and Casa Fénix projects did not obtain the highest rating, scoring just 3 points, because their implementation strategies require greater assembly time for their components, despite having the characteristic of being modular.

C. Modularizable nature

The Casa Fénix, Renaihouse and CASA prototypes achieved the highest score, since their structural resolution is based on modules that interact with each other, being made up of elements with standard dimensions; in addition, it is possible to replace any of these modules with another and/or add more modules without affecting the rest of the system. They are followed by the Casa del Sol project with 3 points and then the rest of the prototypes with 2 points.

D. Prefabrication/industrialization

In the "Prefabrication/industrialization" parameter, the prototypes Proyecto Aura, Kuxtal, SU + RE House, Casa del Sol, Nexushaus and CASA achieved the maximum score, inasmuch as all the elements that compose their structural systems have these characteristics and also consider standard measures in its design. Casa Fenix and Renaihouse got only two points.

E. Weight

The lighter prototype is Nexushaus. As it is located in the first quarter of the rubric of evaluation of this parameter described above, it got 4 points. On the other hand, the heaviest projects were CASA and Casa del Sol; they obtained only 1 point, because they were in the last quarter of the evaluation rubric. In between were Aura, Renaihouse and SU + RE House projects with 2 points and Kuxtal and Casa Fénix with 3.

F. Flexibility and adaptability

Casa Fénix, Renaihouse, and CASA were the best-weighted projects in this parameter, with 4 points, not only proposing a flexible and adaptable structural system, but also giving a plus when designing a system that allows assemblies of other elements or components providing the perfectibility of the living space. The worst qualified were Casa del Sol and SU + Re House with 1 point, followed by Kuxtal with 2 points and Nexushaus and Aura project with 3.

G. Accessibility and availability of materials

In this parameter, the Renaihouse prototype is the only one that obtained the maximum qualification, since the raw material with which the elements used in the structural resolution were manufactured is indigenous, easily accessible and with short transfer distance to the prototype site; in addition, its availability (supply) in the local market is greater than the demand and helps the recovery of the local timber industry. Renaihouse prototype is followed by the Casa Fénix, Nexushaus and SU + Re House projects with 3 points and the rest of the teams with 2.

The following graph (Figure 10) exhibits a comparison of the final weighting by evaluated parameter of each prototype studied, where it is observed that the structural systems of the best rated projects are Nexushaus (proposed by the University of Texas at Austin and Technische Universitat Munchen) and Renaihouse (from the University of Chiba in Japan) with 24 points out of 28 possible. Likewise, the prototype with the lowest score is Casa del Sol (built by the University of California, Irvine, Chapman University and Irvine Valley College) with 19 points.

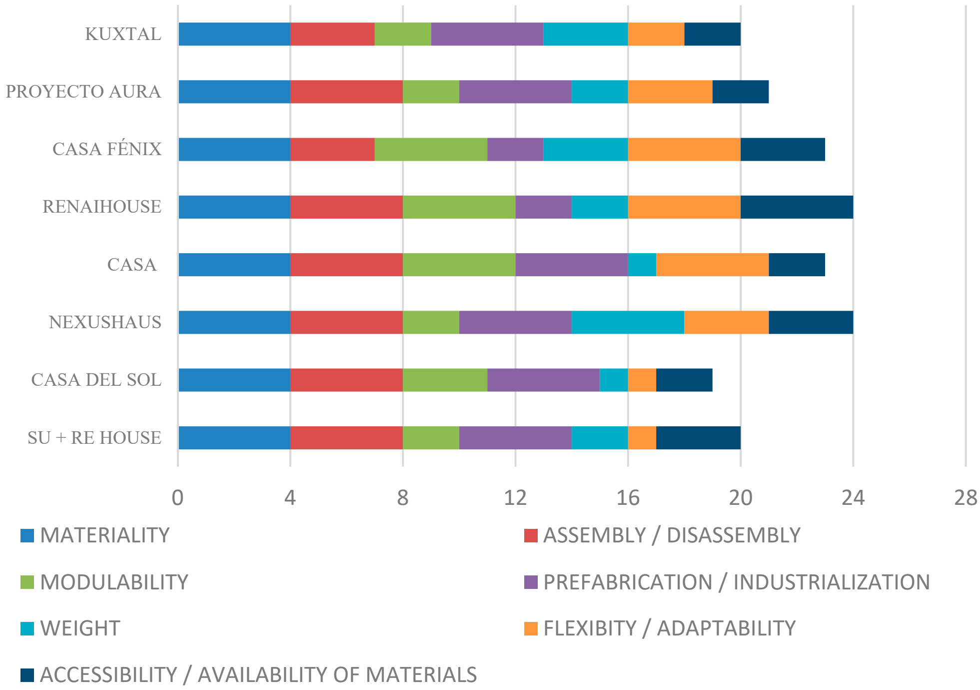

Figure 10. Result across this methodology.

Finally, the following figure shows a comparison of results between the weights obtained by the case study prototypes in this proposed methodology vs. the qualifications obtained in their respective editions of the Solar Decathlon competition (Figure 11). To achieve a more objective comparison, the results are expressed in percentages, considering the maximum score of each edition as 100% (in this methodology 28 points, in the SDLAC 100 points, in the SDEU 80 points and in the SDEEUU 100 points).

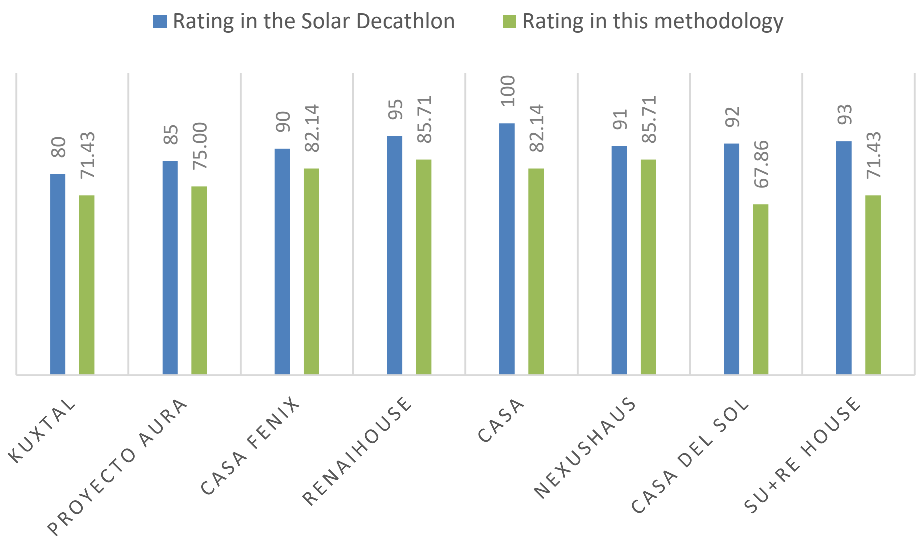

Figure 11. Scores obtained in this methodology vs. scores obtained in the SD.

From the previous graph it follows that the structural system of the CASA project was the best valued in its respective competence of the SD, while the Kuxtal prototype was the one that received the lowest rating. These results are not coincident with the weighting obtained by the projects shown in this methodology.

4. Discussion and Conclusions

From the comparative quantitative evaluation, it is concluded that the Renaihouse prototype is one of the best scored because its structural solution is designed for an emergent housing model in case of disasters, consequently, the accessibility, availability and materiality are optimal for its context. In the same way, its assembly and dismantling and rapidity in placement in site is possible due to prefabricated modules of easy transport that, once placed, can be adaptable and perfectible.

Likewise, the Nexushaus prototype is another of the best weighted because it minimizes the components and spaces of the home, is designed to optimize the materiality and provide lightness, includes elements of high industrialization and practicality of assembly, resulting in a structural solution of fast and easy transportation.

After the descriptive-qualitative–comparative analysis, the characteristics of the prototypes and structural solutions worsened by their environmental impacts with respect to the qualities of those with less deduced impact. That is to say, aspects such as: optimize the living surface as much as possible (dimensions and reduced areas), use lightweight elements, consider the modulation of its components for easy transportation, optimize assembly and assembly times, and propose accessible and available materials (indigenous) preferably. In addition to managing waste during construction and the end of life of the elements used, these are fundamental characteristics that must be taken into account if the aim is to design and propose structural systems whose impacts associated with the life cycle of the system are lower.

From the methodology of quantitative–comparative evaluation of the Solar Decathlon prototypes discussed in this document, it can be deduced that the methodology for evaluating structural systems of the projects presented is merely subjective, so it is fundamentally important to objectify it, as proposed in this document. It is necessary to have a methodology that by means of a set of criteria quantitatively assesses (that score is awarded) the prefabricated/industrialized structural systems and their solutions to the different problems, considering social, climatic, geographical contexts and natural and economic resources, among other factors that intervene depending on the location and/or proposal of the project site. It is also considered essential to take into account and regulate in a concrete way the solutions proposed by each team, including the design, composition, transport, use and end of life of each of the elements that materialize the prototype. Also, the deliverables (plans, memories, construction details, design intentions, etc.) should be generated in the form of a constructive manual, and this in turn should be published and available to any professional or actor involved in the construction, so that, with this, the innovations proposed in the competition are disseminated and taken into account as adaptable and valid solutions. All the above are proposed in search of more sustainable projects.

Finally, the proposals and results from the Solar Decathlon contest in the context analyzed are clearly a point of reference for technological innovations and a meeting of applicable and repeatable knowledge in construction. However, it is necessary to continue working on adjusting the bases and tests of the competition. The implementation of other methodologies for evaluation and comparison of prototypes of the competition, such as the one proposed here, is necessary. The need to develop a quantitative–comparative analysis of the environmental impacts associated with the construction of the structural system of the prototypes in the Solar Decathlon is inferred, because there is no test which weights these impacts, and this evaluation could be implemented based on the parameters used in the qualitative-comparative analysis here exposed and developed.

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