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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 m3 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 m3 and 0 - 547.63 kWh respectively.**

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

# 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-desing-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-PHP 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 CO2 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 (Moradisbistouni, 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 | nº Systems |
| Structure | Linear | Concrete | Heavy lattice | 4 |
| | | Wood | Heavy lattice | 1 |
| | | | 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 | 1 |
| | | | 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 | nº Systems |
| Bathroom | Heavy | Concrete | | 1 |
| | Light | Steel | | 1 |
| Housing | Heavy | Concrete | | 1 |
| | Light | Wood | | 3 |
| | | Subcategory | | 4 |
| | | | 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/m2], 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/m2K], 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 | | | | | |
| **Properties** | | | | | |
| Dead weight | [kg/m2] | No data provided | > 200 | <200 | |
| Transmittance | [W/m2 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 |
| Quality | | No data provided | | | |
| Service life | [Years] | No data provided | 50 | 50-100 | >100 |
| Quality seals | | No data provided | Sí=1 | Sí>1 | |
| On-site installation | | | | | |
| Spatialised workmanship | | No data provided | Sí | No | |
| Joints | [type] | No data provided | Wet | Dry Welded | Dry Screwed |
| Environmental performance | | | | | |
| **Sustainability** | | | | | |
| Sustainability certificates | [kg/m2] | No data provided | Sí | | |
| Environmental product declarations | [kg/m2] | No data provided | Sí | | |
| **Manufacturing** | | No data provided | | | |
| Sourcing of raw materials | | No data provided | Import | Local / Import | Local |
| Percentage recycled | [%] | No data provided | < 50% | >50% | |
| Additional measures | | No data provided | Sí | | |
| **End-of-life** | | | | | |
| 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.

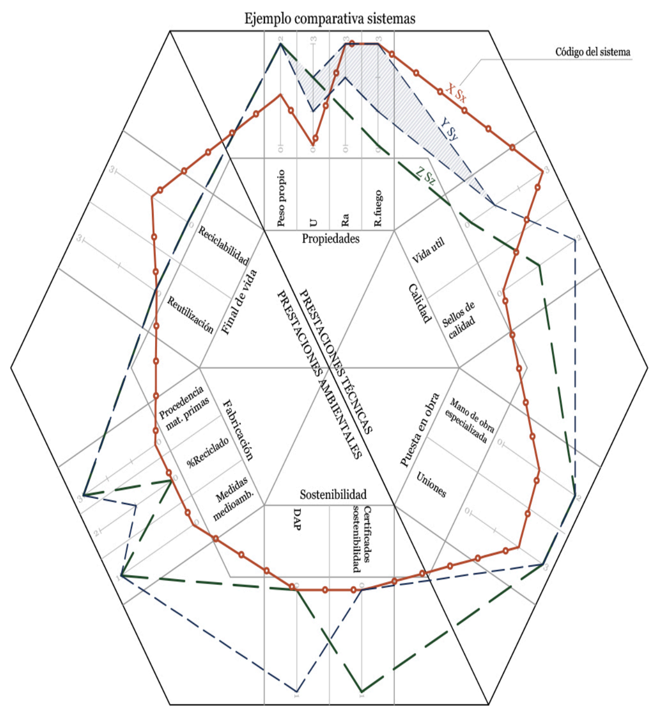


Fig. 1. Evaluation methodology. The figure shows the tool developed, as well as the representation of the performance of three systems to explain how they work.

## 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 | Manifacture | Code |
|---|---|---|---|---|
| | | **Linear structure systems** | | |
| **Concrete** | 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 |
| **Wood** | Heavy Braided | Heavy timber frame | Modulab | 5 E5 |
| | Light weave | Light timber frame | Noem | 6 E6 |
| **Steel** | 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 |
| | | **Slab** | | |
| **Concrete** | 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 |
| **Wood** | 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 |
| | | **Panels system** | | |
| **Concrete** | Double wall | Reinforced concrete double wall | Proerai | 21 E21 |
| | Prefab. panel | BSCP System | BSCP | 22 E22 |
| | Integrated system | Ubiko System | Ubiko | 23 E23 |
| **Wood** | 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).

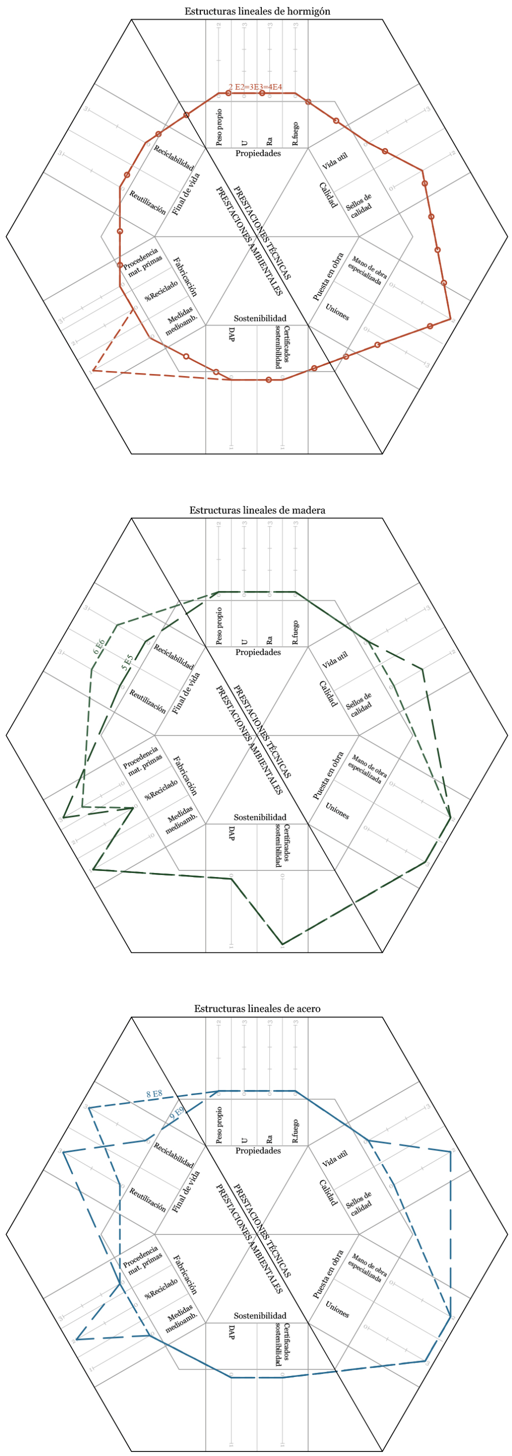


Fig. 2. Concrete, timber, and steel linear framed systems.

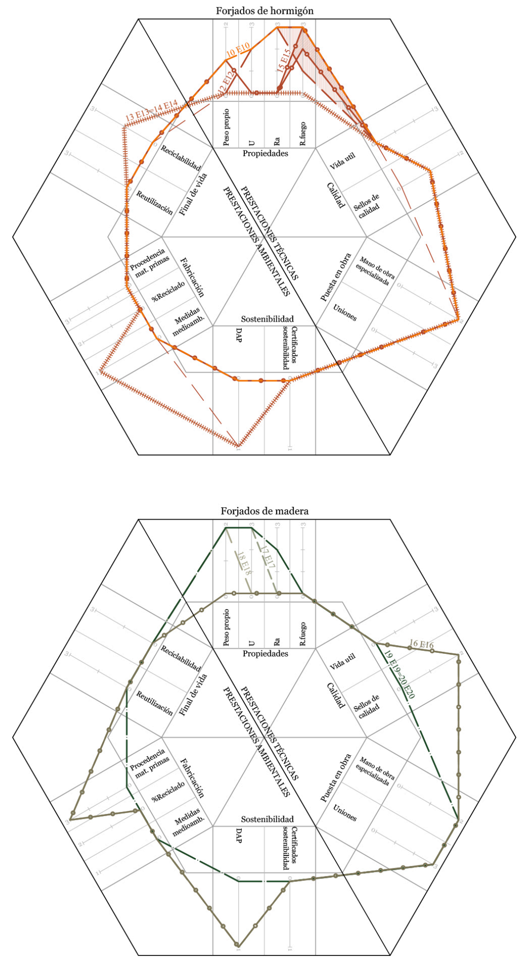


Fig. 3. Concrete, timber and steel linear structures.

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 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 W/m·ºC) 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

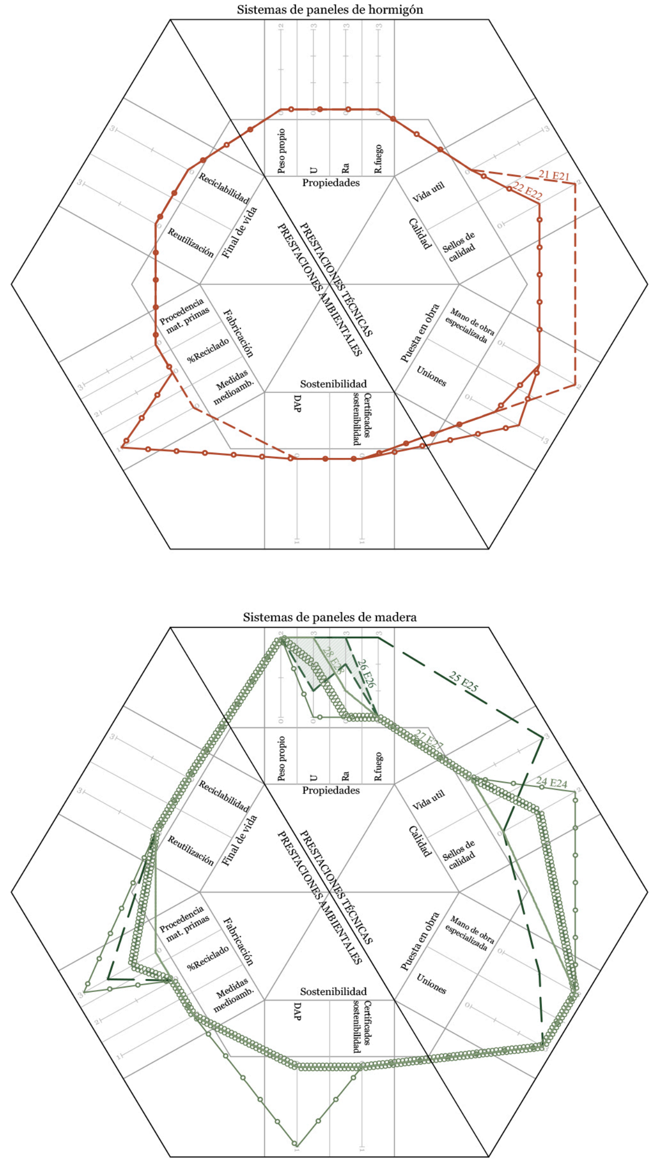


Fig. 4. Concrete and timber structural panel systems

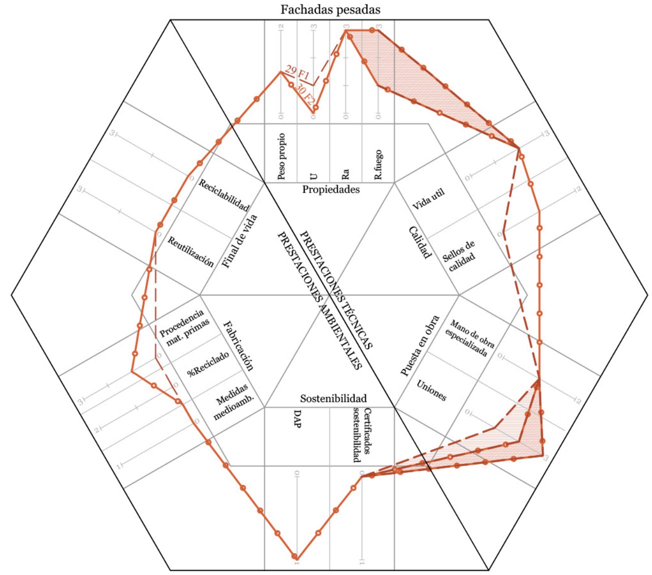


Fig. 5. Heavy façade systems.

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.

| Material | Type | System | Manufacturer | Code |
|---|---|---|---|---|
| | | **Heavy façade systems** | | |
| **Concrete** | Solid panel | Homogeneous concrete panel façade | ANDECE | 29 F1 |
| | | Prefabricated self-supporting architectural concrete panel | Prehorquisa | 30 F2 |
| | Multilayer panel | Concrete sandwich panel façade | ANDECE | 31 F3 |
| | | **Lightweight façade systems** | | |
| **Miscellaneous** | 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 | PlanasArk | 35 F7 |
| | | Prodex ventilated façade | Prodema | 36 F8 |
| | | Arkwall ventilated facade | Isopan | 37 F9 |
| | Not ventilated | GRC sandwich panel façade | ANDECE | 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 | SATE with Aquapanel façade partition wall | Knauf | 42 F14 |
| | | Termochip wall + SATE Termochip | Termochip | 43 F15 |

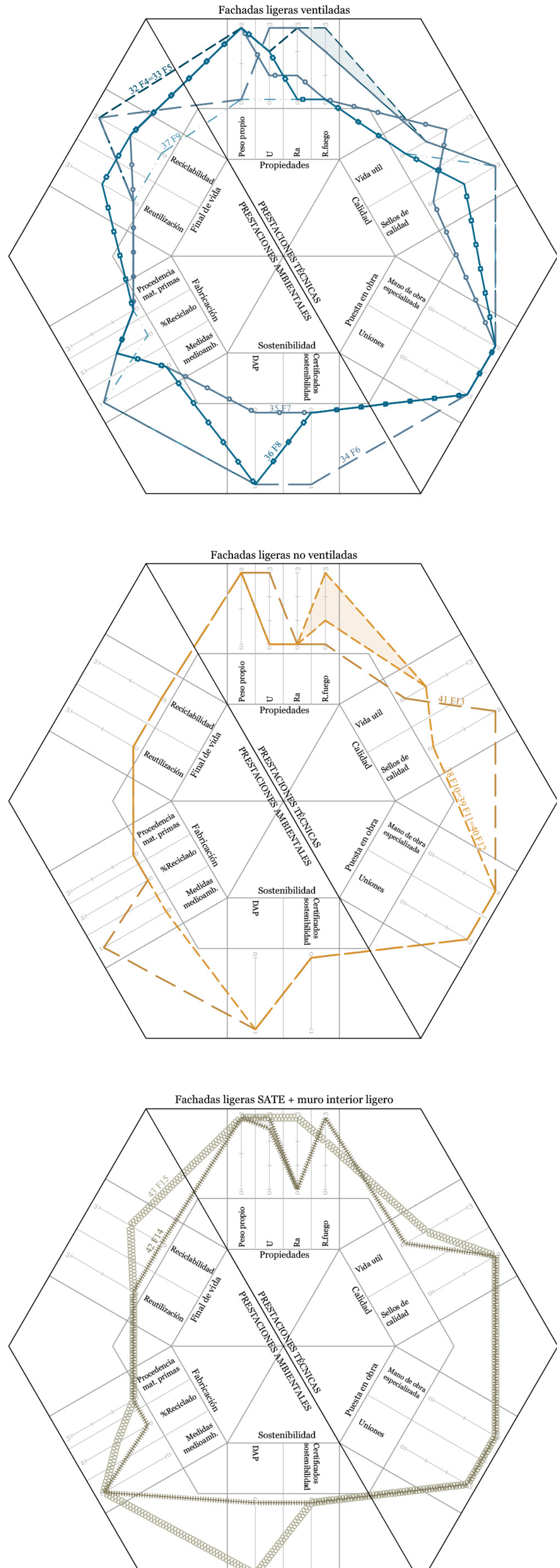

Fig. 6. Lightweight façade systems.

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 | Manufacturing | code |
|---|---|---|---|---|
| **Miscellaneous** | 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

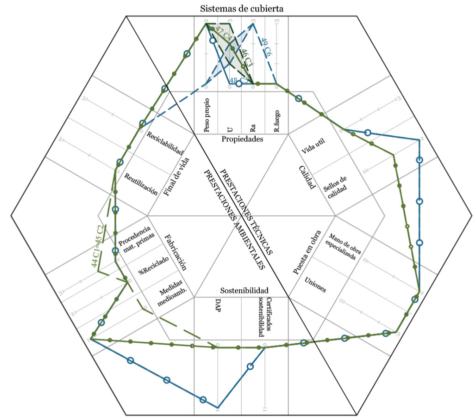


Fig. 7. Lightweight roofs systems.

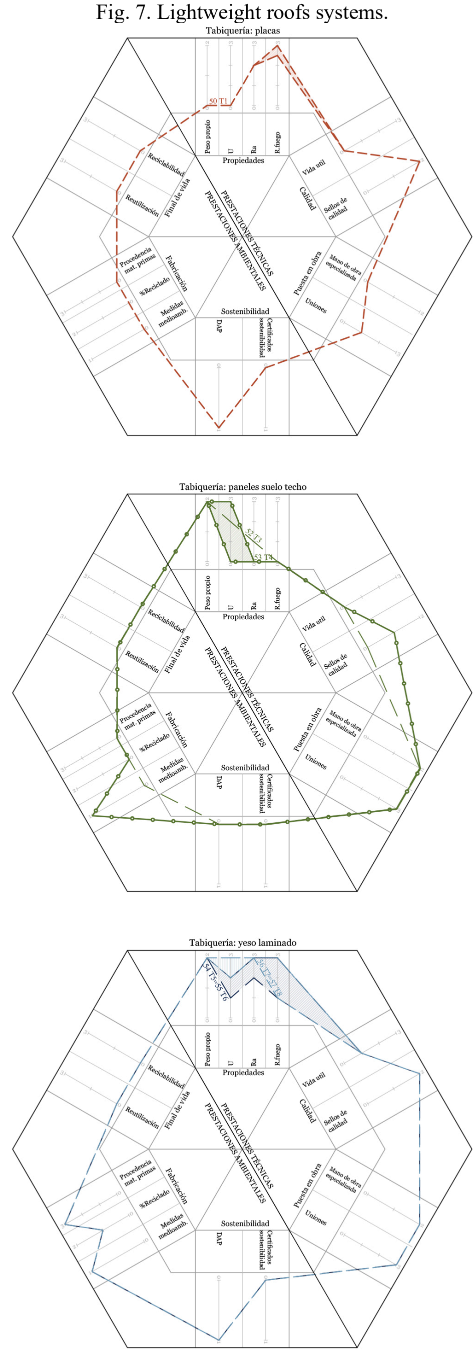


Fig. 8. Partitions 2D systems.

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 |
|---|---|---|---|
| | **Bathrooms** | | |
| **Concrete** | Industrialised bathroom module CUBIK | Hydrodiseño | 59 3D1 |
| **Wood** | Industrialised bathroom module CUBIK Steel | Hydrodiseño | 60 3D2 |
| | **Housing** | | |
| **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.

## References


AVELLANEDA, Jaume ; J.Mº GONZALEZ ; G. MARQUES; J.VIDAL (2009). “La innovación tecnológica desde la promoción de vivienda pública: el Concurso de Innovación Técnica INCASOL” Informes de la Construcción, 61, 513, 87-100.

AZPILICUETA, Enrique; ARAUJO, Ramón (2012) “El mito industrial”, Tectónica, 38, 4-19

CHEN, Ying; OKUDAN, Gül E.; RILEY, David R. (2010). “Decision support for construction method selection in concrete buildings: Prefabrication adoption and optimization”, Automation in construction, 19, 665-675.

Código Técnico de la Edificación (CTE) Documento Básico de Ahorro de Energía (DB-HE) (2019)

Código Técnico de la Edificación (CTE) Documento Básico de Protección Frente al Ruido (DB-HR) (2019)

Código Técnico de la Edificación (CTE) Documento Básico de Seguridad en caso de Incendio (DB-SI) (2019)

Comité Europeo de Normalización “Norma Europea UNE-EN 15804 Sostenibilidad en la construcción. Declaraciones ambientales de producto. Reglas de categoría de producto básicas para productos de construcción”

CRIBBS, John (2020). “Supporting a Model for Increased Labor Time Utilization When Engaging Building Information Modeling for Prefabrication”, Construction Research Congress, 841-850

DEL ÁGUILA GARCÍA, Alfonso (2006) [1987]. “La industrialización de la edificación de viviendas. Tomo 1: Sistemas. Tomo 2: Componentes.”, Madrid, Mairea libros

DU, Qiang; BAO, Tana; LI, Yi; HUANG, Youdan; SHAO, Long (2019).

“Sustainable Impact of prefabrication technology on the cradle to site CO2 emissions of residential buildings”, Clean Technologies and Environmental Policy, 21, 1499–1514.

GALLO, Paola; ROMANO, Rosa; BELARDI, Elisa(2021). “Smart Green Prefabrication: Sustainability Performances of Industrialized Building Technologies”, Sustainability 13, 4701, 1-31.

GÓMEZ JÁUREGUI, Valentín (2009) “Habidite: viviendas modulares industrializadas” ,REVISTA, 61, 513, 33-46 .

GROHE, Gred (2001) “El futuro de la construcción con madera”, Tectónica ,13, 28-37.

HONG, Jingke; QIPING Shen, Geoffrey; LI, Zhengdao; LI, Kaijian (2016). “Life-cycle energy analysis of prefabricated building components: an inputeoutput-based hybrid model”, Journal of Cleaner Production, 112, 2198-2207.

JIANG, Yongsheng; ZHAO, Dong; WANG, Dedong; XING, Yudong (2019). “Sustainable Performance of Buildings through Modular Prefabrication in the Construction Phase: A Comparative Study”, Sustainability, 11,5658, 1-15.

JURADO, José “Naturalidad del acero” (1998), Tectónica, 9, 18-25

LIA, Xiao; QIPING SHENB, Geoffrey; WUC, Peng; YUE, Teng (2018). “Searching for an optimal level of prefabrication in construction: An analytical framework”, Journal of Cleaner Production, 201, 236-245.

LIA, Xiao; QIPING SHENB, Geoffrey; WUC, Peng; YUE, Teng(2019). “Integrating Building Information Modeling and Prefabrication Housing Production”, Automation in Construction, 100, 46-60.

LUCAS, P.; SALAS,J.; BARRIONUEVO,R. (2012) “Cuarenta años del PERVI-LIMA: Algunas enseñanzas para la industrialización de la vivienda de bajo coste en Latinoamérica.”, Informes de la Construcción, 64, 525, 51-62.

MAO, Chao; XIE, Fangyun; HOU, Lei; WU, Peng; WANG, Jun; WANG, Xiangyu (2016). “Cost analysis for sustainable off-site construction based on a multiplecase study in China”, Habitat international, 57, 215-222.

MONTES, J.; CAPS, I.P.; FUSTER, A. (2011). “Industrialización en la vivienda social de Madrid”, Informes de la Construcción, 63, 522, 5-19.

MORADIBISTOUNI, Milad; VALE, Brenda; ISAACS, Nigel (2018). “Evaluating sustainability of prefabrication methods in comparison with traditional methods” Sustainability in Energy and Buildings: páginas 228-237.

PASSIVHAUS INSTITUT (2016) “Criterios y algoritmos para componentes certificados passivhaus: sistemas constructivos opacos” https://passiv.de/downloads/03_certification_criteria_componentes_opacos_ES.pdf

PÉREZ ARROYO, Salvador (2009). “Industrializar” Informes de la construcción, 61, 513, 5-10.

REYES, J.Miguel (2018) “3D-bonding vocabulary (building systems with 3D-components)”, Anales de Edificación, 4, 4, 42-54.

SAIZ SÁNCHEZ, Pablo (2015). “La casa industrializada. Seis propuestas para este milenio.” Tesis doctoral. Escuela Técnica Superior de Arquitectura. Universidad Politécnica de Madrid. http://oa.upm.es/40341/

SAIZ, Francisco (2019) “Encuentro sobre madera y construcción. Industria de la madera” Instituto Torroja TV https://www.youtube.com/watch?v=xB1mnyVXoT8&t=2s

SALAS, Julián (2009) “Por la industrialización de la vivienda aquí y ahora”, Ciudad y territorio, XLI, 161, 629-644.

SALAS, Julián; BLÁZQUEZ, A.; et al. (2013) “Los documentos de idoneidad técnica como potenciales incentivadores de la industrialización de la construcción”, Informes de la Construcción, 65, 531, 275- 288.

SARAIVA FREITAS, Iuri Abreu; ZHANG, Xingxing (2018).

"Green building rating systems in Swedish market- A comparative analysis between LEED, BREEAM SE, GreenBuilding and Miljöbyggnad" Energy Procedia, 153, 402-407.

TECTÓNICA (2001) "La revolución de la madera", Tectónica, 13,1.

TENG, Yue; LI, Kaijian; PAN, Wen; NG, Thomas (2018) "Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies", Building and Environment, 132,125-136.

WAKED, Ingy; VAN BALEN, Koenraad (2019). "Knowledge and Skills associated to Craftsmanship for Built Heritage Conservation and Rehabilitation: Case Study - Historic Cairo", Professionalism in the Built Heritage Sector, 109-116.