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## Evaluación del desempeño de sistemas constructivos para la industrialización: una metodología aplicada a la vivienda en España Assessment of a methodology to evaluate constructive systems for industrialization: the case of dwellings in Spain.

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**Resumen--** Los sistemas de monitorización de edificios proporcionan grandes volúmenes de información y existen herramientas avanzadas de análisis de datos. Un problema de detección y diagnóstico de fallos (FDD) en los sistemas energéticos de los edificios también puede considerarse un problema de aprendizaje automático puro. El objetivo de este trabajo es promover la FDD con aplicaciones de aprendizaje automático en el entorno de los edificios. Como contribución, en este trabajo se procesan series de datos temporales brutos, obtenidos de un SCADA, para la posterior construcción de patrones de una instalación térmica de un edificio. La instalación térmica abastece las demandas de ACS y calefacción de un edificio residencial, compuesto por 26 viviendas sociales y situado en Durango (norte de España). Los datos registrados cada 24 horas en valores acumulados se incluyen en el software R para el cálculo de gráficos estadísticos. Para los valores de los contadores de consumo de ACS y calefacción se obtienen 229 puntos de datos válidos y los rangos de consumo diario están comprendidos entre 1,94 - 5,90 m<sup>3</sup> y 0 - 547,63 kWh.

**Palabras clave—** Detección y diagnóstico de fallos; Instalaciones térmicas; Aprendizaje automático; SCADA; Software R..

**Abstract—** Building monitoring systems deliver large volumes of information and advanced data analysis tools are available. A fault detection and diagnosis (FDD) problem in building energy systems can also be regarded as a pure machine learning problem. The aim of this work is to promote FDD with machine learning applications in building environment. As a contribution, in this work raw time data series, obtained from a SCADA, are processed for further pattern construction of a building thermal facility. The thermal facility supplies the DHW, and heating demands of a residential building, consisting of 26 social dwelling units and located at Durango (northern Spain). Data recorded every 24 hours in cumulative values is included in the R software for computing statistical graphs. For DHW and heating consumption meter values, 229 valid data points are obtained, and the daily consumption ranges are between 1.94 - 5.90 m<sup>3</sup> and 0 - 547.63 kWh respectively.

**Index Terms—** Fault detection and diagnosis; Thermal facilities; Machine learning; SCADA; R software.

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## I. INTRODUCTION

THE loss of traditional trades in the construction industry (Waked, Van Balen, 2019) and the high price of specialised labour, place industrialisation as an alternative to improve the quality of constructions by adjusting their cost (Jiang, Zhao, Wang, Xing, 2019). Indeed, the industrialisation of construction involves a series of advantages over traditional construction, including better quality control in the construction process, derived from its systematisation and the simplification of the checking and control processes. As well as a reduction in the health and safety risks associated with on-site construction, since the processes are carried out in a controlled environment with less unevenness and lower heights than on-site construction and the associated simplification of the necessary health and safety means (Gallo, Romano, Belardi, 2021) (Lia, Qiping, Wuc, Yue, 2018).

In addition to the above, in recent years there has been a clear interest in industrialisation in terms of reducing execution times, taking advantage of administrative times for the start of the factory execution of the building. This circumstance has a direct impact on cost reduction, as investigated by Chao Mao et al. (Mao, Xie, Hou, Wu, Wang, 2016), and is closely related to the implementation of tools based on objective criteria, which facilitate decision-making regarding the industrialisation of buildings; as well as the development of tools that analyse the optimal level of prefabrication, as has been done for the case of concrete buildings (Chen, Okudan, Riley, 2010). Therefore, although the cost is currently comparable to traditional in situ execution, its advantages lie not so much in the reduction of material execution costs, but in the rest of the associated parameters mentioned above (Mao, et al., 2016) (Pérez, 2009) (Pérez, 2009).

It is true that the incorporation of this construction practice requires the modification of traditional ways of working, incorporating construction systems and processes from the very beginning of the project idea (Montes, Caps, Fuster, 2011). This circumstance implies the organisation of work in order to achieve greater productivity in all phases (Saiz, 2015), which leads to a growing interest in the incorporation of new digital technologies such as: AI (Artificial intelligence), AR (Augmented reality), IoT (Internet of Things), BIM (Building Information Modelling) and CAD-CAM (computer aided-designing-computer aided manufacturing); which allow quality improvement and error reduction (Gallo et al., 2021). The rationality imposed by this type of tools provides total control and management of the processes in line with the LEAN methodology, seeking continuous improvement and loss reduction through BIM-4D integration or the definition of an ideal workflow between both concepts (Cribbs, 2020).

Finally, given that the construction industry is responsible for the consumption of half of the world's resources, as well as for one third of the energy consumption and CO<sub>2</sub> emissions that pollute the Earth (Gallo, et al., 2021), industrialisation is proposed as a strategy to reduce emissions during the life cycle of a building by reducing the carbon footprint of materials and products (Teng, Li, Pan, Ng, 2018) ; by reducing waste

(Avellaneda, Gonzalez, Marques, Vidal, 2009) and improving the use of surplus and management of its recyclability (Pérez, 2009). Indeed, according to research carried out by Milad (2015) (Moradibistouni, Vale, Isaacs, 2018), industrialisation is 50% more efficient in energy use, 30% more efficient in water use, it also favours the possibility of reusing and recycling its materials and components, with the energy savings that this entails, and it reduces waste produced on site and in the factory by 40%. Along with this, embedded energy has also been studied during the life cycle of prefabricated components (Teng, et al., 2018), even evaluating specific cases (Hong, Qiping, Li, Li, 2016) (Du, Bao, Huang, Shao, 2019) or specific phases such as construction (Jiang, et al., 2019), contemplating strategies for professionals to improve the sustainability of prefabricated buildings (Gallo, et al., 2021). However, no study has been found that is able to combine both environmental and technical dimensions, assessing the potential for improvement to promote industrialisation and address the optimisation of existing systems.

### A. Market readiness issues

On the other hand, despite the advantages that industrialisation could provide in the construction sector, its implementation in the market is still at a preliminary stage, mainly due to the lack of social acceptance (Moradibistouni, et al., 2018). These types of systems, however, are not new, but their application has been addressed throughout history, adapted to the specific conditions of each time and place. Thus, in some countries with a long experience in industrialisation, such as Germany, Sweden or the United Kingdom, light industrialised systems made of steel and wood, an abundant material in these places, were developed from very early on, except for the period after the Second World War, when heavy systems were used. It is true that their proliferation as a method of reconstruction after the First and Second World Wars has led them to be associated with social, repetitive, temporary, and low-quality housing, without the possibility of being designed and customised (Mao, et al., 2016). This prejudice is also associated with the lack of technical training regarding the construction processes required for this type of execution, as well as the lack of selection tools to simplify and objectify the design process (Chen, et al., 2010).

Despite this circumstance, there are more than a few geographical areas in which there has been a firm commitment to the implementation of industrialised construction methods, especially in collective residential projects and hotels, because it allows their construction by reducing execution times (Lia, Qiping, Wuc, Yue, 2019). This is also the case in the United States, where such systems are used for health, educational and military facilities and different countries are betting on a change in the construction industry, moving from traditional systems to the implementation of technological projects (Mao, et al., 2016).

In the case of Spain, the economic crisis of 2008 led to the loss of skilled labour and the search for alternatives based on the industrialisation of processes and systems. This circumstance, together with the long administrative resolution

periods, makes it possible to opt for an industrial model that is developed in the factory and which, once the licences have been obtained, allows for rapid implementation, thereby reducing the execution periods and associated costs (Mao, et al., 2016). However, the legal framework necessary for financing these actions is an obstacle, which means that they must necessarily be promoted by large developers, as opposed to the boom in two-dimensional solutions by smaller entities (Saiz, 2019).

Therefore, based on the above, the objective of this research lies in the development of a methodology to compare and evaluate the suitability of industrialised construction systems from a technical and environmental point of view, based on objective criteria. As well as detecting weak points of current industrialised systems to promote their implementation. To this end, the study focuses specifically on the industrialisation of housing in Spain.

## II. MATERIALS AND METHODS

### A. Industrialised systems in Spain

The first classification, based on the literature analysed and especially on the texts of Alfonso del Águila (del Águila, [1987] 2006), is the subdivision into components and 2D systems and 3D systems.

Components are two-dimensional elements that are assembled on site with the simplest possible joints, while 3D systems, on the other hand, are prefabricated three-dimensional elements that are transported and assembled on site, giving rise to the complete building. These systems leave the factory finished and only need to seal the joints and add some finishing touches (Saiz, citing José Miguel Reyes, 2015). In turn, to systematise the information gathered, these groups are subdivided into seven categories: five linked to 2D systems or components and two to 3D systems, as shown in Table 1, which indicates the number of systems analysed of each type, 67 in total, according to their availability on the market, which gives an idea of the current panorama of industrialisation in Spain.

Each country or geographical area should adapt the categories to its conditions.

### B. Assessment parameters

For the research to serve as a tool for detecting problems and areas for improvement in these systems, a series of evaluation parameters are established, ranging from technical performance to environmental aspects.

Table 2 summarises the parameters and evaluation criteria, which will be explained in detail in this section. Each parameter is assigned a score of 0-4, where zero corresponds to those cases in which the manufacturer does not provide information and the highest score corresponds to the best performance. The tool developed is adapted to the specific case of housing in Spain, so variables such as the climate zone and the type of building have been considered when rating the systems.

TABLE I  
CLASSIFICATION OF ANALYSED SYSTEMS

Componentes y sistemas 2D				
Category	Subcategory	Material	Type	n° Systems
Structure	Linear	Concrete	Heavy lattice	4
			Wood	Heavy lattice
			Light lattice	1
		Steel	Heavy lattice	1
			Lightweight lattice	1
			Integrated system	1
	Floor slabs	Concrete	Semi-slab/pre-slab	1
			Solid slab	1
			Hollow core slab	2
			Other	2
			Wood	Solid
		Hollow core	4	
	Panels	Concrete	Double wall	1
Prefabricated panel			1	
Integrated system			1	
Wood		Massive	1	
		Alveolar	4	
Façade	Heavy	Concrete	Solid panel	2
			Multilayer panel	1
	Light	Various	Ventilated	6
			Non ventilated	4
			SATE + light interior wall	2
Roof	Light	Miscellaneous	Sandwich panel	5
			Green roof system	1
Partitioning	Light	Miscellaneous	Plates	2
Category	Subcategory	Material	Roof floor	2
Structure			Laminated plaster	4
3D Systems				
Category	Subcategory	Material	Type	n° Systems
Bathroom	Heavy	Concrete		1
	Light	Steel		1
Housing	Heavy	Concrete		1
	Light	Wood		3
		Subcategory		
TOTAL				67

C. Technical performance

The technical performance is systematised into three main groups: properties, quality, and installation. For the evaluation of these parameters, the reference standard in Spain has been considered: the Technical Building Code (CTE) in its latest available version.

The four variables that make up the properties section are:

- Own weight [kg/m<sup>2</sup>], differentiating between light and heavy systems (del Águila, [1987] 2006), the former being prioritised, since weight is directly related to transport and to the amount of energy consumed (Salas, 2009)
- Thermal transmittance U [W/m<sup>2</sup>K], taking as a reference CTE-DB-HE (CTE-DB-HE, 2019), which indicates some indicative values of thermal transmittance in walls and roofs in contact with the exterior. The lowest evaluation corresponds to those systems that do not comply with the regulations on their own, followed by those that may comply depending on the climatic zone and finally, those that comply in all cases.
- Acoustic resistance, according to the CTE-DB-HR (CTE-DB-HR, 2019) establishes the acoustic insulation to airborne noise that facades, roofs, and party walls must have, in conjunction with adjacent construction elements. Considering that for residential use between the dwelling and the exterior this value must be between 30 and 47 dBA depending on the daytime noise index and the use of the room and, for partition walls, it must be greater than 33 dBA. Based on this, the lowest value corresponds to systems that do not comply with the standard on their own, while the highest value corresponds to those that comply with the most demanding noise indices.
- Fire resistance, based on the CTE-DB-SI (CTE-DB-SI, 2019) for walls, ceilings, and structural elements for residential use, from 30 minutes the structure complies with the regulations, with 60 minutes the components can delimit a fire sector above ground level and with 120 minutes they can do so below ground level.

In terms of the quality of the systems, two variables have been considered:

- Useful life, with those systems with greater durability being positively valued, to avoid new energy consumption during maintenance (Azpilicueta, Araujo, 2012).
- Quality seals, among which are the Technical Suitability Documents (DIT, DIT plus or DITE): quality marks that assess the suitability of the application of innovative materials, systems and construction procedures and compliance with certain technical requirements. According to a study carried out by the Torroja Institute, there is a direct relationship between the number of Suitability Documents granted and the number of industrialised systems available (Salas, Blazquez, et al., 2013).

TABLE II  
ASSESSMENT PARAMETERS

Parameter	Units	Valoración			
		0	1	2	3
Technical performance					
<b>Properties</b>					
Dead weight	[kg/m <sup>2</sup> ]	No data provided	> 200	<200	
Transmittance	[W/m <sup>2</sup> K]	No data provided	> 0,56	0,56-0,22	<0,22
Acoustic resistance	[dBA]	No data provided	<30	30-40	>40
Fire resistance	[min]	No data provided	30	60	≥ 120
<hr/>					
Quality		No data provided			
Service life	[Years]	No data provided	50	50-100	>100
Quality seals		No data provided	Sí=1	Sí>1	
<hr/>					
On-site installation					
Spatialised workmanship		No data provided	Sí	No	
Joints	[type]	No data provided	Wet	Dry Welded	Dry Screwed
Environmental performance					
<hr/>					
<b>Sustainability</b>					
Sustainability certificates	[kg/m <sup>2</sup> ]	No data provided	Sí		
Environmental product declarations	[kg/m <sup>2</sup> ]	No data provided	Sí		
<hr/>					
<b>Manufacturing</b>					
Sourcing of raw materials		No data provided	Imp ort	Local / Import	Local
Percentage recycled	[%]	No data provided	< 50%	>50%	
Additional measures		No data provided	Sí		
<hr/>					
<b>End-of-life</b>					
Recyclability	[%]	No data provided	< 50%	>50%	
Re-use	[%]	No data provided	< 50%	>50%	

Finally, this section analyses the commissioning, which indicates the degree of industrialisation of the system and is one of the essential parameters in this type of building. Specifically, we analyse:

- The need for skilled labour, the lowest qualification being for those systems that require it, including those with welded joints.
- Joints, priority is given to dry joints, which allow for easy installation (Grohe, citing Wachsmann, 2001). And a distinction is made between bolted and welded dry joints, as the latter are considered to require a certain degree of specialisation on the part of the operator (Jurado, 1998).

#### D. Environmental performance

The purpose of this section is to evaluate, with objective criteria, the environmental performance of the different systems, thus including different parameters relating to the evaluation of their sustainability, ranging from the origin of the raw materials of which they are made, to the possibility of reuse or recycling at the end of their useful life.

It is worth noting the difficulty encountered in compiling this data, which most manufacturers do not provide. Despite this, it has been decided to include them, to highlight the scarce information available in this respect and to take it as a starting point for a possible way of improving the industrialisation market.

Specifically, the indicators considered in this section are grouped into sustainability, manufacturing, and end-of-life. Considering specific stages of the analysis of the life cycle of the systems, which have an impact on the impact of the building.

The two variables that make up the sustainability group are:

- Sustainability certificates, LEED (UK), BREAM (USA) and VERDE (Spain) are some of the most widespread environmental certifications in our country that, by means of different criteria evaluate the sustainability of buildings (Pladur, 2020). These certifications are not given to specific systems, but to the building. Along with them, Passivhaus is a German sustainability certificate that promotes buildings with high thermal comfort and low energy costs. Unlike the previous ones, this body does issue certificates to some materials and systems with high energy efficiency (Passivhaus Institut, 2016).

Given the scarce information on this type of certificates from manufacturers, the scale of values is limited to those systems that have one of them.

- Environmental Product Declarations (EPD), documents that certify the environmental quality of a product, based on information from the life cycle analysis (LCA). The European Standard EN 15804 defines the requirements that these declarations must meet for construction products (Aenor, 2020), which is why they have been considered of great interest for the comparison between systems, given that they are based on technical and comparable criteria. Moreover, these types of declarations are currently considered in LEED, BREAM, or GREEN certifications. (Aenor, 2020).

Building manufacture accounts for a large part of energy consumption in architecture and is a major source of pollution. Faced with this situation, industrialisation is seen as an alternative to reduce such consumption (Azpilicueta, Araujo, 2012). In this sense, the following are considered:

- Origin of raw materials, the use of local raw materials empowers the population and avoids massive emigrations to industrialised areas in search of a better quality of life. It also reduces the energy consumed in transporting raw materials to the factory and from the factory to the building site. In

the absence of more precise information that would allow more demanding criteria to be established, a range has been established according to the data obtained, differentiating between local and imported raw materials, as shown in Table 2.

- Recycled percentage, which is related to industrialised construction, since, by reusing components or recycling materials, it is possible to reuse them (Azpilicueta, Araujo, 2012).
- Additional measures, finally, if the manufacturer takes any environmentally beneficial measures that are not included in the previous categories. An example of this would be the reuse of rainwater or not using water in the manufacture of its components. Due to the variety of measures recorded, only whether additional measures are taken is assessed.

Finally, manufacturers that consider the end of life of their systems are considered, the following are analysed:

- Recyclability, being the best valuation for those systems in which more than half of the materials are recycled.
- Reusability, with a positive evaluation for those systems in which most of the components are reused.

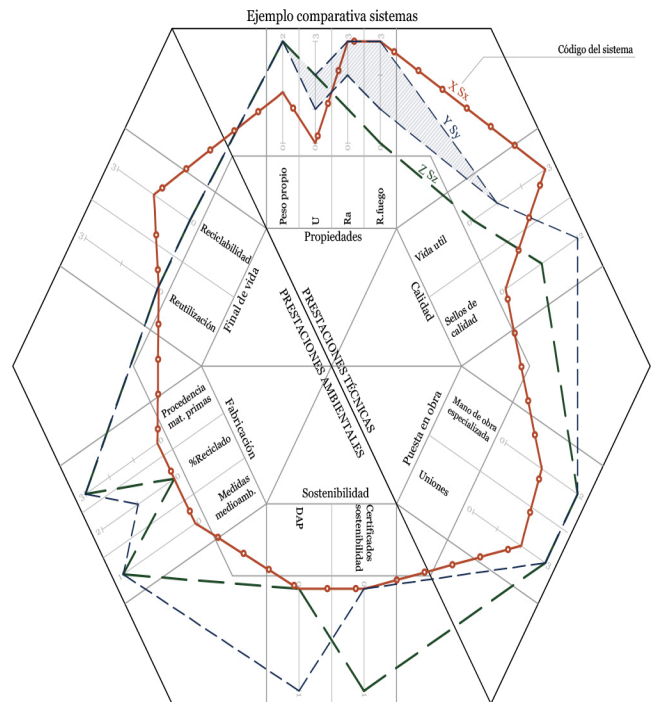


Fig. 1. Evaluation methodology. The figure shows the tool developed, as well as the representation of the performance of three systems to explain how they work.

### III. RESULTS AND DISCUSSION

In this section, a comparative analysis of the industrialised components and systems will be carried out, using the methodology designed. It will start with the structural systems, passing through the façade, roof, and partition walls, until reaching the three-dimensional industrialisation of bathrooms and dwellings, in accordance with the classification set out above (Table 1).

TABLE III  
ELEMENTS AND 2D SYSTEMS

Material	Type	System	Manufacture	Code
<b>Linear structure systems</b>				
<b>Concrete</b>	Heavy Entramado	Precast reinforced concrete columns with rectangular cross section	Tecnyconta	1 E1
		Precast rectangular and circular section HA columns	Gilva	2 E2
		Precast reinforced concrete beams	Gilva	3 E3
		Precast reinforced concrete beams	ANDECE	4 E4
<b>Wood</b>	Heavy Braided	Heavy timber frame	Modulab	5 E5
	Light weave	Light timber frame	Noem	6 E6
<b>Steel</b>	Heavy braided rug	Structural steel sections	CDL	7 E7
	Light weave	Steel frame	Casas de acero	8 E8
	Integrated system	Teccon system	Teccon evolution	9 E9
<b>Slab</b>				
<b>Concrete</b>	Semi-slab/pre-slab	Prestressed ribbed slab floor slab	Zenet	10 E10
	Solid slab	Solid slab floor slab	ANDECE	11 E11
	Hollow core slabs	Hollow core slab slab	ANDECE	12 E12
		Hollow core slabs	Formac	13 E13
	Other	Prestressed ceramic slabs	Cerámica Pastrana	14 E14
		Ligezen slab: Prestressed joists and polystyrene hollow core slabs	Zenet	15 E15
<b>Wood</b>	Solid	CLT double T slab	Egoing	16 E16
	Hollow core	EGO CLT-mix slab	Egoing	17 E17
	Semi-slab/pre-slab	EGO CLT-light slab	Egoing	18 E18
		Light timber-framed panel slab	Arhip	19 E19
		Lightweight timber-framed panel deck slab	Arhip	20 E20
<b>Panels system</b>				
<b>Concrete</b>	Double wall	Reinforced concrete double wall	Proerai	21 E21
	Prefab. panel	BSCP System	BSCP	22 E22
	Integrated system	Ubiko System	Ubiko	23 E23
<b>Wood</b>	Solid	CLT solid panels	Egoing	24 E24
	Alveolar	Sawn laminated timber and strawboard panels	Arropa	25 E25
	Double wall	Plywood and XPS Gbrick deco panels	Garnica	26 E26
		Plywood and XPS Gbrick sip panels	Garnica	27 E27
		Paneles de entramado ligero de madera	Arhip	28 E28

### A. Elements and 2D systems

The structural systems have been grouped into three main categories: linear structures, floor slabs and panel systems; a total of 28 systems have been analysed and are shown in Table 3.

#### a. Linear Systems

This category, whose name is taken from the literature (del Águila, [1987] 2006), includes prefabricated structures with linear elements. In turn, it is structured according to the main material, distinguishing: concrete, wood and steel; with heavy and light framing systems. The latter presents the highest degree of industrialisation due to its dry joints and speed of assembly.

Of the concrete systems, we must highlight their durability, fire resistance and good thermal inertia, among others (Lucas, et al., 2012). However, the fact that their joints are wet (although they may include welding) means that their assembly slows down the strength gain of the bonding mortar. In other

words, their assembly makes it possible to shorten execution times compared to traditional concrete solutions, but despite this, they still depend on the injection of mortar or concrete to guarantee their performance.

Wooden systems, on the other hand, have the advantages of lightness, easy transport, and handling. It is a recyclable material, with low energy consumption in the construction phase, especially if locally sourced timber is used. The disadvantages are its durability and maintenance, which requires, on the one hand, protection against water absorption due to humidity and preventive protection of the wood to guarantee its durability against insects and fungi. On the other hand, in the case of continental climates such as that of the centre of the peninsula, with low relative humidity and high thermal jumps, its use must be limited especially to the interior of the building, protecting it from photo-degradation and making it more stable in its dimensional variability in the face of changes in temperature and relative humidity (Tectónica, 2001).



Fig. 2. Concrete, timber, and steel linear framed systems.

Finally, linear steel systems present a high degree of industrialisation with dry welded or bolted joints, the latter being more commonly used, as the former require greater precision, being relegated more frequently to execution in the workshop, for example, in 3D systems, where conditions are more favourable than on site (Jurado, 1998) and also guarantee greater immobility of the parts during the transport of modules. On the other hand, in the structures of this material, there is a tendency to use computer tools that automate the processes and improve their quality. In addition, its main component, steel, is

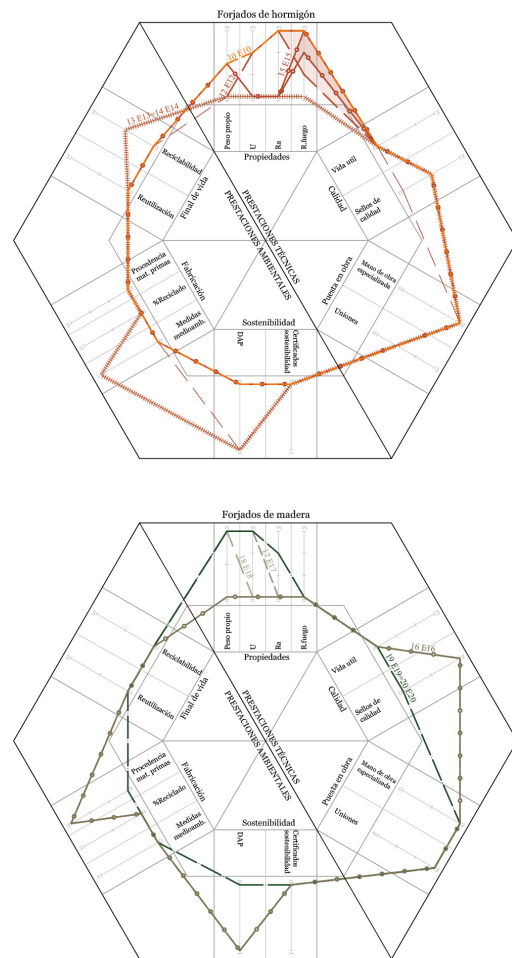


Fig. 3. Concrete, timber and steel linear structures.

100% recyclable, so it has a higher degree of recyclability at source and at the end of its useful life, allowing the reuse of its components. However, it performs poorly in the face of fire, and its high thermal conductivity ( $42 \text{ W/m}^{\circ}\text{C}$ ) means that the effects of fire spread rapidly through the structure. This is solved by avoiding contact between the steel and the fire by means of fireproofing materials that envelop the structure (Jurado, 1998), which is essential in this type of building.

b. Slabs

Among the industrialised floor slabs, concrete slabs, some mixed steel-concrete solutions and, lastly, timber solutions stand out.

Concrete slabs are subdivided into: semi-slabs or pre-slabs, solid or lightened section slabs and ribbed or lightened slabs stiffened by ribs (del Águila, [1987] 2006); in all cases, we must highlight the fact that these are heavy solutions, which require auxiliary means for their handling and installation and that the joints are of the wet type, in order to guarantee structural continuity.

In all cases, these types of wood systems stand out for their lightness, and therefore, the associated transport costs will be lower. On the other hand, the fact that the joints are screwed together means that they can be quickly installed on site.

In the case of CLT systems, there is only one manufacturer in Spain, whereas concrete systems, which are more widespread, have several manufacturers. Most of the

components have quality seals. In addition, hollow-core slabs and CLT slabs have a DAP. The origin of the raw materials in the concrete systems is not provided, although it is foreseeable that the cement will come from nearby cement plants, while in the CLT systems, wood from nearby forests is used, with PEFC Chain of Custody certificates.

c. Panel systems

This group is structured into concrete and timber systems. In this case, there is a clear difference between the two materials in such a way that, compared to the typification of concrete systems in which their shapes and characteristics are standard or more repeated, in the case of wood there is great variability, and it is in this type of system where the greatest innovations have taken place (Grohe, 2001).

The advantage of concrete panels is the possibility of including insulation in their interior, fulfilling a double structural and enclosure function; they can also include installations; however, this makes it difficult to repair them in the event of a possible breakage. Both in this type of system and in the linear concrete systems, the fact that their joints are damp slows down the construction process in comparison with systems made of other materials.

Regarding wood surface systems, two types can be distinguished: composite section and solid section.

Composite section systems have a structural character, although they leave a space inside, which is filled with insulation or left hollow for the passage of installations (Grohe, 2001). In all cases, it should be noted that the joints foreseen with these systems are screwed, so they have a high degree of industrialisation, with the limitation of the joint with the foundation, which must be designed to guarantee separation from the ground and prevent damp.

On the other hand, the manufacturers of these wooden panels consider lightness as a fundamental value of their systems, and in some cases, they can be handled by one or more people, without the need for auxiliary lifting equipment. They therefore present better conditions for their handling and installation on site.

Regarding environmental performance, it should be noted that it is mainly in the case of wood-based panels that manufacturers provide data on the origin of their raw materials. These come in most cases from sustainably managed forests, although only in some cases are the forests close to the place of manufacture and distribution, which would be the most appropriate way to guarantee and promote local industry and reduce the impact associated with transport.

d. Façade

This section includes façade systems that do not have a structural function in the building. This type of system can function as an enclosure for both industrialised and traditional housing (del Águila, [1987] 2006). They can also be used as building envelopes for other uses.

Depending on their weight, façade systems can be classified into heavy and light (del Águila, [1987] 2006), the first group includes façades of reinforced concrete panels, while the second group includes: ventilated façades; non-ventilated façades of

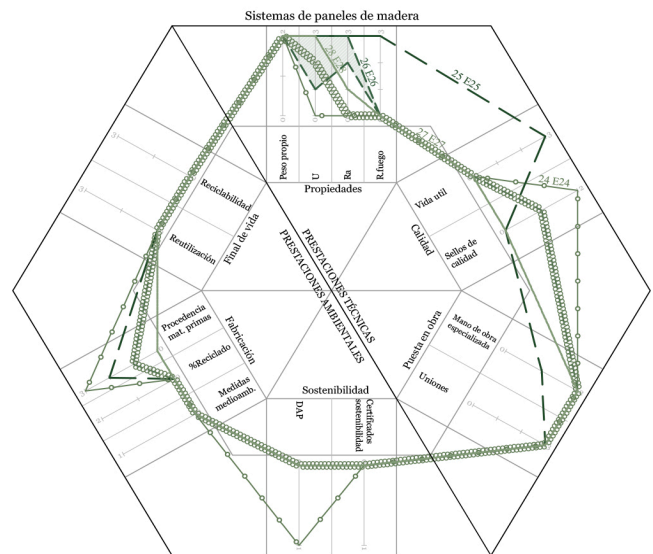


Fig. 4. Concrete and timber structural panel systems

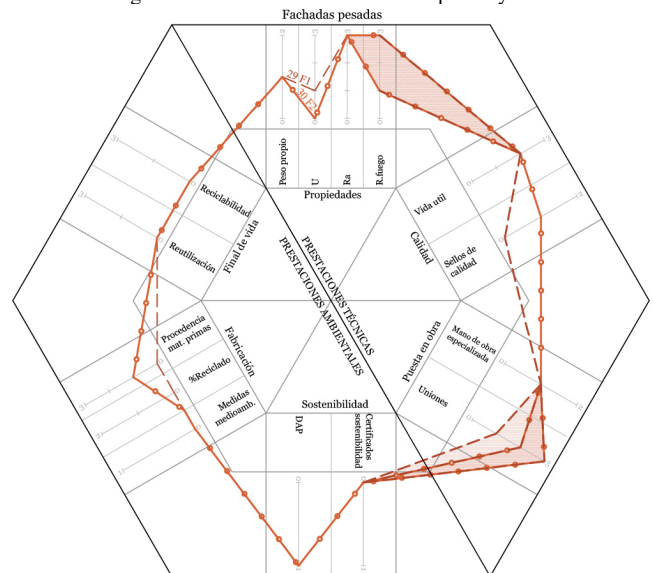


Fig. 5. Heavy façade systems.



homogeneous panels, or sandwich panels; and thermal insulation systems on the outside with a light supporting wall.

Again, heavy façade panels are very widespread and present little variation in terms of types, although they do have a variety of finishes, with dry or wet joints. They are classified as: homogeneous or multilayer concrete panels, depending on their composition (del Águila, [1987] 2006).

Lightweight façade systems have a greater variety in terms of types and finishing materials than heavy systems. This variability and extension may be since they can be dismantled and are lightweight, which is an important advantage, as well as to their dry screwed joints, which allow them to be installed quickly. Compared to these, heavy systems have the advantage of a longer service life, according to the information gathered.

On the other hand, of the façade systems, although only one of them has a sustainability certificate, almost all of them have Environmental Product Declarations. Some of them also include statements that the use of their systems allows points to be obtained for environmental certificates, but without greater technical rigour.

TABLE IV  
 ELEMENTS AND 2D SYSTEMS. FAÇADE.

Materia l	Type	System	Manufa cturer	Code
<b>Heavy façade systems</b>				
<b>Concret e</b>	Solid panel	Homogeneous concrete panel façade	ANDEC E	29 F1
		Prefabricated self-supporting architectural concrete panel	Prehorq uisa	30 F2
	Multilayer panel	Concrete sandwich panel façade	ANDEC E	31 F3
<b>Lightweight façade systems</b>				
<b>Miscella neous</b>	Ventilated	Partition wall for ventilated façade	Knauf	32 F4
		External cladding for ventilated façade	Knauf	33 F5
		Passivehaus ventilated façade	Knauf	34 F6
		GRC ventilated façade	PlanasA rk	35 F7
		Prodex ventilated façade	Prodema	36 F8
		Arkwall ventilated facade	Isopan	37 F9
	Not ventilated	GRC sandwich panel façade	ANDEC E	38 F10
		Lightweight façade with double-skinned partition wall	Knauf	39 F11
		Lightweight façade with double-skinned partition wall and intermediate panel	Knauf	40 F12
		Isoparete sandwich panel	Isopan	41 F13
		SATE+ light interior wall	Knauf	42 F14
		Termochip wall + SATE Termochip	Termoc hip	43 F15

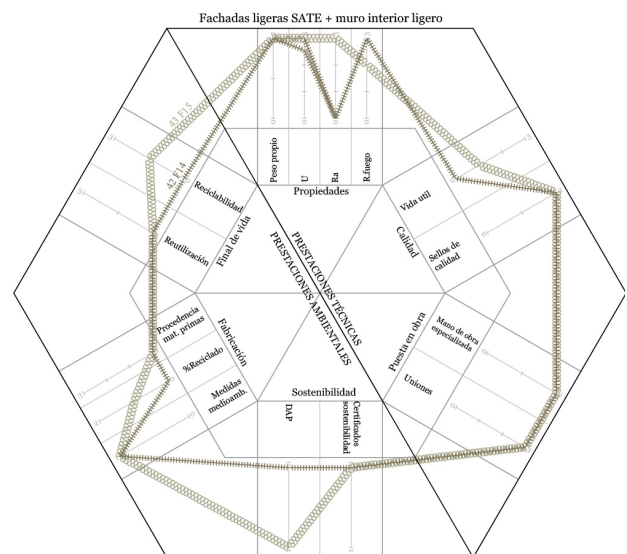
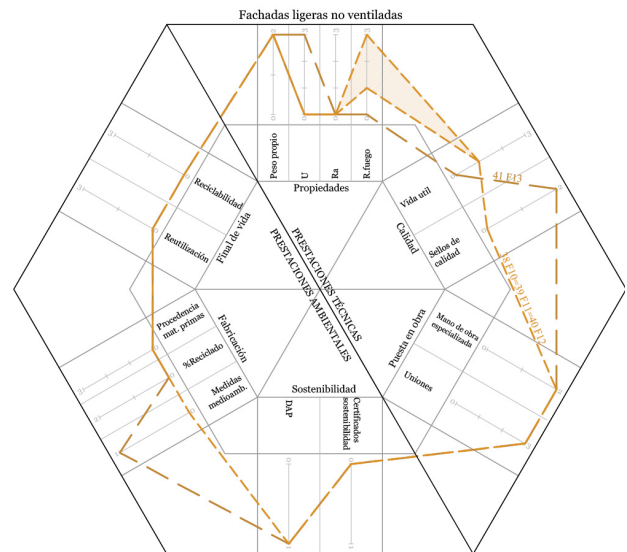
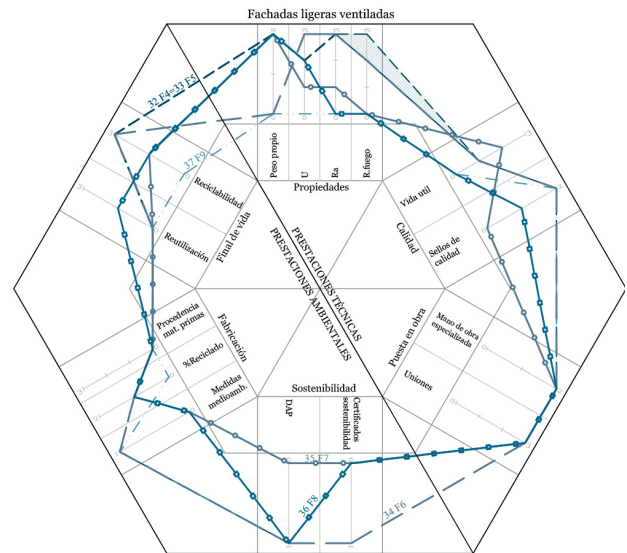


Fig. 6. Lightweight façade systems.

e. Roofs

This section includes roofing components with two types of systems: sandwich panels made of different materials and an industrialised system for green roofs.

Regarding sandwich panels, there are different variations depending on the type of finishing material on each side, as well as the type of thermal insulation used. The most common are exterior plywood panels (Gbrick) and fibre cement panels (Thermochip) with extruded polystyrene insulation in most cases (Thermochip and Gbrick), although wood fibre can also be used (Gbrick). Finally, the interior can be finished with plywood panels (Gbrick) or with a layer of fibre plaster (Thermochip).

All these systems are lightweight, especially the Gbrick panel with extruded polystyrene insulation, which has a weight of 17 kg per panel that can be handled by one person. The systems have quality seals, with easy-to-install screwed dry joints. From an environmental point of view, the Isopan panels stand out, which have WTP. In the case of Garnica wood panels, the raw material comes from sustainable European plantations, with PEFC and F certificates.

TABLE V  
ELEMENTS AND 2D SYSTEMS. ROOF.

Material	Type	System	Manufactu ring	code
Miscella neous	sandwich Panel	Gbrick cover	Garnica	44 C1
		Termochip roof flat roofs	Termochip	45 C2
		Termochip roof sloped roof	Termochip	46 C3
		Termochip roof WF	Termochip	47 C4
		Isodomus	Isopan	48 C5
	Landscaped system	Green Roof TP	Isopan	49 C6

f. Partitions

Industrialised partition walls have several advantages over traditional ones, such as improved quality, reduction of debris and the possibility of including installations inside them (del Águila [1987] 2006).

Industrialised partitioning systems have been classified into panel partitioning, floor-ceiling panel partitioning and laminated plaster partitioning (del Águila, [1987] 2006). The latter is the most widespread system at present, of which there are four manufacturers in Spain: Knauf, Gypfor, Placo and Pladur.

All the registered partitioning systems are lightweight, most of them have dry screwed joints and a high degree of industrialisation, except for plasterboard, plaster and cellular concrete partitions, whose degree of industrialisation is lower. In the case of laminated plasterboard partitions, the great variability of the configurations offered is noteworthy, covering a wide range of thermal transmittance, acoustic resistance, and fire resistance, offering solutions for almost any situation. It is also noteworthy that this manufacturer indicates the origin of its main raw material, which is

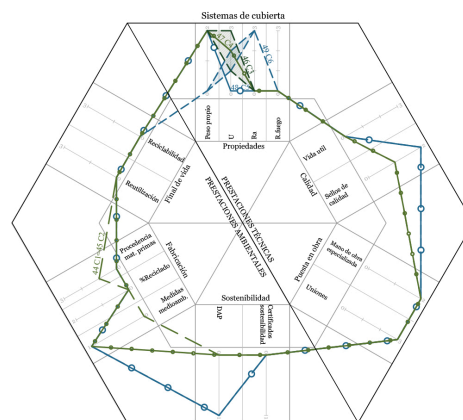


Fig. 7. Lightweight roofs systems.

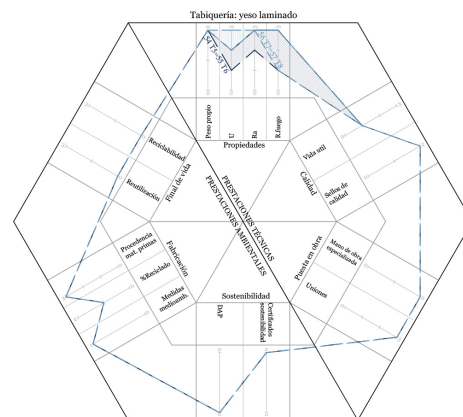


Fig. 8. Partitions 2D systems.

TABLE VI  
 ELEMENTS AND 2D SYSTEMS. PARTITIONS.

Material	Type	System	Manufacturer	Code
Miscellaneous	Panels	Aerated concrete slab partition wall	Ytong	50 T1
		Gypsum plasterboard partition wall	Escayesos	51 T2
	Floor-ceiling panels	Partition wall made of light-weight framed panels	Arhip studio	52 T3
		Extruded polystyrene partition walling	Termochip	53 T4
	Gypsum plasterboard Panels	Single gypsum plasterboard partition	Pladur	54 T5
		Multiple gypsum plasterboard partition	Pladur	55 T6
		Gypsum plasterboard partition wall single double-chamber structure	Pladur	56 T7
		Gypsum plasterboard partition wall with independent double-chamber structure	Pladur	57 T8

obtained 4.6 km from the factory, its boards have DAP and the material discarded by the quality management system is incorporated in its manufacture as recycled material.

### B. 3D Systems

Three-dimensional systems represent the highest degree of industrialisation. The entire dwelling, or a bathroom or kitchen module, is built in the factory; these modules leave the workshop finished, incorporating their installations, interior finishes and external surfaces; the only operation carried out on site is the joining of the modules, the placement of some finishing touches and the connection with the general networks (del Águila, [1987] 2006).

This type of system allows the most significant reduction in construction times, given that the manufacture of the modules in the workshop overlaps with the time required to process licences.

There are two groups of 3D systems, those in which a kitchen or bathroom module is industrialised, and those in which the entire dwelling is industrialised.

#### a. Bathrooms

They can be called "pods" or technical units and are kitchen and bathroom modules (Gómez, 2009). These types of cells include at least the following: sanitary appliances, horizontal and vertical ductwork, accessible registers, interior cladding and finishes, electrical installation, heating apparatus and an extractor fan (del Águila, [1987] 2006).

This type of system can be classified in turn into heavy and light cells (del Águila, [1987] 2006), both types are marketed in Spain, manufactured by Hydrodiseño, which offers the

possibility of customising the system to adapt it to the project by varying its dimensions, technical and decorative specifications. The heavy cells are made of concrete, while the light cells are composed of a metal structure and laminated plaster walls. It is noteworthy that this manufacturer's products have carbon footprint certificates.

#### b. Housing

As mentioned above, in our country there is a general tendency towards 2D industrialisation due to the greater ease of transport and simpler financing. Even so, there are several cases of 3D systems whose advantage is the speed of their overall execution, although, in general, these systems are relegated to large-scale developers.

With regard to 3D housing modules, it should be noted that sustainability standards are generally pursued, with high energy ratings. Moreover, in most of the cases analysed, the modules are stacked, allowing both horizontal and vertical spatial connection between the different pieces, without the size of a module needing to correspond to the size of the space produced (Reyes, 2018). In contrast to the view that industrialising housing would result in mass-produced, identical housing, new technologies allow for mass customisation, i.e. variations can be introduced in the production of systems, resulting in a wide variety of solutions.

Such systems consist of three main materials: concrete in heavy systems; wood and steel, which constitute lightweight systems (del Águila, [1987] 2006).

Heavy systems are conditioned, as their name indicates, by their heavy weight, which makes them difficult to transport and

TABLE VII  
 3D SYSTEMS.

Material	Tipo	Fabricante	Código
<b>Bathrooms</b>			
Concrete	Industrialised bathroom module CUBIK	Hydrodiseño	59 3D1
Wood	Industrialised bathroom module CUBIK Steel	Hydrodiseño	60 3D2
<b>Housing</b>			
Concrete	Self-compacting reinforced concrete six-sided modules	Worldmetor	61 3D3
Steel and concrete	Linear steel structure and concrete panels	inHaus	62 3D4
Steel	Cube and Premium models	Cube	63 3D5
	Hauss System	Hauss	64 3D6
	Bhome MAS system	ArcelorMittal, Baragaño y Neoblock Modular	65 3D7
	Modultec Modular Systems	Modultec	66 3D8
Wood	Travelling Suite	Modultec	67 3D9
	Prototype 2008	Modultec	68 3D10
	Noem go	Noem	69 3D11

install on site. However, they have the advantage of the stability and rigidity of their modules, which represents an advantage, as possible deformations are avoided during their installation on site. They also stand out for their good thermal and acoustic insulation and their greater durability compared to other systems (Azpilicueta; Araujo, 2012). However, one of its disadvantages is that, in the event of a breakdown, as the installations are embedded in the concrete, it is difficult to repair them (Gómez, 2009).

Only one heavy 3D concrete system has been found in our country, which, unlike the structural systems of this material, has dry joints and is therefore more industrialised, as the stability of the whole is entrusted to the high weight of the modules.

In contrast, the main advantage of lightweight systems is their ease of transport and assembly, as well as their demolition and dismantling at the end of their useful life, which allows the reuse or recycling of their elements (Gómez, 2009), a characteristic shared with some two-dimensional lightweight systems.

The most widespread systems have laminated steel structures and composite sheet metal slabs. Their joints are dry bolted or welded, with the latter prevailing again to adapt to their unique on-site installation. The weak points of lightweight steel systems are their fire resistance and acoustic insulation, which require additional costs to achieve acceptable performance (Azpilicueta; Araujo, 2012) and the lack of thermal inertia which, in climates such as continental ones, have the disadvantage of a lack of bioclimatic suitability.

Finally, there are some three-dimensional wooden houses, which, like other systems of this material, stand out for their environmental performance with: the search for a low impact on the environment; the use of certified wood from the area and closed-cycle materials; and the incorporation of passive and active environmental control and water management systems.

#### IV. CONCLUSIONS

Based on the theoretical bases and foundations of industrialisation and, through the experimental study, classification and standardisation of the information gathered, a visual evaluation system has been developed that allows quantitative comparison of the different parameters considered, from which conclusions are drawn about the current industrialisation panorama in Spain. The search for assessment standards that allow an objective, effective and agile comparison of the systems would encourage the use of industrialised systems among technicians. In contrast, the different manufacturers provide very different and, in some cases, insufficient data to assess the systems from the point of view of their technical and environmental performance. Specifically, the parameters that, following the research, are key to improving the demand for these systems by technicians are:

- The definition of objective technical parameters for each type of system, which are provided by the manufacturers, and allow the comparative assessment of the performance

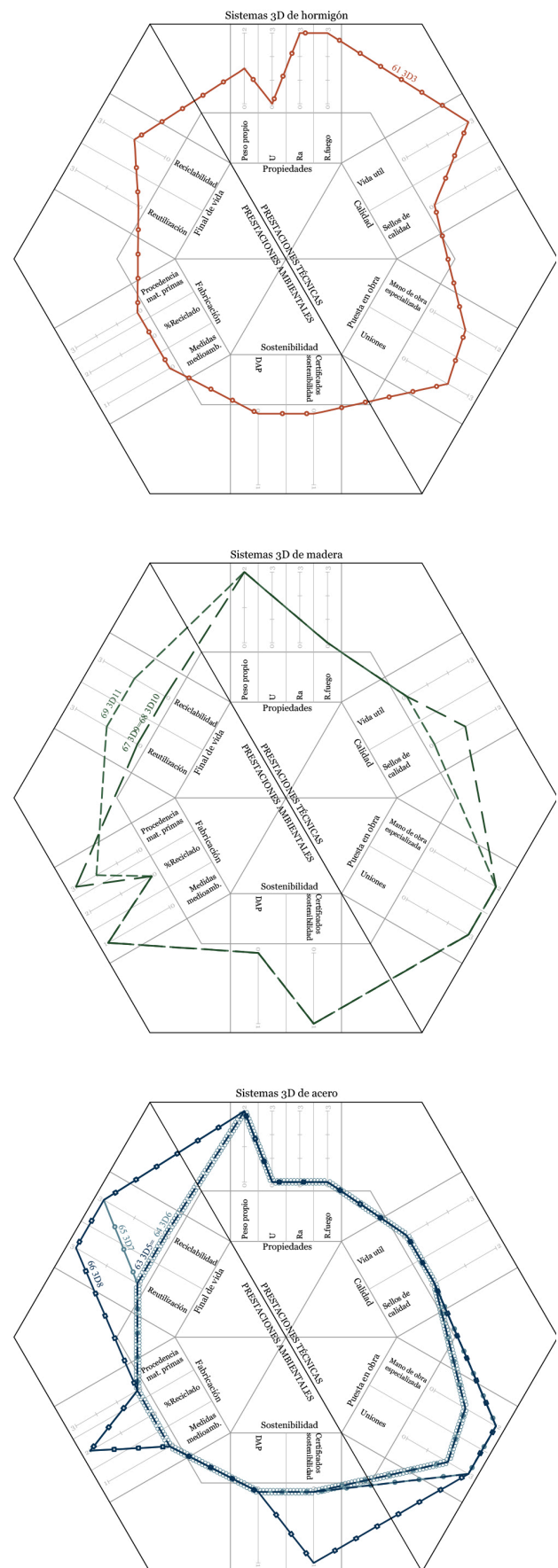


Fig. 9. Housing 3D Systems.

of their systems.

- The analysis of the impacts associated with the life cycle of the systems and their repercussions on the building, from cradle to grave. Providing rigorous information on the origin of raw materials to promote local industry and reduce the impacts associated with transport. Incorporating the end of life of systems as a selection criterion, seeking to reduce waste through reuse and recycling.
- The search for sustainability standards with high energy certifications based on existing sustainability certifications.

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