Universitat de Lleida

Sustainable industrialized house-building design customization under costs and environmental criteria

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TESI DOCTORAL

Sustainable industrialized house-building design customization under costs and environmental criteria

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Founding

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Summary

The construction sector has been the object of constant transformations in the design and construction methods motivated by the needs of the market and the evolution of society. Today there is a clear trend in the industry towards productivity, sustainability and customization. This has led to the gradual consolidation of industrialized house-building (IHB) in the market as a solid alternative to traditional construction due to its environmental and economic benefits, the increase in productivity and the contribution to the performance of the quality and safety standards.

European legislation and directives in the field of energy efficiency in buildings focus on renovating the building stock, giving priority to reducing the sector's high energy consumption. At the same time, there is a growing demand for tailored products where users are increasingly interested in home design configuration. In this context, the demand for customized housing that meets high standards of sustainability with the lowest cost appears to be a challenge for the industry. While industrialized house-building (IHB) allows for a sustainable construction phase in comparison to traditional construction methods, the field of design for the sustainable use of housing is not yet sufficiently exploited. In fact, existing house-building design optimization techniques are not valid for the industry because they require excessive human and machinery resources. Therefore, today the IHB industry is able to offer sustainably manufactured housing but does not guarantee a reduction in energy consumption during its use phase.

To cover this need, this thesis studies and presents a design process that allows to customize homes considering cost and environmental impact criteria during the use phase of house-buildings and also allows to assess the associated costs. This procedure and the proposed improvements significantly reduce the resources required during the design process, enable customization, and encourage the reduction of the environmental impact of house-buildings. This design process has been adapted to the singularities of the industrialized building system of the company PMP Prêt-à-Porter Cases (Lleida - Spain), which is based on the prefabrication of concrete modules (2D) or panels.

It is worth highlighting the sustainability and cost studies associated with the industrialized building system of PMP carried out throughout this thesis, which represent a useful contribution of experimental and analytical data for the IHB industry. It is also provided a study of the IHB design stage state of the art as well as a technical analysis of the industrialized building system design of different firms in the sector, identifying the industrialization index as a key factor for achieving high productivity. The results obtained during these analyses, and the reflections provided, should set the guidelines for future works in this field of research.

Resum

El sector de l'edificació ha sofert una constant transformació en els mètodes de disseny i construcció d'habitatges marcada per les necessitats del mercat i l'evolució de la societat. Avui en dia hi ha una clara tendència de la indústria cap a la productivitat, la sostenibilitat i la customització. Això ha comportat que, poc a poc, la industrialització d'habitatges (IHB) es vagi consolidant al mercat com una alternativa sòlida a la construcció tradicional pels seus beneficis mediambientals i econòmics, l'increment de productivitat i la contribució a l'acompliment dels estàndards de qualitat i seguretat.

La legislació i les directives Europees en el camp de l'eficiència energètica dels edificis es centren en renovar el parc edificatiu donant prioritat a la reducció de l'elevat consum d'energia del sector. Al mateix temps, existeix una demanda creixen de productes fets a mida on els usuaris s'interessen cada cop més en la configuració del disseny dels habitatges. En aquest context, la demanda d'habitatges customitzats que acompleixin els alts estàndards de sostenibilitat amb el menor cost associat a la construcció apareix com un repte de la indústria. Si bé és cert que la industrialització d'habitatges (IHB) permet una fase de construcció sostenible en referència als mètodes de construcció tradicional, el camp del disseny per a l'ús sostenible dels habitatges encara no està prou explotat. De fet, les tècniques d'optimització de dissenys d'habitatges existents no són vàlides per la indústria degut a que requereixen excessius recursos humans i de maquinària. Per tant, avui en dia la indústria és capaç d'oferir habitatges fabricats de manera sostenible però no garanteix una reducció del consum d'energia durant la seva fase d'ús.

Per cobrir aquesta necessitat, en aquesta tesi s'estudia i es presenta un procés de disseny que permet customitzar els habitatges considerant criteris de costos i d'impacte mediambiental durant la fase d'ús i, a més, permet avaluar-ne els costos associats a la fase de construcció. Mitjançant aquest procediment i a les millores proposades es redueixen notablement els recursos necessaris durant el procés de disseny, s'habilita la customització i es fomenta la reducció de l'impacte mediambiental dels habitatges. Aquest procés de disseny s'ha adaptat a les singularitats del sistema constructiu de l'empresa PMP Prêt-à-Porter Cases (Lleida - Espanya), basat en la prefabricació de mòduls (2D) o panells.

Val la pena destacar els estudis de sostenibilitat i costos associats al sistema de construcció industrialitzat de PMP efectuats al llarg d'aquesta tesi, que representen una aportació de dades experimentals i analítiques útil per a la indústria IHB. També s'aporta un estudi de l'estat de l'art de l'etapa de disseny IHB així com un anàlisi tècnic del disseny del sistema constructiu de diferents empreses del sector, identificant l'índex d'industrialització com a factor clau per l'assoliment d'una alta productivitat. Els resultats obtinguts al llarg d'aquests anàlisis, així com les reflexions aportades, han de marcar les directrius de properes recerques en aquest camp d'investigació.

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Figures and tables

Document structure

This document is structured in the following six chapters.

- **Chapter 1. Introduction**. The motivation, the context and the challenges of this thesis are presented. The concept of industrialized house-building is described and the benefits of industrialization techniques in the construction sector are listed. The chapter explains the importance of energy efficiency, customization and costs reduction in the residential sector.

- **Chapter 2. Objectives**. The general objective of the thesis is presented and the specific objectives are listed in detail.

- **Chapter 3. State of the art: industrialized house-building design**. A historical review of the IHB design is carried out and, at the same time, the evolution of the technology applied to the sector is studied. The study is based on an extensive literature search of articles and books in the field of housing industrialization. It serves to identify the main features of the history of the IHB, which is divided into different periods. The chapter explains these periods in detail. In addition, the main needs of the sector are considered and their future trends are identified. Then, the most important results of the study are summarized in a homogeneous and continuous timeline following a methodology based on the analysis of different key factors of industrialized house-building design.

- **Chapter 4. Firms industrialized building system analysis**. The industrialized building system (IBS) design of 29 IHB firms from around the world is analysed and compared following a suggested characterization and evaluation criteria. The criteria consist of 9 technical parameters considered key when designing a building system, weighted from 0 to 100 according to CTE (https://www.codigotecnico.org/) regulations and/or PMP experience in the sector. The CTE is the official technical code for building construction in Spain. The results of the study allow PMP company (https://pretaportercasas.com/) to position itself with respect to competitors, detecting the virtues and margins for improvement of its IBS.

- **Chapter 5. PMP industrialized building system sustainability study under heating, cooling and construction costs criteria**. A comparative study under criteria of energy efficiency during the use phase of houses (operational phase) between the PMP building system, prefabricated concrete modules (2D) with exterior insulation technology building system and lightweight wood frame building system is presented. The heating and cooling energy demands of 12 different house-building design scenarios (4 scenarios for each building system) were evaluated in EnergyPlus (https://energyplus.net/). The construction costs of each scenario were also calculated in parallel in a (.csv) developed file. Studies of air leakages, thermal bridges, opaque envelope and openings were done to characterize thermal and economic data to characterize the three building systems under study.

- **Chapter 6. Industrialized house-building design customization under heating, cooling and initial investment costs criteria**. A time-efficient design procedure in terms of human and computing resources that allows the design of homes to be customized under the criteria of energy costs and initial investment costs is developed. The procedure integrates 4 cornerstones: (1) template, (2) configurator, (3) result viewer and (4) customer-oriented decision-making. The procedure developed is based on the following 6 stages: (1) catalogue: a finite catalogue of construction elements that the house-building company offers to its customers to integrate into the design of their homes; (2) briefing: a meeting between technicians and customers to agree on the minimum requirements for the building to be designed; (3) template and configurator: a customer-focused adaptation of the study according to the agreed decisions; (4) calculation; (5) result-viewer: a graph that shows the initial investment cost and the annual heating and cooling costs of multiple studied design configurations and; (6) decision-making.

The methodology, material and tools used to carry out the different sections of this document are detailed at the beginning of each chapter.

Chapter 1. Introduction

Motivation

This doctoral thesis is part of a joint collaboration between the University of Lleida (Spain) and the company PMP Prêt-à-porter cases (Lleida-Spain) in the framework of the "Doctorats Industrials de la Generalitat de Catalunya" program (https://doctoratsindustrials.gencat.cat/es/).

PMP Prêt-à-porter cases (https://pretaportercasas.com/) is a firm in the industrialized house-building (IHB) sector that is dedicated to the development of projects that include the design, production and construction of custom house-buildings. PMP has its own industrialized building system (IBS) based on the prefabrication of concrete non-volumetric modules (2D) and/or panels. This IBS, together with other key factors in all PMP projects such as planification, customer service and/or logistics makes PMP house-buildings stand out above the traditional on-site construction for its environmental benefits, increased productivity and reduced delivery time. In addition, the commitment to a mass customization building system allows PMP to focus on the production strategy to create value by tailoring the product to the specific needs of customers (Hvam et al. 2017).

In general, society is becoming increasingly aware of the paramount importance of sustainable development in building, which involves the production, construction and use of environmentally friendly, economically profitable and well-guaranteed house-buildings. In this context, the design for the sustainable use of buildings appears as a necessary strategy for IHB sector firms to be able to offer a sustainable product beyond production and construction. In fact, the costs and levels of environmental sustainability of buildings are defined in the early stages of design (Wang, Zmeureanu, and Rivard 2005). At the same time, there is a growing demand to customize the interiors and facades of buildings which makes, today, the user participation in product configuration a key factor in building design (Larsen et al. 2019).

The motivation of this thesis is to develop solutions that contribute to the progress of the industrial fabric of the IHB sector focused on the sustainable design of custom products under costs and energy consumption criteria.

Context

Industrialized house-building

Industrialization in construction, commonly linked to the concepts of prefabricated construction, industrialized building systems (IBS) and/or offsite construction, appeared in the mid-20th century all over the world as a solid alternative to traditional building construction (Kamali and Hewage 2016).

In the context of this thesis, the labels industrialized house-building (IHB) and industrialized building system (IBS) are two distinguished concepts. IBS refers only to the set of properties of prefabricated modules, such as width, volume and/or material. In contrast, industrialized house-building (IHB) is a more complex concept defined by Lessing (2006) where the focus is not only in the product itself, or in its prefabricated modules, but also in the process, organization and technical issues integrated and reinforced by continuous improvements.

This thesis focuses on the client and the decision-making associated with architectural design, IBS design and production strategy design. The development of technical solutions, use of ICT and re-use of experience and measurements are also considered. Other areas such as logistics, manufacturing or process control are beyond the scope of this doctoral thesis. On the contrary, the use phase of house-buildings (operational phase) that in the conceptual framework established by Lessing (2006) is not considered as a characteristic area, appears as a key factor in this research.

IBSs design depends on many factors, for example the construction materials or the prefabricated parts (Boafo, Kim, and Kim 2016). As Gibb (2001) established, four different building systems could be differentiated analysing their prefabricated parts: (1) component manufacture and sub-assembly (1D[1]), (2) non-volumetric preassembly (2D), (3) volumetric preassembly (3D), and (4) modular building (3D). The PMP (https://pretaportercasas.com/) IBS, which is based on concrete panels (2D) belongs to non-volumetric preassembly. After, in chapter 4, the PMP IBS is detailed. In this thesis, a new important key factor to classify IBSs design, never used before, is defined, characterized and evaluated in chapters 3 and 4, the industrialization index.

There are a number of benefits associated with practicing IHB: (1) environmental sustainability, (2) productivity, and (3) quality and safety.

- **Environmental sustainability**. In the construction sector, there is a wide variety of environmental benefits related to industrialization, such as: less depletion of natural resources (Aye et al. 2012), reducing dust, dirt and noise on-site (Jaillon and Poon 2009) and the reduction of construction waste on-site (Baldwin et al. 2009). In addition, these techniques make it easier to deconstruct buildings, eliminating the need to completely demolish their structures once they reach the end of their useful life. This means being able to reuse materials and/or structures.
- **Productivity**. Industrializing construction processes, traditionally done on site by operators, favours the reduction of construction costs and shortens the delivery time of buildings (Gibb 2001). Moreover, productivity is increased (Akmam Syed Zakaria et al. 2018) and mass production, which is needed to meet the growing demand for buildings, is guaranteed.
- **Quality and safety**. Traditional outdoor working conditions during part of the on-site construction process are being replaced by a controlled work environment inside industrial buildings (Lou and Kamar 2012). This allows to contribute to the fulfilment of the standards of security and health of the workers (Li, Shen, and Xue 2014). Also, quality control of materials, components and structures is improved (Akmam Syed Zakaria et al. 2018).

Energy consumption

This thesis focuses on the concept of sustainability in the IHB sector from the point of view of energy consumption and, specifically, energy consumption in relation to heating and cooling.

According to official data from EUROSTAT (Eurostat 2022), the final energy consumption of the residential sector in 2019 accounted for 26.3% of total energy consumption in the European Union. This consumption was directly translated into carbon emissions into the atmosphere. In addition, it contributed negatively to the depletion of materials and water.

In this context, state regulations CTE-DB-HE (Fomento 2019) in Spain and European directives in the field of energy efficiency of buildings as NZEB (Commission 2016) are focused on renewing the park of public and private buildings giving priority to energy efficiency. To achieve

[1] "D" means the dimension of the prefabricated parts or modules.

these goals, it is necessary to use more sustainable construction methods and, at the same time, design passive buildings under environmental criteria (Attia et al. 2021). Moreover, it would also be interesting to educate society to make a sustainable use of buildings.

To properly assess the levels of environmental sustainability, it is necessary to analyse the depletion of natural resources, energy consumption, carbon emissions and the generation of waste during the complete house-building life-cycle, that is divided into the following five phases shown in Figure 1-1: (1) planning and design, (2) production, (3) construction, (4) operational, and (5) deconstruction. This thesis focuses on the study of energy consumption for heating and air conditioning of industrialized homes.

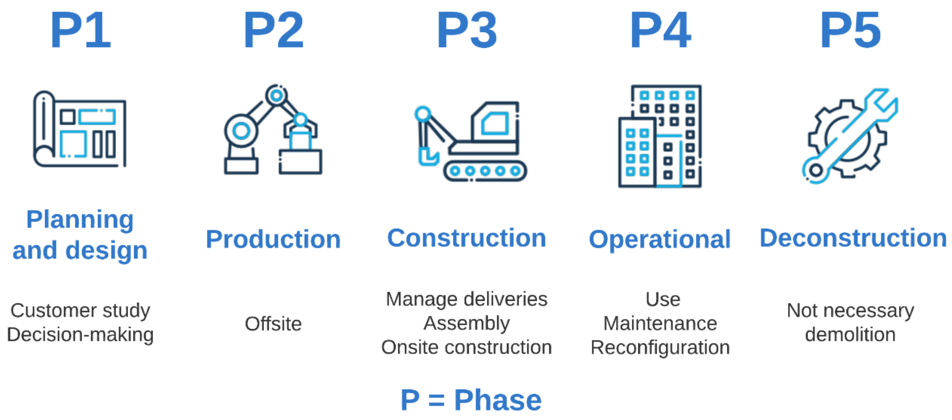


Figure 1-1. House-building life-cycle. Phases adapted from (Gosling et al. 2016).

The initial phase of the house-building life-cycle is planning and design, which includes a study aimed at identifying customer needs and defining building objectives, such as thermal performance and/or number of stories. Then, the proposals related to the architectural design and the design of the building system are proposed, evaluated and discussed.

Conventional building design strategies under environmental criteria seek, on the one hand, to reduce the thermal transmittance of the envelope and, therefore, its energy losses (Arbor 2009). On the other hand, proper management of solar gains through windows in the summer and winter seasons appears to be a powerful tool for reducing the energy demands of buildings (Ochoa et al. 2012).

After, the customer agrees on the final design of the building and the conditions of purchase. The production and construction processes are then studied, planned and programmed. The environmental impact that is generated in this initial stage (planning and design phase) is negligible compared to what is generated in the later phases. But paradoxically, key factors for a building sustainable performance such as the thermal insulation or the orientation are established early in the design stage (Wang, Zmeureanu, and Rivard 2005). For this reason, design has a paramount importance to achieve sustainable development in the housing sector.

The next steps are the execution of the production phase, which integrates the supply of raw materials and the off-site manufacturing of modules, and construction phase, which includes the management of deliveries, the assembly of the IBS modules and the other necessary on-site construction tasks. In these two stages, industrialized construction has a great advantage in terms of sustainability over traditional on-site construction for its efficient management of natural resources, reduction in energy consumption and reduction in the on-site environmental impact (Jaillon and Poon 2009).

After construction, the operational phase is characterized by the use of buildings and its retrofitting. The environmental impact during the use of buildings has its most important component in the energy consumption of heating, cooling and ventilation systems (HVAC systems). In addition, the water consumption and the waste generated by the activity of using the buildings must be added. This environmental impact does not depend on industrialization. The design of the thermal envelope of the buildings determines the heating and cooling loads, as well as the comfort levels, natural light and ventilation (Acar, Kaska, and Tokgoz 2021). Hence, the architectural design and the design of the building system are highly related to the environmental impact during the operational phase.

Moreover, the energy efficiency of HVAC systems and user's activity also contribute to the environmental impact during this phase, accounting the 50% of building energy consumption (Pe 2008). Thus, it is not only worthwhile to bet on designing sustainable buildings but also educating owners to make a sustainable use of them.

Finally, deconstruction phase begins once the useful life of the building comes to the end. The specific activities of deconstruction and the environmental impact generated depend on the building system used. For example, a detachable modular system is characterized by a deconstruction process that will not require the demolition of the building. Some IBSs have the advantage of building using components and modules that can be disassembled, reused, and/or relocated. However, it is not the purpose of this thesis to analyse sustainability at this stage (deconstruction phase) or to study the design process for deconstruction.

House-building costs

Reducing costs in the construction sector would ensure accessibility to quality housing (Cao et al. 2021). The costs related to planning and design phase are negligible compared to those of the later stages. However, in the same way as the key factors that define the environmental sustainability performance of a building are defined early in design, so are the costs.

Production and construction are the phases that have a greater weight in the cost of the buildings. All the production and construction tasks have a specific cost. The total cost of those phases is the sum of all specific costs. Each task is performed by a different team of specialists. These specialists are grouped into designers, contractors, subcontractors, customers and suppliers. An important factor that affects the final cost of a building is the coordination between all these stakeholders (Hegazy, Zaneldin, and Grierson 2001). If the coordination between them is not correct, non-value-added activities may appear. An activity with no added value is an unnecessary task that results in an increase in the cost of the final product. For example, an error in communication between designers and painters may result in the use of a wrong colour to paint walls and, after done, the need to repeat the activity with the correct colour. Therefore, it is necessary to establish proper coordination between all the actors involved in the construction of a building in order to be able to control its final cost.

Building information modelling (BIM) has appeared since the early 2000's and is considered a key technology in meeting this challenge. However, despite the advances in this technology, its final benefits have not yet been fully capitalized by industry stakeholders (Huang et al. 2021). As a result, there is still room for improvement in this area and new technological solutions continue to be required to efficiently control the costs associated with building construction. However, the aim of this thesis is not to study the costs related to organization, manufacturing and construction.

An important cost factor, that is object of study, is the cost relative to the use of house-buildings (operational phase). In fact, it is not common that house-building design strategies contemplate this costs item even if, for customers, it represents a significant expense over the years. An example of cost in the use phase is the annual bills of the energy supply companies. Maintenance costs, for example the cost relative to repair aerothermal equipment, are also included in this phase. Those costs depend on the energy performance of the building, the use of HVAC systems and the HVAC systems energy efficiency.

This thesis considers the life-cycle cost (LCC) which includes the costs of the production, construction and operational (heating and cooling systems annual consumption and maintenance) phases. It is not the purpose of this thesis to study the costs related to deconstruction phase.

Customization

Building design is a complex process where a design team of multiple professionals specialised in different fields of architecture and engineering have to make decisions. Ideally, once the construction process begins, the decisions made during the design stage should not be reconsidered. Therefore, the design team must integrate their skills and collaborate jointly with the construction team, contractors, subcontractors and customers in the initial design stage, for example by adopting BIM strategies (Tsai, Mom, and Hsieh 2014).

Traditionally the design of buildings has been adapted to the needs of the users. Today, user have multiple needs, so designing a building that meets all the requirements optimally is not an easy task. Current design techniques require a time-consuming creative process where multiple design solutions are suggested, evaluated and compared. This makes it tedious to reach a design that matches with the building objectives. As a result, the industry is not prepared to offer customers a specific design study that fits their needs. This problem is more serious in the current context where the response speed is increasingly valued in the market (Chonko and Jones 2005). Therefore, a knowledge gap is identified by developing a time-efficient custom design process that allows multiple building solutions to be evaluated and compared (Touloupaki and Theodosiou 2017).

Challenges

Considering the importance of environmental and economic criteria in house-building, it is expected that the most sustainable construction approaches in these two areas will have greater approval by society. This is one of the reasons why the IHB is today a solid alternative to traditional on-site construction and so, PMP is positioned favourably in the house-building market. However, betting on the IHB is not enough to fully address the goal of achieving sustainable development and customization in house-building. Mainly because the IHB contributes to the production and construction of sustainable house-buildings, but not to the customization of design for sustainable use of buildings. Today, reduce the environmental impact throughout the energy consumption in house-buildings use phase and reduce costs related to initial investment, use and maintenance are challenges for the industry (Figure 1-2).

To ensure that the products of the IHB industry can be configurated and also guarantee a more sustainable use phase, it is necessary to review and improve the way in which house-buildings are designed today. To do this, the challenge of developing a time-efficient customer-focused house-building design process under costs and energy consumption criteria must be faced (Figure 1-2).

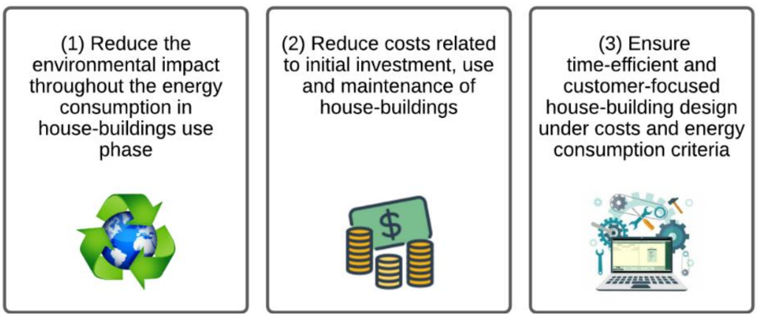


Figure 1-2. Thesis challenges

Chapter 2. Objectives

The general objective of this thesis is to develop a solution that allows a time-efficient design customization of industrialized house-buildings under heating, cooling and initial investment costs criteria. This general objective is divided into the following specific objectives:

- Study the industrialized house-building (IHB) design state of the art.
    - Identify and define key factors for decision making during the industrialized house-building (IHB) design stage.
    - Study and describe the defined key factors evolution in relation to the industrialized house-building market trends over the course of history.
    - Identify new trends for the defined key factors.
    - Develop a timeline that shows the results of the study.
- Evaluate and compare the PMP industrialized building system (IBS) against its competitors in the IHB market.
    - Define a criteria for characterizing and evaluating IBSs design
    - Identify IHB firms with specific IBSs around the world.
    - Characterize, evaluate and compare IHB firms IBSs
    - Identify in which key factors the IBSs of PMP stands out with respect to the other IBSs analyzed, and in which not.
- Carry out an extensive study of costs and heating and cooling energy consumption applied to the PMP building system.
    - Analyse air leakages from industrialized PMP house-buildings.
    - Calculate the thermal bridges of the PMP system.
    - Evaluate and compare the impact on heating, cooling and initial investment costs of alternative building systems that stand out in the market.
- Develop a time-efficient design process that allows customization of housing under criteria of heating, cooling and initial investment costs.
    - Review the current house-building design process based on parameterization and optimization strategies.
    - Evaluate and consider life-cycle costs (LCC) in the design process.
    - Implement improvements that reduce the resources needed to conduct design studies.
    - Define and describe the improved design process.
    - Adapt the design process to the singularities of the PMP building system.

Chapter 3. State of the art: industrialized house-building design

Methodology and structure

This chapter presents the state of the art of industrialized house-building (IHB) design phase. Figure 3-1 summarizes the main contents of the study and the applied methodology. The research is based on a review of published international papers and books on the subject of IHB until 2020. Figure 3-1 details the search engines and keywords used.

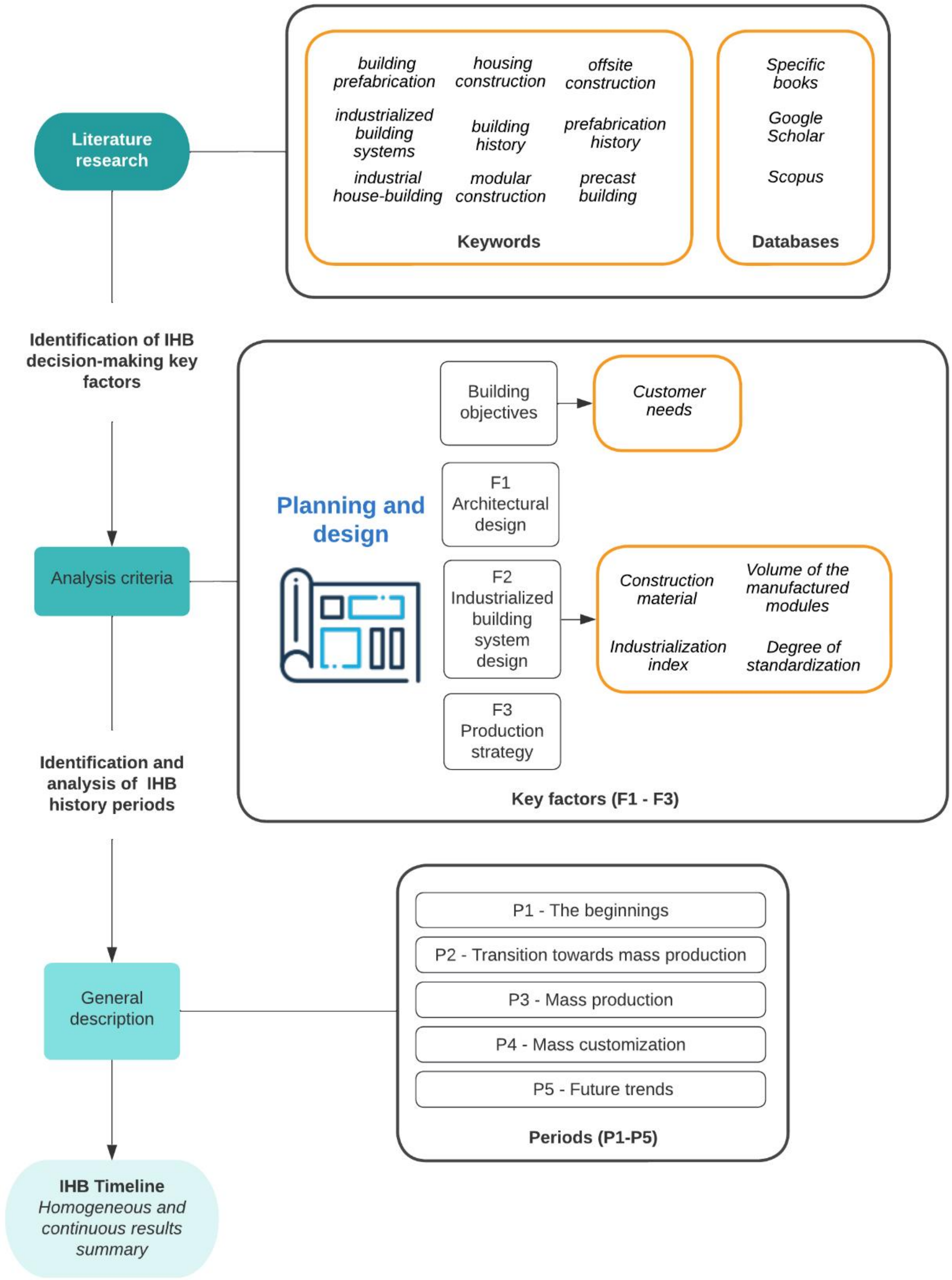


Figure 3-1. Chapter 3 contents and methodology

When reviewing the literature, it becomes clear that market tendencies, such as environmental sustainability, cost reduction and customization, have been conditioning the supply chain of IHB projects. As a consequence, IHB has been the object of relevant transformations in design, production and construction. It is worth taking a close look to identify the key factors which have allowed IHB to both evolve and solidify over time. In this context, and especially in view of the environmental challenges that the building sector must face in the coming years, it is a good time to report on the best practices and lessons learned in the IHB industry and establish its future guidelines.

Previous studies addressing the evolution of industrialization in construction have successfully contributed to describing good practices in the sector throughout history. In general, they describe building real-cases adopting industrialization techniques by using the analysis criteria that each author has considered appropriate at the moment of conducting each study.

Arieff and Burkhart (2002) explained a brief history of prefabricated housing based on house-building examples and contributions from different architects, designers, and manufacturers, such as Le Corbusier, W. Gropius and Buckminster Fuller.

Some years after, Jaillon and Poon (2009) reviewed the evolution of precast systems in high-rise residential developments in the public and private sectors from the mid-80s to 2007. The authors analysed the volume of precast elements, degree of prefabrication and construction cycle (days/floor). A timeline of precasting innovations was also included to show and highlight when each innovation occurred, both in the public and private sector

More recently, Agren and Wing (2014) summarized the main improvements in IH from 1750 to 1972, also by placing these improvements along a timeline. The authors used many parameters to characterize the diverse developments that appeared in their "five moments in the history of industrialized building". One example was W.H. Lascelles's precast concrete panels introduced in 1878, characterized by the building system (prefabricated concrete panels).

After, Lessing, Stehn, and Ekholm (2015) analysed and compared the housing outputs of three IH firms from Scandinavia, characterizing the building system and process and focusing on business models, logistics, use of ICT, organization, and market requirements.

These previous authors, although they use similar real-case description methodology, have not used the same analysis criteria neither studied the same historical stages. This makes it tedious to compare the results obtained in those studies and impossible to gain a complete and useful view of the advances made in IHB over the course of history. Consequently, there is a knowledge gap which makes it impossible to get the full picture of how IHB key factors have historically adapted to market tendencies.

In order to remedy this lack of uniformity, this chapter presents the evolution of IHB (from 1624 to today) as a homogeneous and continuous timeline showing the transformation of three key factors in IHB design. To do this, an analysis criteria was established taking into account that all the decisions and efforts affecting an IHB project are geared toward cost-efficiently constructing a house-building that satisfies the customer's needs.

During the design and planning stage, a market study is conducted where the building objectives are agreed upon. Building objectives define the customer priorities, that can be related for example to the design customization, price or delivery time (Lessing and Brege 2018).

Then, architectural design (F1[2]), industrialized building system (IBS) design (F2), and production strategy (F3) are chosen in decision-making based on the building objectives (Peltokorpi et al.

[2] "F" means key factor

2018). Thus, the analysis criteria consisted on the study of IHB design responses (F1, F2 and F3) to market tendencies (building objectives).

The industrialized building system (IBS) design (F2) was analysed based on four parameters: construction material, volume of the manufactured modules (1D, 2D or 3D), industrialization index (low-high) and degree of standardization (low-high).

The industrialization index is a parameter that was defined in this study that takes into account not only the volume of the prefabricated parts but also the ratio of the complete building that is manufactured. To evaluate the industrialization index of construction processes, the following building core elements were analysed (Figure 3-2): foundations, services, structure, skin and fit-out. Moreover, a weight was assigned to each core element according to the percentage it costs with respect to the total cost of the PMP projects as follows: structure, skin and fit-out (35%), foundations (20%) and services (45%). For example, one manufacturer may produce strucural load-bearing concrete panels (non-volumetric preassembly) including all the skin elements and, also, the fit-out. Meanwhile, another manufacturer may do the same but also manufacture services in a different off-site production line. Hence, the industrialization index is higher in the second case (80%). Hence, the higher the number of building core elements manufactured for an IBS, the higher the industrialization index.

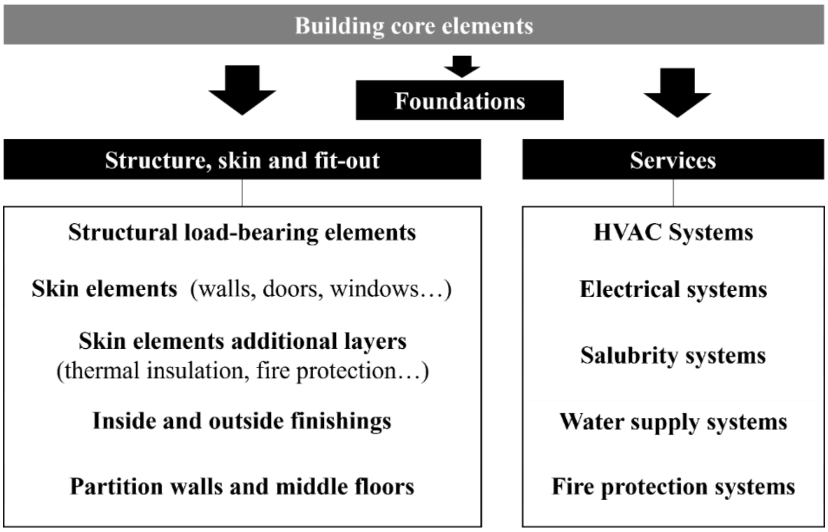


Figure 3-2. Building core elements. Adapted from Nadim and Goulding (2010).

This analysis criteria allowed, first, to organize the IHB evolution throughout history in the following identified periods:

- Period 1. The beginnings (1624-1913)
- Period 2. Transition towards mass production (1914-1945)
- Period 3. Mass production (1946-1989)
- Period 4. Mass customization (1990-present)
- Future trends

Those periods are described and, after, the results of the analysis are presented in a timeline.

Historical review

The beginnings (1624-1913)

Around the 17th century, the IHB industry emerged in the British Isles to provide materials and prefabricated handcrafted elements to distant colonies. One example of those developments was when, in 1624, wooden panels were shipped from England to build a fishing fleet in Cape Ann, Massachusetts (Boafo, Kim, and Kim 2016). The primary purpose was to cope with the growing demand for housing for newcomers in these unexplored areas where the quantity and type of raw material were unknown.

Moreover, at that time, logistics and transport in the colonies were not efficient enough, making the easy manipulation of elements an essential requirement for such systems. Apart from the English, the Swedes introduced techniques for the easy construction of wood cabins (Arieff and Burkhart 2002). Those techniques were the first approach in housing construction towards what is currently known as the circular economy (Kyrö, Jylhä, and Peltokorpi 2019). Thus, the basis was that elements manufactured with simple tools from one area could be used in another place to generate new economic activities.

The most famous examples of IHB during the 19th century are the Manning Portable Colonial Cottage (Australia, 1830), the first kit houses (California, 1849), and the Crystal Palace (London, 1851), all of them manufactured in the UK (Ågren and Wing 2014). The increasing demand for housing linked to the first innovations derived from the Industrial Revolution resulted in the use of new materials such as iron and glass. In addition, the prefabrication appeared with a higher degree of manufacturing and standardization.

The first American companies, such as Aladdin (1906) and Sears (1908), to begin selling homes in kits of precut, numbered components via catalogue appeared by the end of this period, offering their customers the chance to buy affordable dwellings. Another example is Frank Lloyd-Wright's American System-Built Homes (1911) company, which provided low-priced houses made of standardized timber frame modules that were also sold by catalogue. The main goal of these companies was to develop both a low-cost and an easy-to-build house produced by the combination of wood standardized elements, since customization had started to be a requirement for a specific profile of customers. Moreover, another noticeable issue is that architects, designers and housing companies focused their efforts on design, planning and production stages rather than construction itself. External contractors or even the owners themselves carried out the on-site tasks. Hence, coordination between stakeholders, manufacturers, constructors and customers, during the different stages of projects, was limited or non-existent.

Transition towards mass production (1914-1945)

The second period on the IH timeline lasted for around three transitional decades characterized by innovations and changes in an industry where the main objective was the mass production of buildings. Prefabricated construction emerged as an effective alternative to traditional on-site construction (Kamali and Hewage 2016) during the 20th century, mainly since it became a clear way to save on labour (Nadim and Goulding 2010), building time and costs (Gibb 2001).

From the beginnings of the 20th century to the end of the Second World War (1945), the increasing demand for social buildings, military residences and hospitals, on top of the general labour shortage, set off the eruption of new construction methods in the building sector. "Quonset huts" (Decker and Chris, 2005) are examples of prefabricated buildings developed during the Second World War.

Throughout this period, to cope with the high demand for cheap and fast-erected buildings, an industry of standardized light prefabricated elements was developed in the UK, France, Germany, and Sweden (Arieff and Burkhart 2002). Moreover, as reuse and potential for relocation were crucial market requirements for the development of the new systems, circular economy was also present in the production strategies of house-builders.

During this period, European architects made relevant contributions to the IH industry. The best developments were associated with the architect Le Corbusier, who created a framework construction of reinforced concrete that made it possible to eliminate load-bearing walls and turned concrete into a key material in the sector. The first building constructed with this idea was the Dom-ino House (1914). Later, in 1926, he created the Citrohan House (Arieff and Burkhart 2002), a mixture of the technologies previously applied in the Dom-ino House's design with new technologies acquired from the French automobile industry. Moreover, in 1940 the designer and architect Buckminster Fuller introduced the first example of a modular bathroom used in the Dymaxion House (Neder 2008). The modular bathroom was the first prefabricated volumetric functional unit ever seen.

Therefore, the innovations throughout this stage were the first step to the diversification of IHB not only in terms of materials but also in terms of building systems, from simple light-components (1D) and panels (2D) to functional volumetric modules (3D). Notice that 1D (one dimension), 2D (two dimensions) and 3D (three dimensions) are the volume of the manufactured components and modules. However, it was not until the next stage that the benefits of volumetric modules (3D) begin to be exploited.

Mass production (1946-1989)

Over the years, during the 1940s and 1950s, when the political situation around the world had become more stable, there was an increasing need for new housing, the purposes of demand being different from those in the previous periods. Market demands shifted to less critical buildings, and the priorities were productivity, achieving value for money, and working around the shortage of skilled labour (Jaillon and Poon 2009). The construction industry quickly evolved from a craft-based sector to a more automated and technologically developed industry. The increase in demand implied industrial manufacturing, the emergence of mass-produced housing, and the standardization of construction elements and modules.

The standardized manufactured parts started to be more complicated than just walls (2D), slabs (2D) and stairs (2D), and different production systems appeared, each with specific characteristics (Badir, Kadir, and Hashim 2002). Moreover, industrialized building systems appeared with different industrialization indexes.

Habitat 67 (Blake and Sorkin 1998) and the Capsule Tower (Lin 2011) are examples of the use of standardized volumetric modules (3D) manufactured on a production line where the electrical systems, the bathroom and even other services were incorporated.

Moreover, the introduction of pre-cast concrete panels (2D) imported from France and Scandinavia became very popular due to their production advantages (Finnimore 1989). Some examples are the Finnish concrete panel systems. Although during the mass production period, precast concrete became the essential material, steel and other traditional materials like timber and iron continued to be relevant (Ågren and Wing 2014).

In addition, regardless of the system used, builders tried to improve productivity (Rudberg and Wikner 2004) to achieve economies of scale and reduce non-value activities by using both lean thinking (Akmam Syed Zakaria et al. 2018) and supply chain management (Segerstedt and Olofsson 2010).

Around the 1970s, the energy crisis represented an essential barrier for housebuilding practices. However, that crisis was the kick-off of improvements related to sustainability, lifecycle energy consumption, and energy efficiency. Therefore, by the end of the 20th century, quality, durability, and sustainability started to be essential, becoming objectives not only for IHB but for the whole construction sector. As a result, governments began to apply stricter construction energy efficiency standards, which was an excellent opportunity for the future development of the IHB industry.

Mass customization (1990-present)

The interest in both the industrialization and customization of house-building had been growing since, approximately, 1990 (Rudberg and Wikner 2004), when housing suppliers shift their attention to product differentiation (Barlow et al. 2003). Moreover, reducing the environmental impact of buildings' lifecycles and complying with health standards have become increasingly important targets around the world. Governments were stricter about the degree of thermal insulation, the consumption of non-renewable energy and the quality of indoor air. Hence, sustainability and quality are new housing requirements.

Hence, in such a complex market, many companies with different building objectives have emerged to satisfy the diverse market conditions and segments, but with equally efficient responses (Barlow and Ozaki 2005), leading the IHB industry to expand even more. In this context, choosing a cost-efficient strategy and production system that matches manufacturing outputs to market requirements (design customization, environmental sustainability, quality and/or cost) was a crucial decision for developers, owners, contractors and suppliers in the IHB industry (Kyrö, Jylhä, and Peltokorpi 2019). Jonsson and Rudberg (2014) suggested a framework for classifying production systems and manufacturing outputs (Figure 3-3).

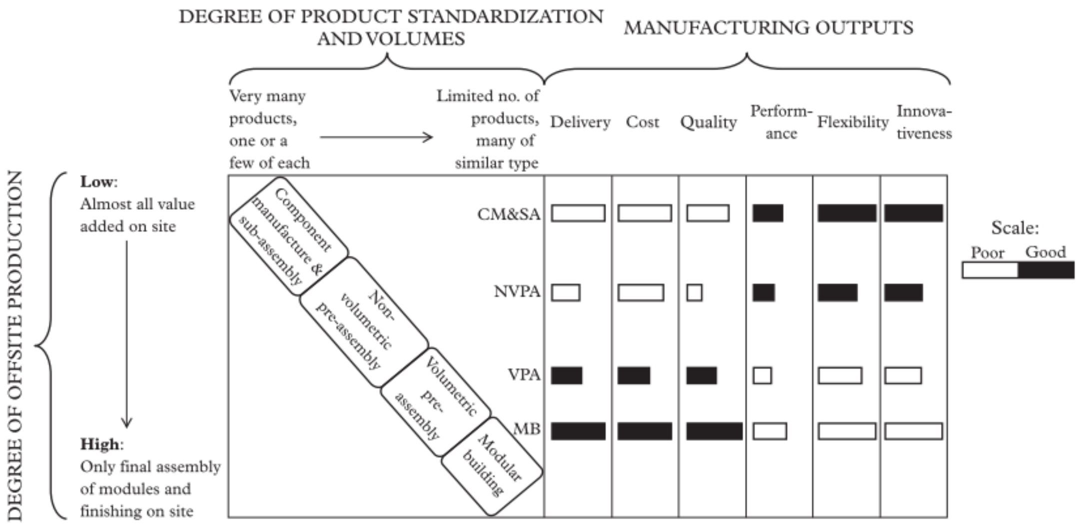


Figure 3-3. Framework for classifying construction production systems and manufacturing outputs. Extracted from Jonsson and Rudberg

Today, it is not easy to identify individual developments in the IHB industry because of the massive production and increase in demand. A few variations exist on the main techniques of timber frame, steel frame, and precast concrete. Generally, each individual company stays within the same construction technology and offers similar types of products (e.g. a company oriented toward manufacturing affordable concrete apartments with low levels of design customization).

More and more homeowners are taking an increasing interest in design, quality and comfort, requiring firms to develop flexible building systems that allow them to produce not only multiple buildings but also customized ones. Hence, the importance of the industrialized building system

(IBS) selection, for example non-volumetric pre-assembly or panelised (2D), is vital to design and produce these buildings with such a high level of product flexibility. Many companies have evolved towards quality, comfort and/or high levels of design customization.

From the economic point of view, IHB companies have also benefited from economies of scope by developing processes that facilitate the production of a variety of models by using the same machinery and material inputs (Barlow et al. 2003). Significantly, mass production systems are included in the lowest customization stage of mass customization systems. This means that some customer profiles could be efficiently satisfied by using production systems based on entirely standardized elements, components, interfaces, and processes. Economies of scale and reductions in cost and delivery time are also predominant priorities for many manufacturers.

Computational design and building information modelling methodologies (BIM) appeared in the IHB industry in the first decade of the 21st century. Hence, by using those new computational tools as well as applying lean concepts, supply chain management, and cost-efficient strategy choices, projects can quickly achieve the objective of improving both cost-efficiency and quality and safety standards. All current processes are designed to reduce non-value activities, improve coordination between stakeholders (Mao et al. 2015), and take advantage of new technologies. However, the current computational design tools used in the industry are not focused on optimizing the thermal behaviour of buildings or their energy consumption, and this is an aspect that needs to be improved.

Future trends

On the basis of the latest scientific advances and evidence on market tendencies, this section will suggest a few ideas about the future of IHB design.

The first interesting point to remark is that the house-building industry should/must respond both to lifestyle changes in society and to future governmental regulations on construction.

Considering that the influence of environmental aspects on building design is increasing (Commission 2016; Fomento 2019), it is expected that environmental sustainability will be the pillar of the construction industry in the coming years. In this context, the industrialized building sector, which has a clear advantage over traditional construction (Jaillon, Poon, and Chiang 2009), will have the key to success.

One of the main problems in the construction sector today, and which is becoming a challenge for the IHB, is to implement improvements that reduce the energy consumption and costs associated with the life-cycle of buildings. Especially in the context of the growing need for customization and fast delivery. It is necessary to focus not only on production and construction processes but also on the energy consumption throughout house-buildings use. Then, environmental impact and costs of the IHB life-cycle should be improved, from the design phase to demolition, deconstruction, and reuse. In the near future, the IHB sector should integrate efficient computational tools to design buildings based on industrialized systems that ensure low energy demand during use phase (operational phase). Therefore, it is necessary that the computer design integrates criteria of energy efficiency as well as customization to improve the thermal behaviour of the buildings (e.g. reducing air leakages). In addition, the industry needs to integrate tools that advise homeowners on the best way to achieve high levels in sustainability when inhabiting their homes. In this direction, a proposal for improvement could be to customize house-building designs from the perspective of the buildings' operational phase (Mateo et al. 2019), focusing and advising customers on features that can be optimized to make their houses more energy-efficient and/or cost-effective over time. Customers expect not only to participate in the architectural design of their homes, they are also aware of the influence their decisions can have on their homes' environmental impact and expect to participate in design decisions that can improve the ecological behaviour of these buildings.

Moreover, IHB companies will have to strive harder to develop building renovation systems and design for deconstruction (Spanish Government 2020). Therefore, companies will be required to address the transformation of their IBSs, incorporating techniques that allow deconstruction to proceed without damaging the structure and main function of the industrialized components to recycle the materials or reuse them in future applications. One possible solution could be to improve the connectors and interfaces between panels, modules and other industrialized elements to ensure an easy, quick and secure assembly and disassembly.

In the same direction, the versatility offered by industrialized construction must enable the building sector to position itself at the forefront of technological innovations that must make the architectural designs of the houses of the future possible, where not only do organic forms predominate, but the building also becomes a physical support that allows vegetation to be incorporated into roofs and facades, as well as solar and rainwater capture systems (Perez and Perini 2018). Thus, the adaptation of industrialized construction to the new trends in architectural design is one of the inevitable challenges to face in the coming years.

Another interesting path that IHB firms must explore to reduce the lifecycle environmental impact and the costs of the house-buildings they produce is to lower the number of on-site tasks and the amount of time they take. In other words, construction systems need to have the highest possible industrialization index. In this way the panelised systems (2D) must increase the complexity of the manufactured panels by designing them to include components which nowadays are incorporated on-site when the building is completely erected (e.g. plugs). These types of improvements are expected to lead to reductions in projects' delivery time, costs and environmental impact during production and construction phases. Modular (3D) systems have a building system that has practically no on-site tasks (high industrialization index), so improvements in this area will be complicated. In those cases, improving connectors, interfaces, foundations or developing other techniques to reduce on-site activities could be profitable in the future.

Moreover, it is worth highlighting that the building sector must also aim to improve project efficiency, stakeholder relationships, and the use of new design, manufacturing, transport, and construction technologies. One example is the inclusion of 3D printing (Aye et al. 2012) techniques in the construction process to increase automation and quality, and to reduce time and workforce. However, companies should address research to adapt their main construction material and/or structure of the building system to take advantage of this innovative way to construct. Another example would be to rectify the lack of skills and experience in BIM and, especially for small firms, to use this tool not only as a 3D modelling engine but also as a way of managing design and construction itself, in addition to costs, schedules and exchange of information (Ghaffarianhoseini et al. 2017).

Finally, from a customer-satisfaction point of view, another priority that is expected to increase in the future is the demand for adaptable buildings whose designs can be modified to fit the owner's lifestyle over the years (Femenias and Geromel 2020). Hence, design for adaptability will be another pillar in the future housing industry. It is important to highlight that this idea is focused, again, on the development of easily mountable and demountable housing elements.

Results and discussion

After a comprehensive analysis of the evolution of IHB over the course of history, a timeline containing the main improvements of each period is presented in Figure 3-4. The timeline shows, in a big picture, how IHB has evolved as a response to the evolution of both market and society from the very beginnings until today, and how it is expected to develop in the coming years.

During the early, transitional and mass production stages in the history of IHB, the industry responded to society's basic needs. Over the last four centuries, the demands of the housing market (building objectives) have basically evolved from a single focus on reducing costs and time towards quality, sustainability, productivity and design customization.

The architectural design (F1) basically evolved from manual to more automatic creative processes, result of building information modelling methodologies (BIM) and computational design environments. In the future, the implementation of new computational design customization tools could enhance the customer experience at the same time that allow the design for an environmentally friendly use of customized, adaptable and reusable building designs from the perspective of the buildings' operational phase (Mateo et al. 2019). The IBS design (F2) is deeply analysed in the timeline where construction materials, volume of modules, industrialization index and degree of prefabrication are individually studied and compared.

Most of the main construction materials used nowadays are the same as those used throughout history, predominantly wood, steel and concrete. In many current cases, construction material is also a market requirement due to customers preferring one specific material over another. However, in other cases, proximity to raw materials is the key of this decision. Moreover, material properties influence the decision to use one material or another depending on the purposes the building is expected to fulfil.

The choice of IBS is strongly related to production strategy, meaning that systems with high industrialization indexes and degrees of standardization are preferable when the aim is to mass produce, and systems with lower industrialization indexes and degrees of standardization are preferable when the aim is to completely customize. Then, there are other more balanced systems through which it is possible both to reduce time and costs and to customize, to varying extents. Panelised (2D) systems are normally used when the aim is to customize whether than volumetric modular systems (3D) are normally used to increase productivity and reduce delivery time and costs. As a novelty, this study identifies that in the future house-building systems must have a high industrialization index and a high degree of standardization to increase productivity and reduce costs and environmental impact. In this way, one of the future challenges of the IHB industry is to design industrialized modules (2D) with high level of complexity that allow a mass customization (e.g. including piping in flexible panels).

At the same time, Governments and legislation are increasingly stricter about environmental criteria in the house-building sector. For this reason, the industry needs to develop both building systems and design strategies that reduce house-buildings environmental impact. One example is improving design strategies to reduce house-buildings energy demand for air conditioning. Thus, computational design customization tools for sustainability appear to be relevant in the near future of the IHB industry.

Production strategies (C3) have evolved from the concept of circular economy to mass production and, finally, mass customization, when the decision-making process became critical to cost-efficiently produce the house-building desired by customers. If the main market requirements are cost and time reduction (as in the first three historical stages), mass production is the best strategy to achieve economies of scale that benefit developers. However, in the era of customization, it is also important to take advantage of product differentiation, as creating an economy of scope can be a lucrative production strategy. Hence, nowadays it is important to design a product strategy that balances product customization and mass production, depending on to what extent the customer wishes to participate in product design.

The timeline shows that the IHB industry is developing more complex processes based on satisfying customers by designing not only the house-buildings they desire but also the production processes and building systems that fit them best. Hence, house-building firms need to understand the evolution of society, the worries of its members and the product outputs they will be willing to pay for. Furthermore, the IHB industry must face up to the environmental issues of the construction sector, no matter who the customer is.

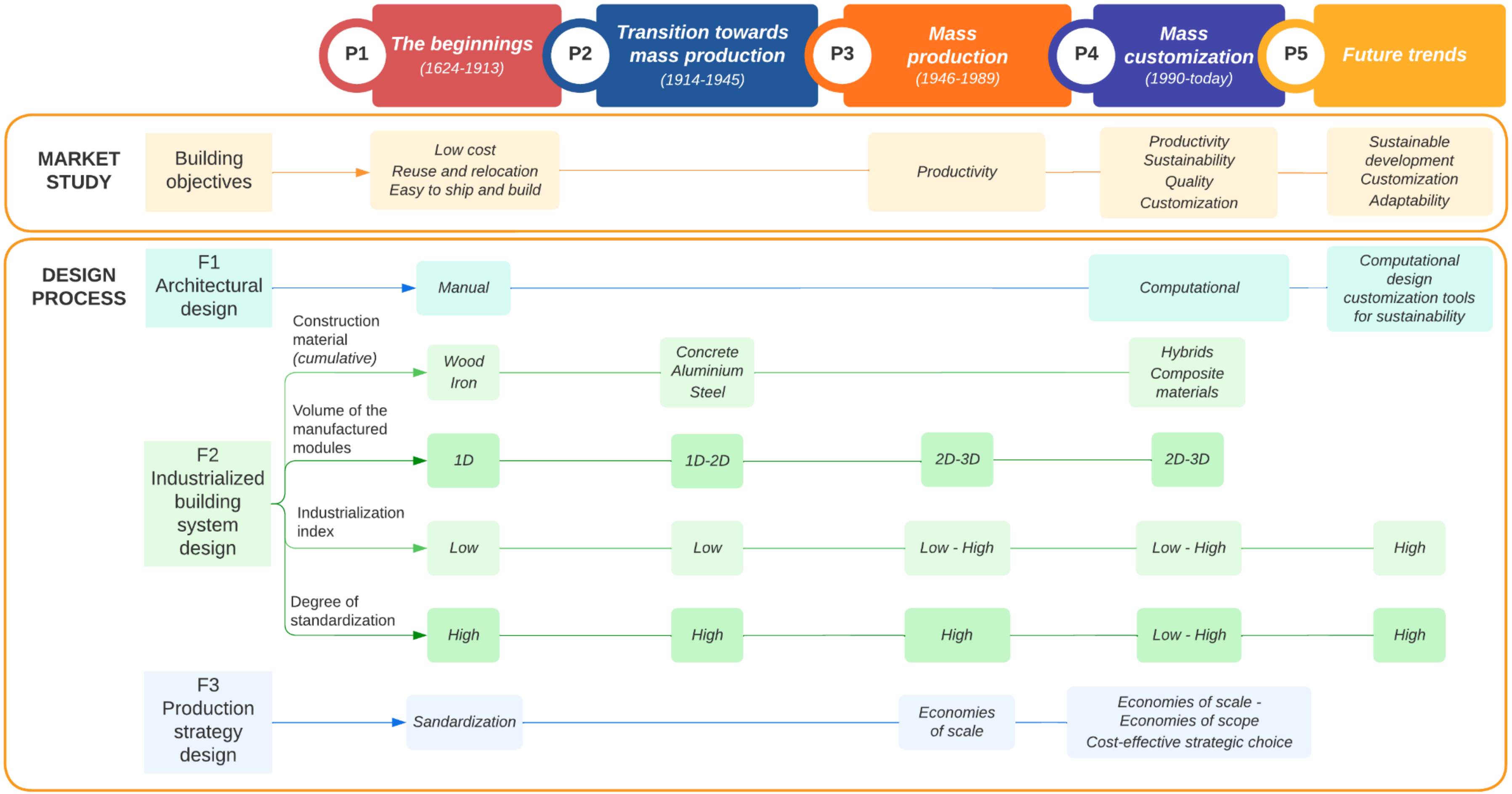


Figure 3-4. IHB timeline

Chapter 4. Firms industrialized building system design analysis

Methodology and structure

In this chapter, the industrialized building system (IBS) design of 29 IHB firms from around the world (PMP included) is analysed and compared following the procedure summarized in Figure 4-1.

To do this, a criteria was first defined to characterize firms IBS design. This criteria consists of 9 technical parameters considered key when designing a building system: (1) degree of design customization, (2) maximum number of stories, (3) fire resistance of the structure, (4) acoustic damping of the structure, (5) thermal transmittance of walls, (6) CO_2 emissions in fabrication phase, (7) average delivery time, (8) industrialization index and (9) average price. These 9 parameters were grouped into 6 indicators aimed at informing non-technical staff of the company and/or consumers of the virtues and defects of each system: (1) customization, (2) fire safety, (3) acoustic damping, (4) environmental impact, (5) delivery time and (6) price. The indicators were classified into 4 areas that represent the pillars of decision making: (1) construction and design, (2) quality and security, (3) environmental sustainability and (4) costs and productivity.

Second, a criteria was established to evaluate each parameter between 0 and 100 according to CTE (https://www.codigotecnico.org/) regulations and/or PMP (https://pretaportercasas.com/) experience in the sector.

This was followed by a search of firms in the IHB sector around the world and their IBS was studied, characterized and evaluated under the defined criteria.

Finally, with the results of the study, the PMP company (https://pretaportercasas.com/) positioned itself with respect to its competitors, detecting the virtues and margins for improvement of its IBS.

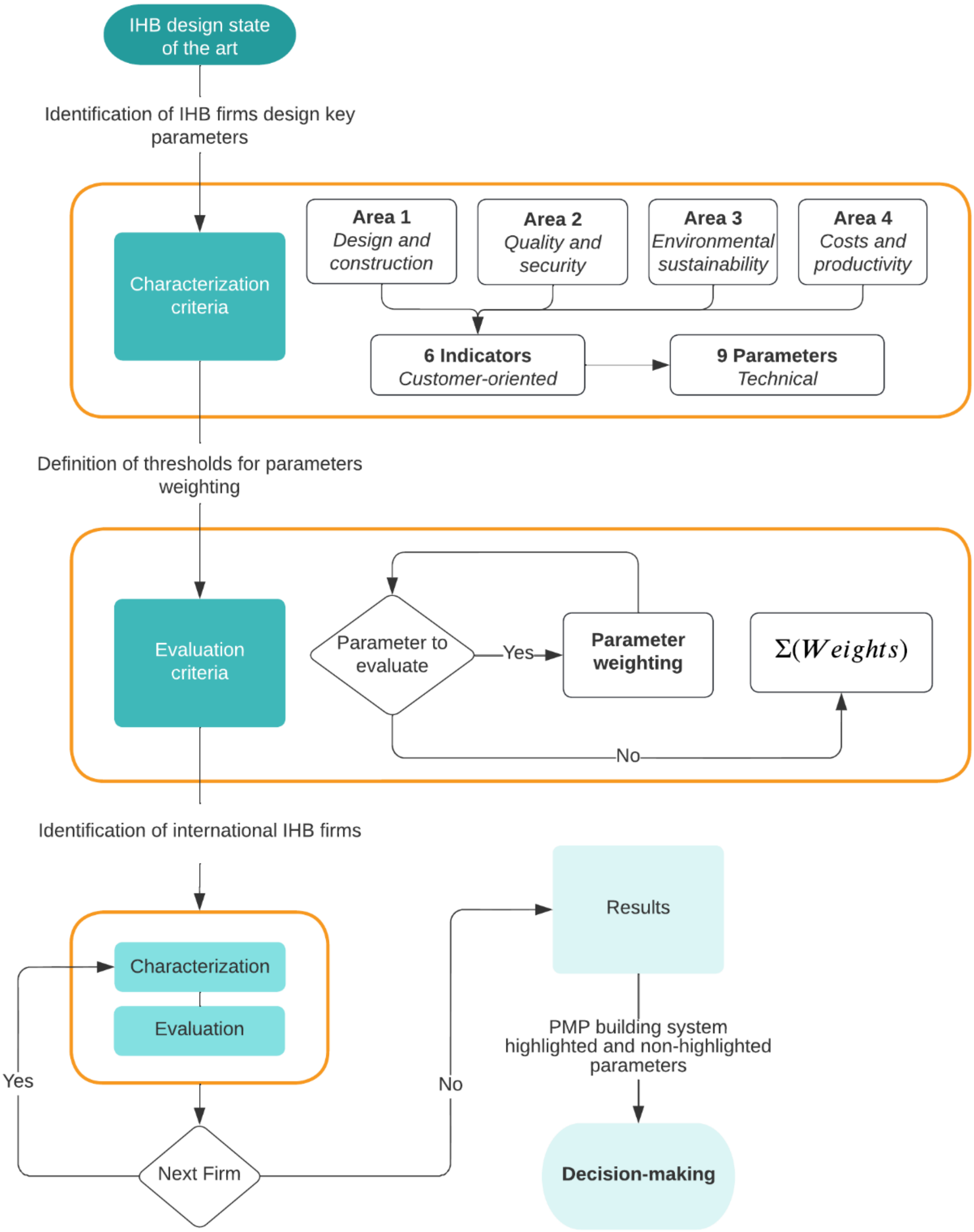


Figure 4-1.Chapter 4 methodology

Characterization criteria

Based on the state of the art of the IHB defined in chapter 3, and in the context of the current and future tendencies of the construction market, a criteria to analyse industrialized building system (IBS) design key factors was defined. The criteria is based on three levels: areas, indicators and parameters. Each level has a different goal.

- Areas represent the building objectives and/or the market requirements in a general level.
- Indicators aim to inform, using a common language between technicians, company staff and customers, about the strengths and the weaknesses of an IBS in each of the areas.

- Parameters analyse IBSs to guarantee to elaboration of indicators under a technical criteria.

An example of area is the building objective of environmental sustainability. The defined indicator in this area was the environmental impact, which allows to inform customers if the IBS is more or less environmentally friendly. To calculate this indicator the following technical parameters were used: (1) thermal transmittance of walls (W/m^2K) and (2) CO_2 emissions in fabrication phase ($kgCO_2/m^2$).

Areas were defined by adapting the key factors of an IHB project decision-making process identified by Sharafi et al. (2018) to the needs of this study. The selection criteria consisted on choosing parameters that can be evaluated under building regulations (https://www.codigotecnico.org/) and/or parameters that, according to chapter 3 state of the art, mark the differences in the house-building market, as is the case of the industrialization index.

The key performance indicators (KPIs) suggested by Jonsson and Rudberg (2017) served as the basis for defining the characterization criteria indicators. However, these authors focused their study on the production strategy perspective. This is why some of the suggested KPIs, such as the KPI for quality, oriented to identify production defects, were not used to define the characterization criteria. In contrast, other KPI's such as KPI for cost and KPI for delivery were considered and adapted to the necessities of the study. For example, the average delivery time (I5) takes into account the total time of the projects (design, production and construction) whereas the delivery speed KPI only measures the production time (Jonsson and Rudberg 2017).

AREA		INDICATORS		PARAMETERS	
A1	Construction and design	**I1**	Customization	**P1**	Degree of design customization
				P2	Maximum number of stories
A2	Quality and security	**I2**	Fire safety	**P3**	Fire resistance of the structure
		I3	Acoustic comfort	**P4**	Acoustic damping of the structure
A3	Environmental sustainability	**I4**	Environmental impact	**P5**	Thermal transmittance of walls
				P6	CO_2 emissions in fabrication phase
A4	Costs and productivity	**I5**	Delivery time	**P7**	Average delivery time
		I6	Price	**P8**	Industrialization index
				P9	Average price

Table 4-1. Characterization criteria

Area 1 - Construction and design

Customization takes into account the flexibility of the IBS associated to the architectural design possibilities (Jonsson and Rudberg 2014).

- I1 - customization:
  - P1 - degree of design customization: refers to the flexibility of the IBS to build customized design geometries.
  - P2 - maximum number of stories: quantifies the capacity of the IBS to build in height. It is worth noting that the construction of the basement is not included in this indicator.

A2 - Quality and security

The reliability that a building guarantee is an important concept for customers when choosing a manufacturer and/or a product. A quality building has a high durability, zero maintenance and safety in case of fire and/or exceptional seismic or meteorological accident. Since all the processes being evaluated belong to the IHB sector, they all share the virtues of factory quality control

(Akmam Syed Zakaria et al. 2018). Therefore, small differences were expected between the systems in the area of quality.

This study considered the resistance of the structures to fire, as in the climatic zone of Lleida (Spain), that is the PMP market area, the case of fire is more common than that of earthquake or other meteorological accidents.

Thermal, acoustic and visual comfort are synonymous with health and quality of life. Thermal comfort depends on the thermal parameters of the IBS that are evaluated in the environmental impact indicator. Visual comfort depends on the physical design of the building, its orientation and the solar factors of the window openings. It was assumed a high relation between visual comfort and construction and design (A1). Therefore, only acoustic comfort was characterized in this area.

Air quality is also an important health factor but was not considered in the proposed characterization.

- I2 - fire safety:
  - P3 – fire resistance of the structure: represents the fire resistance of the materials that predominate in the structure of the building.
- I3 - acoustic comfort:
  - P4 - acoustic damping of the structure: it is determined according to the sound insulation in dB of the predominant material of the structure.

A3 - Environmental sustainability.

The energy consumption during the use phase of buildings and CO_2 emissions during the manufacturing stage were considered. The emissions generated in the manufacture of *sandwich* panels (prefabricated modules (2D) with insulation layer inside), any type of coating or finish have not been taken into account, nor the incorporation of the facilities. It also remained, apart from this analysis, the characterization of emissions in the elaboration and transport of the modules since these data are not available. The machinery needed to handle modules and build houses were not taken into account either.

- I4 - environmental impact:
  - P5 - thermal transmittance of the walls: it has a direct relationship with the energy consumption during the use phase (Operational phase) of the buildings (Su and Zhang 2016).
  - P6 - CO_2 emissions in fabrication phase: represents the CO_2 emissions/m^2 of manufactured materials generated in the fabrication stage.

A4 - Costs and productivity

Costs and productivity are key factors in decision-making and design of the building system (Sharafi et al. 2018). However, although it was not the object of the study to go into the details of the processes beyond the design, it should be noted that these indicators also represent the later stages of house-building projects (production and construction).

- I5 - delivery time:
  - P7 - Average delivery time: represents the delivery time in months of a standard home of each company divided by its total gross floor area.
- I6 – price:
  - P8 - industrialization index: this is the most representative parameter identified in chapter 3 when it comes to technically characterizing the cost control of a building system. The higher the industrialization rate of a process, the lower the

construction costs. The reason is the improvement in productivity and the reduction of non-value-added activities characteristic of any construction activity carried out on site, such as schedule overruns or vulnerability to weather conditions.
    - P9 - average price: represents a value of average price of a finished house in €/m^2,

Evaluation criteria

Parameters

Each parameter was evaluated from 0 to 100 and scored according to building normative (https://www.codigotecnico.org/) and/or PMP technical and commercial criteria thresholds based on the company's experience in the sector (Table 4-2).

- P1 - degree of design customization. In the IHB sector, three types of companies can be differentiated: (1) those that offer fixed designs without customization possibilities, (2) those that offer fixed designs with some customization possibilities and (3) those that offer designs fully flexible and adaptable to user needs. The weights given to each type of firm are proportional to this flexibility.
    - P1 (0) - The firm has a catalogue of pre-set designs with no customization options.
    - P1 (25) - The firm has a catalogue of pre-set designs with some customization options.
    - P1 (100) - the firm, which may or may not have a catalogue, is distinguished by customizing completely the designs.
- P2 - maximum number of stories: quantifies the capacity of the system to build in height. In the PMP market, in which highlights the residential construction of detached single-family homes, internal studies of the company state that 25% of customers would be interested in a system being able to build two stories in addition to the ground floor, and 75% of customers at least one. Based on these results, P2 weights were defined.
    - P2 (25) - the building system allows only the ground floor to be built.
    - P2 (75) - the building system allows to build the ground floor and a another story.
    - P2 (100) - the building system allows to build a ground floor and more than one story.
- P3 - fire resistance of the structure: represents the fire resistance of the predominant structural material in minutes. Although any construction is restricted to building safety standards, the response of construction materials under extreme safety conditions was taken into account. Then, P3 was rated in accordance with the regulations CTE-DB-HR (Fomento 2019 (b)).
    - P3 (75) - the fire resistance of the predominant building material does not exceed 60 minutes.
    - P3 (100) - the fire resistance of the predominant building material equals or exceeds 60 minutes.
- P4 - acoustic damping of the structure: it was determined according to the sound insulation in dB of the predominant material of the structure. The same assessment criteria was followed in P4 as in P3, based on regulations CTE-DB-SI (Fomento 2019 (c)).
    - P4 (75) - the acoustic damping of the predominant material of the structure is less than 60 dB.
    - P4 (100) - the acoustic damping of the predominant material of the structure is equal to or greater than 60 dB.

- P5 - thermal transmittance of walls: it has a direct relationship with the energy consumption during the use phase of the buildings (He et al. 2021). In order to obtain P5, either the value shared by the manufacturer in technical data sheets was used, or it was calculated based on its construction technology using the Therm software (https://windows.lbl.gov/tools/therm/software-download). In cases where the manufacturer allowed it, both things were done and the average value was chosen.
  To assess P5, a criteria of thermal transmittance (W/m^2K) was established based on the CTE DB-HE (Fomento 2019) regulations for the climatic zones of Lleida (D3 and E1, form CTE-DB-HE) and on 8 case-studies. Each case-study consisted on a PMP building tested by the official energy certification (Spain) procedure using different values of thermal transmittances of walls. It is worth noting that although at the time of the study the regulations in force in Spain were the CTE-DB-HE-2012, the defined scoring criteria was based on the current regulations CTE-DB-HE-2019 (Fomento 2019), then approved. In the study it was verified that:
  (1) In two cases the regulations were complied with if the walls have thermal transmittances equal to or greater than 0.3 (W/m^2K).
  (2) In four cases the regulations were complied with if the walls have thermal transmittances less than or equal to 0.30 (W/m^2K) but greater than 0.27 (W/m^2K).
  (3) In six cases the regulations were complied with if the walls have thermal transmittances less than or equal to 0.27 (W/m^2K), but greater than 0.22 (W/m^2K).
  (4) In all cases the regulations were complied with if the walls have thermal transmittances less than or equal to 0.22 (W/m^2K).
  According to these results, the P5 weighting was established as follows:
    - P5 (25) – walls thermal transmittances equal to or greater than 0.3 (W/m^2K).
    - P5 (50) – walls thermal transmittances less than or equal to 0.30 (W/m^2K) but greater than 0.27 (W/m^2K).
    - P5 (75) – walls thermal transmittances less than or equal to 0.27 (W/m^2K), but greater than 0.22 (W/m^2K).
    - P5 (100) - walls thermal transmittances less than or equal to 0.22 (W/m^2K).
- P6 - CO_2 emissions in fabrication phase: represents the CO_2 emissions/m^2 of manufactured material that IBSs generate due to the manufacture and treatment of raw materials. The CTE (https://www.codigotecnico.org/) does not consider these emissions and, therefore, the evaluation criteria was based on the report (Mercader, Ramírez de Arellano, and Olivares 2012).
    - P6 (0) - CO_2 emissions equal to or greater than 0.45 ($kgCO_2/m^2$) of manufactured material.
    - P6 (25) - CO_2 emissions equal to or greater than 0.14 ($kgCO_2/m^2$) of manufactured material but less than 0.45 ($kgCO_2/m^2$).
    - P6 (100) - CO_2 emissions of less than 0.14 ($kgCO_2/m^2$) of manufactured material.
- P7 - Average delivery time: represents the delivery speed in months of a standard home of each company. The delivery speed offered by any IHB process is always shorter compared to any on-site construction process (Akmam Syed Zakaria et al. 2018). The valuations of this parameter were established according to the criteria of the PMP technicians, and the commercial experience of the company in the sector.
    - P7 (25) - delivery time greater than 1 day/m^2
    - P7 (50) - weaning period less than or equal to 1 day/m^2 and greater than 0.5 days/m^2
    - P7 (100) - delivery time less than or equal to 0.5 days/m^2
- P8 - industrialization index: this is the most representative parameter when it comes to technically characterizing the cost control of an IBS. P7 (average delivery time) and P8 are closely related. Usually, the higher the industrialization rate of a building system, the

higher the productivity and the shorter the delivery time of the finished product (Jonsson and Rudberg 2014). To calculate P8, the components that are industrialized in an IBS were counted first. After, a weight was assigned to each component according to the percentage it costs with respect to the total cost of the PMP projects as follows (this criteria was the same in all cases):

- P8 (+5) - the openings
- P8 (+5) - carpentry
- P8 (+20) - insulation
- P8 (+45) - home installations (MEP[3] Systems)[4].
- P8 (+5) - indoor equipment
- P8 (+20) - manufactured modules facilitate basement construction

Then, P8 was calculated by adding the values represented by each industrialized component. For example, if the manufactured modules of a company contained the opening's and the carpentry, the IBS of the company obtains a P8 weight of 10.

- P9 - average price: represents an average of the finished house price in €/m^2, established on the basis of prices (€/m^2) of different models of housing offered by each company on its website and/or in data sheets. The value of the average price takes into account the design, production and construction phases. P9 was valued in the same way as P7 (average delivery time).
    - P9 (25) - average price higher than 1800 €/m^2.
    - P9 (75) - average price less than or equal to 1800 €/m^2 and more than 1300 €/m^2.
    - P9 (100) - average price less than or equal to 1300 €/m^2.

<u>Indicators</u>

All the indicators were calculated based on the equation [4-1], where "i" represents the specific parameters of each indicator.

$$I = \frac{1}{i}\sum_{i} P_i \quad [4\text{-}1]$$

<u>Parameters average value</u>

To calculate the parameters average following equation [*4-2*] it was assumed that the value of all the 9 parameters had the same weight.

$$Parameters\ average\ value = \frac{1}{9}\cdot\sum_{i=1}^{i=9} P_i \quad [4\text{-}2]$$

[3] MEP means mechanical, electrical and plumbing

[4] If instead of being completely industrialized, individual MEP parts are industrialized, then P8 (+35).

CASE		DESCRIPTION	VALOR (0-100)
P1	1	The firm has a catalogue of pre-set designs with no customization options	0
	2	The firm has a catalogue of pre-set designs with some customization options	25
	3	The firm, which may or may not have a catalogue, is distinguished by customizing completely the designs	100
P2	1	The building system allows only the ground floor to be built	25
	2	The building system allows to build the ground floor and another story	75
	3	The building system allows to build a ground floor and more than one story	100
P3	1	The fire resistance of the predominant building material does not exceed 60 minutes	75
	2	The fire resistance of the predominant building material equals or exceeds 60 minutes	100
P4	1	The acoustic damping of the predominant material of the structure is less than 60 dB	75
	2	The acoustic damping of the predominant material of the structure is equal to or greater than 60 dB	100
P5	1	Walls thermal transmittances equal to or greater than 0.3 (W/m^2K)	25
	2	Walls thermal transmittances less than or equal to 0.30 (W/m^2K) but greater than 0.27 (W/m^2K)	50
	3	Walls thermal transmittances less than or equal to 0.27 (W/m^2K), but greater than 0.22 (W/m^2K)	75
	4	Walls thermal transmittances less than or equal to 0.22 (W/m^2K)	100
P6	1	CO_2 emissions equal to or greater than 0.45 ($kgCO_2/m^2$) of manufactured material	0
	2	CO_2 emissions equal to or greater than 0.14 ($kgCO_2/m^2$) of manufactured material but less than 0.45 ($kgCO_2/m^2$)	25
	3	CO_2 emissions of less than 0.14 ($kgCO_2/m^2$) of manufactured material	100
P7	1	Delivery time greater than 1day/m^2	25
	2	Delivery time less than or equal to 1day/m^2 and greater than 0.5 days/m^2	50
	3	Delivery time less than or equal to 0.5 days/m^2	100
P8	1	(+5) - the opening's	5
	2	(+5) - carpentry	5
	3	(+20) - insulation	20
	4	(+45) - home MEP Systems	45
	5	(+35) - part of the home MEP Systems	35
	6	(+5) - indoor equipment	5
	7	(+20) - manufactured modules facilitate basement construction	20
P9	1	Average price higher than 1800 €/m^2	25
	2	Average price less than or equal to 1800 €/m^2 and more than 1300 €/m^2	75
	3	Average price less than or equal to 1800 €/m^2	100

Table 4-2. Building system evaluation criteria

IHB firms' identification

The study was based on a research of international IHB firms during 2020. The search engine was Google and the keywords used were: "building prefabrication firm", "prefab housing firm", "off-site housing firm", "industrialized housing firm" and "modular construction firm", in both languages Spanish and English.

From the search, 28 companies were selected, in addition to PMP. The data necessary to characterize and evaluate their IBSs were obtained and/or calculated based on the information provided by firms on their web portals in technical data sheets, video clips and/or images of manufacturing, transport and/or assembly, etc. 21 of those companies are from Europe and 8 from North America.

It is common for companies in the IHB sector to have IBSs adapted to their needs based on a decision-making process and their own experience. Throughout the study, the same parameters were evaluated and the IBSs were characterized according to the same standardized criteria. The aim was to give a quality value to each indicator that allows to classify the virtues of each competitor of PMP in the IHB market.

PMP industrialized building system analysis

Industrialized building design

The PMP (https://pretaportercasas.com/) IBS is based on the industrialization of 2D concrete modules, also known as prefabricated concrete panels. There are basically three types of modules: load-bearing walls, non-load-bearing walls and prestressed alveolar slabs Figure 4-2.

Each type of module has a specific function in the final construction.

Load-bearing walls: 2D modules and/or panels that are placed on-site perpendicular to the plane defined by the ground that contains the prefabricated foundations. They have the function of supporting the loads of buildings and, at the same time, separating the outdoor climate from the indoor environment. They contain the brackets, elements that support the alveolar slabs. In addition, depending on each project, they include elements such as doors and/or windows.

Non-load-bearing walls: 2D modules and/or panels that on-site are placed perpendicular to the plane defined by the terrain that contains the prefabricated foundations. Its function is to close the structure and separate the outdoor climate from the indoor environment. Depending on the project, they may contain other elements such as doors and/or windows.

Prestressed alveolar slabs: 2D modules and/or panels that are mounted on the site parallel to the plane defined by the ground that contains the foundations. In the case of homes with gabled roofs, these modules are mounted in a specific direction according to the slope of the roof. The function of these modules is to separate the different levels of each house and, at the same time, to support the loads of the elements that are placed on top of it. In some cases, they also separate the interior from the outside.

Prefabricated founding: modules that are mounted on top of the concrete footing that are traditionally made on-site. They have the characteristic "U" shape (Figure 4-2).

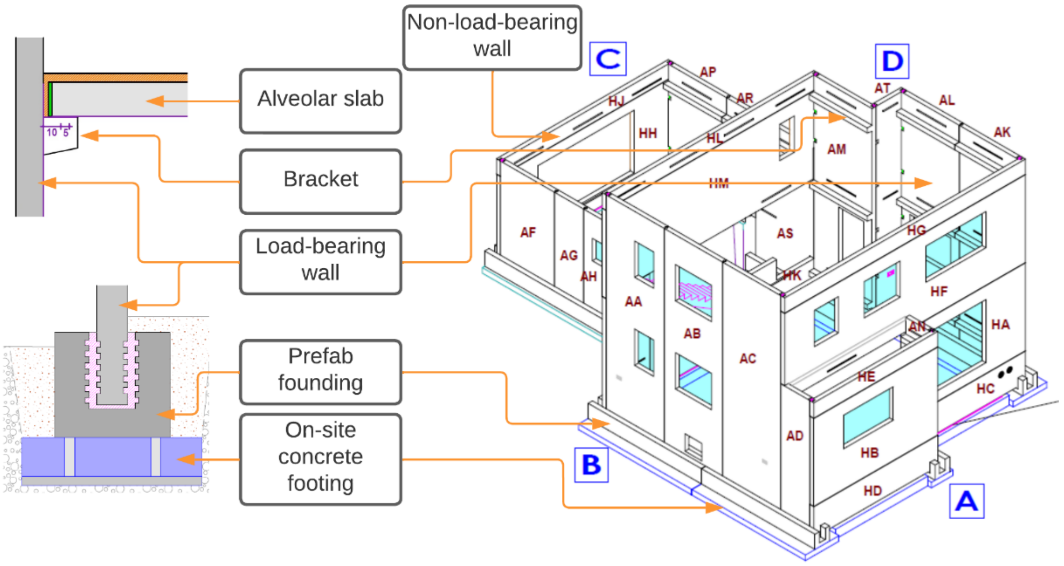


Figure 4-2. PMP industrialized building system (IBS)

Each building is made up of a set of modules of all types. The characteristic feature of the PMP industrialized building system is the flexibility in prefabricating each of the modules, which are tailor-made for each project. This allows PMP to offer custom designs while maintaining cost control.

Production process

1) Load-bearing walls and non-load-bearing walls are fabricated using molds as shown in Figure 4-3. Depending on the characteristics of each part the mold is prepared with the reinforcement, pre-frame and other necessary construction elements as the brackets.
2) The concrete is filled in the mold. Then, a treatment is applied to these modules with additives that allow the concrete to cure quickly.
3) The carpentry (windows, doors and shutters) is installed in the pre-frames.
4) A strip of neoprene is placed on the brackets to reduce the thermal bridges and, a first layer of insulation with XPS is applied to load-bearing walls and non-load-bearing walls through its inner layer (the part of the module that looks towards the interior of the house).
5) Load-bearing walls and non-load-bearing walls are labelled and stored waiting to be transported.

In parallel to 1-5 steps, in another production line, the prestressed alveolar slabs are manufactured. Its manufacturing process begins with a cable tensioning on a prepared base which is then concreted. Finally, the piece is cut. The prefabricated foundations are also manufactured in a similar procedure.

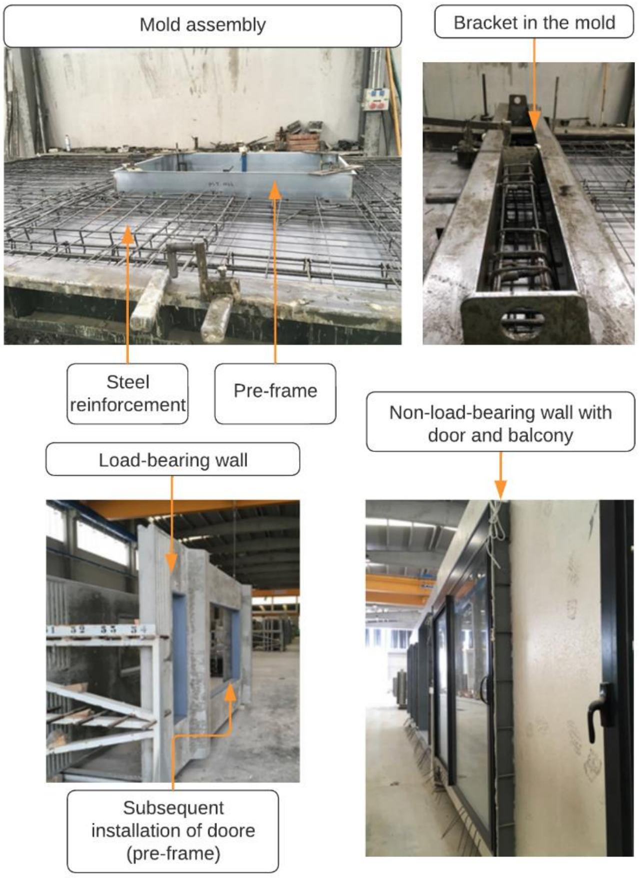


Figure 4-3. PMP production process

On-site assembly

1) On-site foundations are executed in parallel with the factory production of the modules, to reduce time (Figure 4-4).

Figure 4-4. Foundations

2) Once the prefabricated modules are ready, they are loaded onto trucks, transported to the site and unloaded.
3) The prefabricated foundations are installed on top of the concrete footing, the load-bearing walls are placed, fitted at the bottom with the prefabricated foundations, and then the structure is sealed with mortar.
4) The rest of the walls and alveolar slabs are assembled as shown in Figure 4-5.
5) The modules are joined by means of the compression layer.
6) In the event of a radiant floor installation, the water circuits and collector switchboards are installed. The entire surface of the radiant floor is then covered with mortar.
7) The plasterboard uprights are executed; the remaining thermal insulation layer is placed and plasterboard is installed. The necessary holes are drilled for the passage of the mechanical, electrical and plumbing (MEP) systems and the coupling of mechanisms such as switches and/or plugs.
8) Corrugated tubs and pipes are installed.
9) Bathrooms and kitchen are assembled and tiled.
10) The exterior of the house is painted.
11) The parquet is assembled.
12) The connections of the mechanical, electrical and plumbing (MEP) are finished.
13) The interior layer of the house is painted.
14) The house-building is cleaned.

Figure 4-5. PMP construction process

PMP IBS characterization and evaluation

Table 4-3 presents the analysis and assessment made to the PMP industrialized building system (IBS) as an example of the application of the characterization (Table 4-1) and evaluation (Table 4-3) criteria defined in this chapter.

The results show that the PMP IBS stood out in the Customization indicator (I1), especially in terms of the degree of designs customization (P1). Even more remarkable and, unbeatable, the system stood out in the area of quality and security (A2), where the indicators of fire safety (I2) and acoustic comfort (I3) had the highest score.

On the other hand, the score of the PMP IBS in the environmental impact indicator (I4) was poor, mainly due to the high CO_2 emissions in fabrication phase (P6). The system also did not stand out in the area of costs and productivity (A4), where the average delivery time (P7) and the industrialization index (P8) also had a low score.

		Indicators *(0 - 100)*		Parameters *(0 - 100)*			
						Value	**Average**
A1	Construction and design	**I1**	Customization	**P1**	Degree of designs customization	100	65,6
				P2	Maximum number of stories	75	
A2	Quality and security	**I2**	Fire safety	**P3**	Fire resistance of the structure	100	
		I3	Acoustic comfort	**P4**	Acoustic damping of the structure	100	
A3	Environmental sustainability	**I4**	Environmental impact	**P5**	Thermal transmittance of walls	50	
				P6	CO_2 emissions in fabrication phase	0	
A4	Costs and productivity	**I5**	Delivery time	**P7**	Average delivery time	50	
		I6	Price	**P8**	Industrialization index	40	
				P9	Average price	75	

Table 4-3. PMP building system evaluation

The average score parameters, calculated with equation [*4-2*], rated the PMP IBS with a score of 65,6. This result indicated that the PMP IBS had potential for improvement. The next step was to research, characterize and evaluate the IBSs of 28 more firms in the IHB sector. The aim was to establish a classification of IBSs that would help to analyse the results of PMP IBS evaluation and make the final decision making.

Results and discussion

Figure 4-6 shows the parameter average value of the PMP IBS (yellow line) compared to the IBSs of the remaining 28 companies in the study analysed according to the criteria established in this chapter. According to the results, it can be stated that the PMP IBS obtained a rating that is slightly above the total average by the 28 companies (brown line). The wood IHBs had a much higher average value than that of PMP (yellow line). This is mainly due to the fact that wood IBSs had a significantly higher environmental impact indicator (I4) than that of the PMP IBS, and that of any concrete company. As a general rule, the IBSs of wood companies did not have any parameters that penalize them as much as the P6 (CO_2 emissions in fabrication stage) penalizes concrete companies. Steel IBSs were halfway between wood and concrete IBSs. However, the positioning of the PMP IBS with respect to the rest of the concrete IBS was very remarkable. Only one concrete IHB system (f-21) had a better rating than PMP. As can be seen in Figure 4-7, this was basically due to the index of industrialization. However, this company offered a product of similar cost to PMP, which means that if PMP increases the industrialization index would exceed the valuation of this company (f-21). This was probably due to greater efficiency in the production and construction processes of the PMP IBS.

The best IBS (f-15), in addition to offering a leading price, meets the conditions to have better indicator of environmental sustainability (I4) and a better industrialization index compared to PMP (Figure 4-7).

Figure 4-8 shows the comparison of results according to the volume of the IBS modules. It is clear that the IBS with 1D modules had a poor rating. There was a small difference between the mean value of 2D (orange line) and 3D (grey line) modules IBSs, which positions the 2D modules IBSs more favourably. This was basically because there was an IBS of 2D wooden modules (f-15) that clearly stood out above the others. As a general rule, 2D systems had a low industrialization index (P8) which penalized them as they manufactured only structural modules (load-bearing walls, non-load-bearing-walls and slabs) and not other components of the house such as the MEP facilities. This penalized them in terms of cost and delivery time compared to 3D systems. On the other hand, 2D systems were characterized by high flexibility and product customization compared to 3D systems (Peltokorpi et al. 2018). The building system of (f-21) stood out precisely because it combinates both aspects, was a modular 2D system that allows high customization and at the same time integrated a modular system of industrialized MEP facilities. This resulted on a high industrialization index.

According to this study it was concluded that PMP IBS:

- Leaded in customization (I1), fire safety (I2) and acoustic comfort (I3).
- Did not stand out in delivery time (I5) or price (I6). An area for improvement identified was the industrialization index (P8).
- Had a clear margin for improvement in environmental impact (I4). The thermal transmittance of walls (P5) and the CO_2 emissions in fabrication phase (P6) could be improved.

The study has not only served to identify the IBSs existing in the market and compare them with that of PMP, but also to identify the most efficient practices in the IHB market. The results are directly related to Jonsson and Rudberg (2014) classification of production systems for industrialized building. However, it is worth noting the identification of a key factor that Jonsson and Rudberg (2014) did not take into account, the industrialization index (P8). This study, together with the chapter 3 one, has helped not only to identify this key factor but also to show that it is really relevant when designing a building system. The industrialization index (P8) should not be confused with 3D modules production. It is possible to have a high industrialized process manufacturing 2D modules and join them, on-site or in the factory, to generate the spaces. In fact, the study identified a company (f-15) with a 2D modules IBS that prefabricated, also, a MEP systems core. This allowed the IBS to have a higher industrialization index (P8) and maintain the customization of the designs.

Finally, based on the results, it is concluded:

1) Customization is best done using 2D modules
2) A high industrialization index helps to have a more cost and time efficient performance

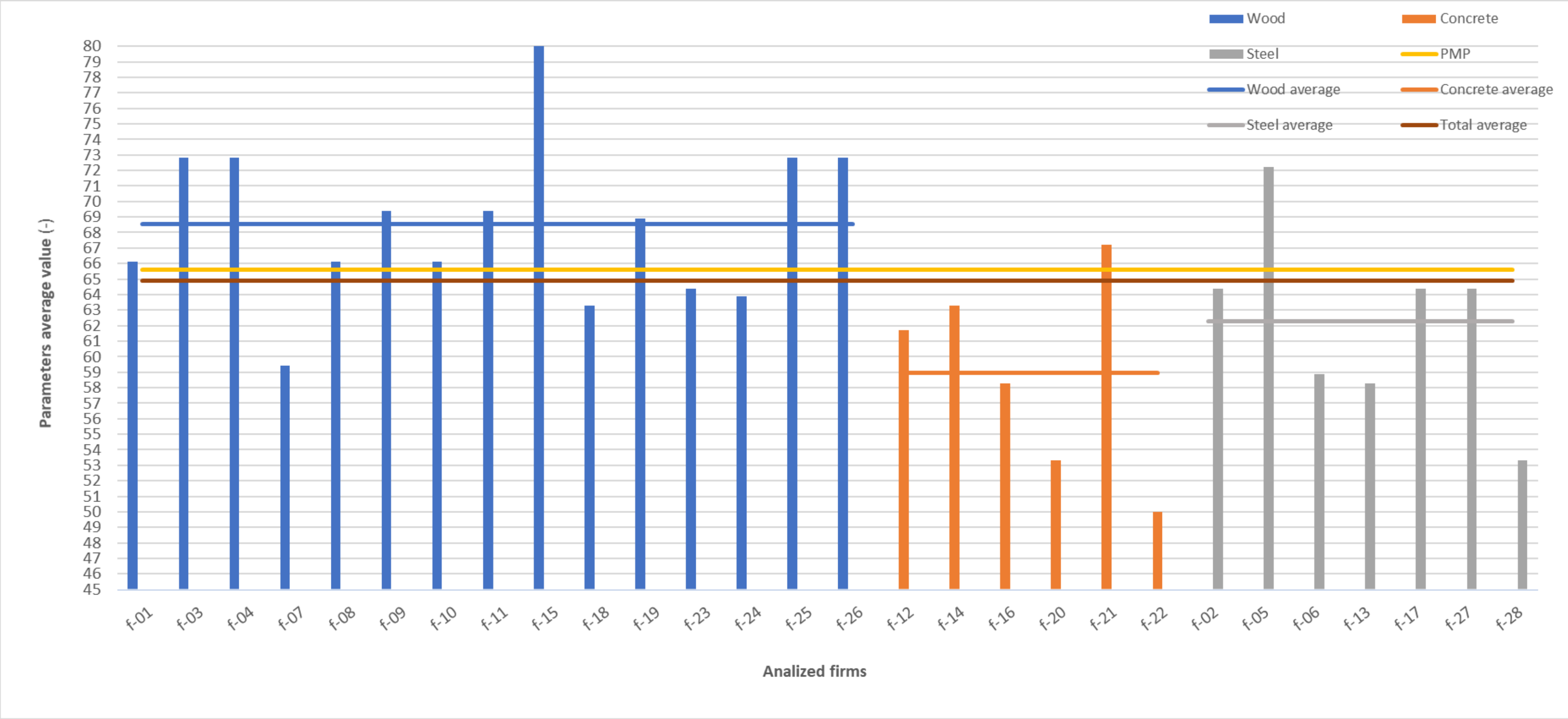


Figure 4-6. Parameters average value (material sub-analysis)

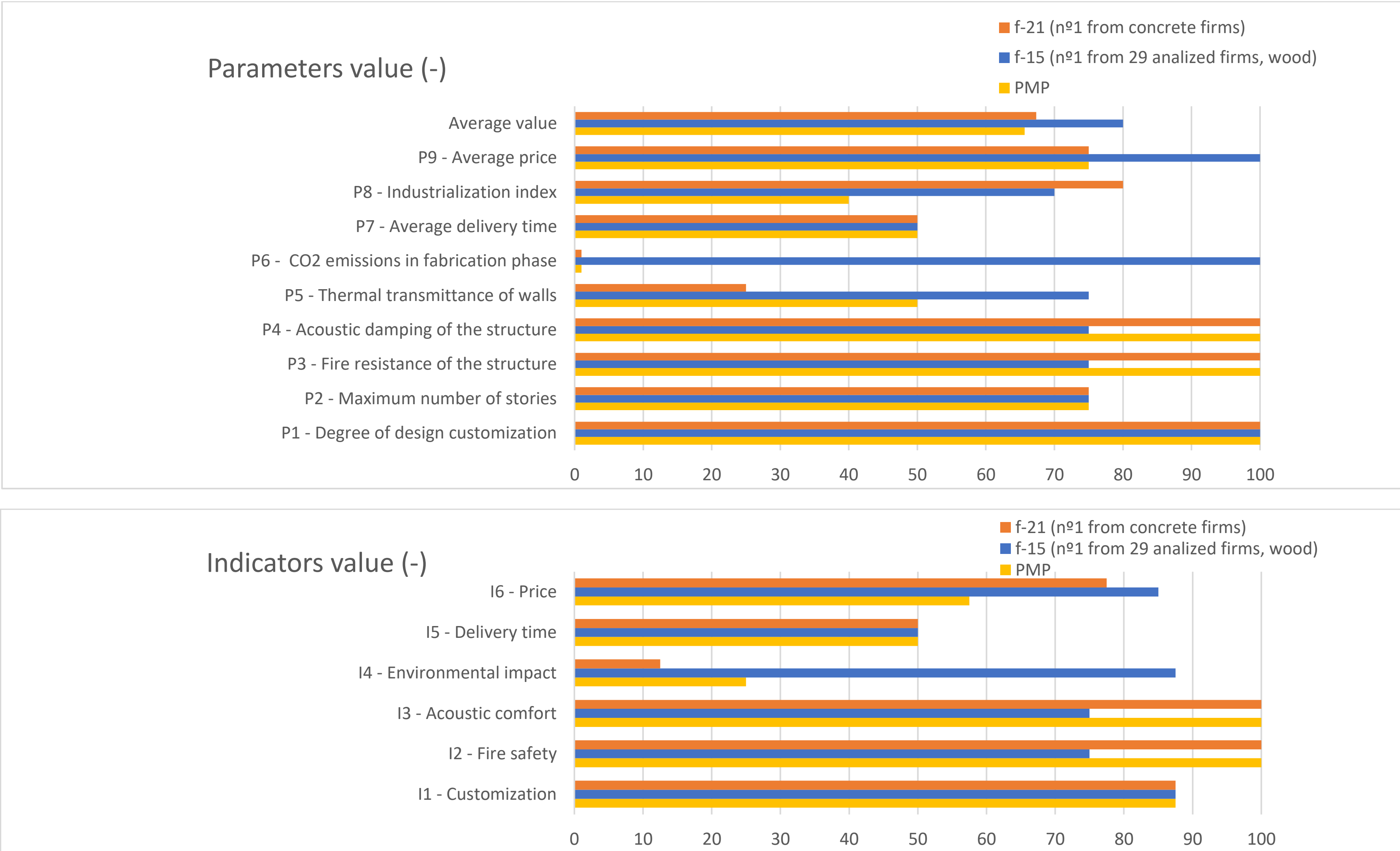


Figure 4-7. Parameters and indicators evaluation comparison

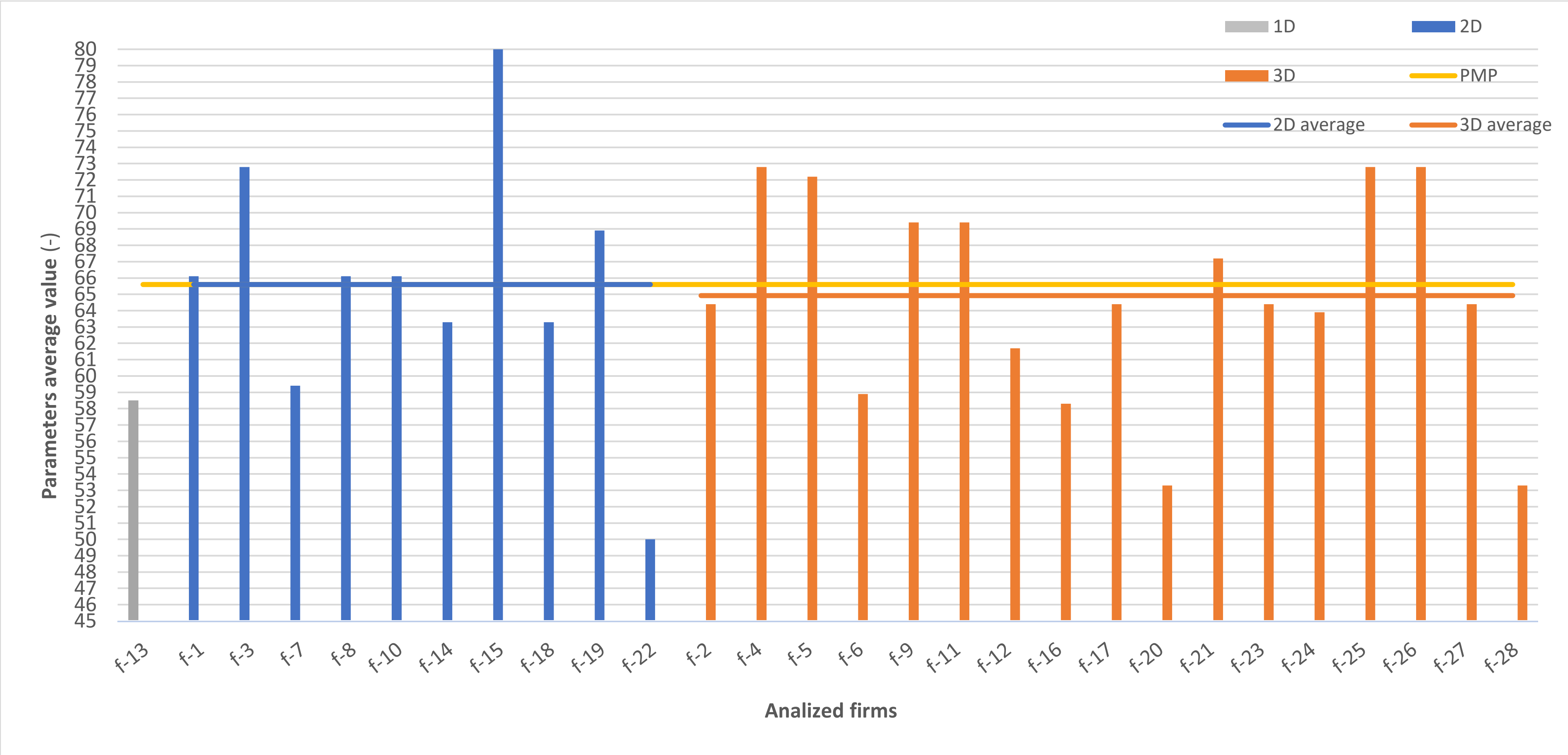


Figure 4-8. Parameters average value (volume of the manufactured modules sub-analysis)

Chapter 5. PMP industrialized building system sustainability study under heating, cooling and construction costs criteria

Methodology and chapter structure

In the context of the trends in the construction sector towards energy-efficient building systems during the use phase (operational phase), and in view of the conclusions of chapter 4, the PMP company (https://pretaportercasas.com/) considered how to reduce the environmental impact of their homes.

The technicians of the PMP company (https://pretaportercasas.com/) proposed to make a comparative study under criteria of energy efficiency during the use phase of the houses (operational Phase) between their building system and the following two building systems:

- Prefabricated concrete modules (2D) with exterior insulation technology
- Lightweight wood frame

The PMP building system consists of prefabricated concrete modules (2D) with interior insulation technology.

These two IBSs were identified, according to the results of the chapter 4 study, direct competitors in the PMP market, especially in the area of environmental sustainability.

An assessment under criteria of economic viability had to be done on whether or not to modify the building system of PMP by one of the two systems analysed. Thus, this study had the following purposes:

- To analyse in depth energy efficiency parameters affecting the energy consumption during the use phase (operational phase) of the current PMP buildings (e.g., thermal bridges).
- Calculate and compare the heating and cooling demands of homes defined by two different prefabricated concrete modules (2D) building systems, one with interior insulation technology and the other with exterior insulation technology. Also, analyse the economic viability of each system.
- Calculate and compare the thermal behaviour and economic viability of a lightweight timber frame building system with the two prefabricated concrete modules (2D) building systems.
- Decide if it was feasible to apply any of these two modifications to the PMP building system.

Chapter 4 defines the P5 parameter (thermal transmittance of the walls) as an indicator of environmental sustainability to compare the different building systems in broad terms. Now, this chapter looks in depth at the "energy demand for home heating and air conditioning" as an advanced indicator of environmental impact. It is called an advanced indicator because it is more accurate and is used in the energy certifications of buildings in Spain according to the regulations of the CTE-DB-HE (Fomento 2019). Unlike the P5 parameter (thermal transmittance of the walls), the energy demand must be evaluated under specific case studies and following the procedure indicated in the CTE-DB-HE regulations (Fomento 2019).

This procedure (Figure 5-1) consisted of calculating the heating and cooling energy demands of the building under analysis in a building performance simulation (BPS) environment regulated by the CTE-DB-HE, such as the EnergyPlus (https://energyplus.net/).

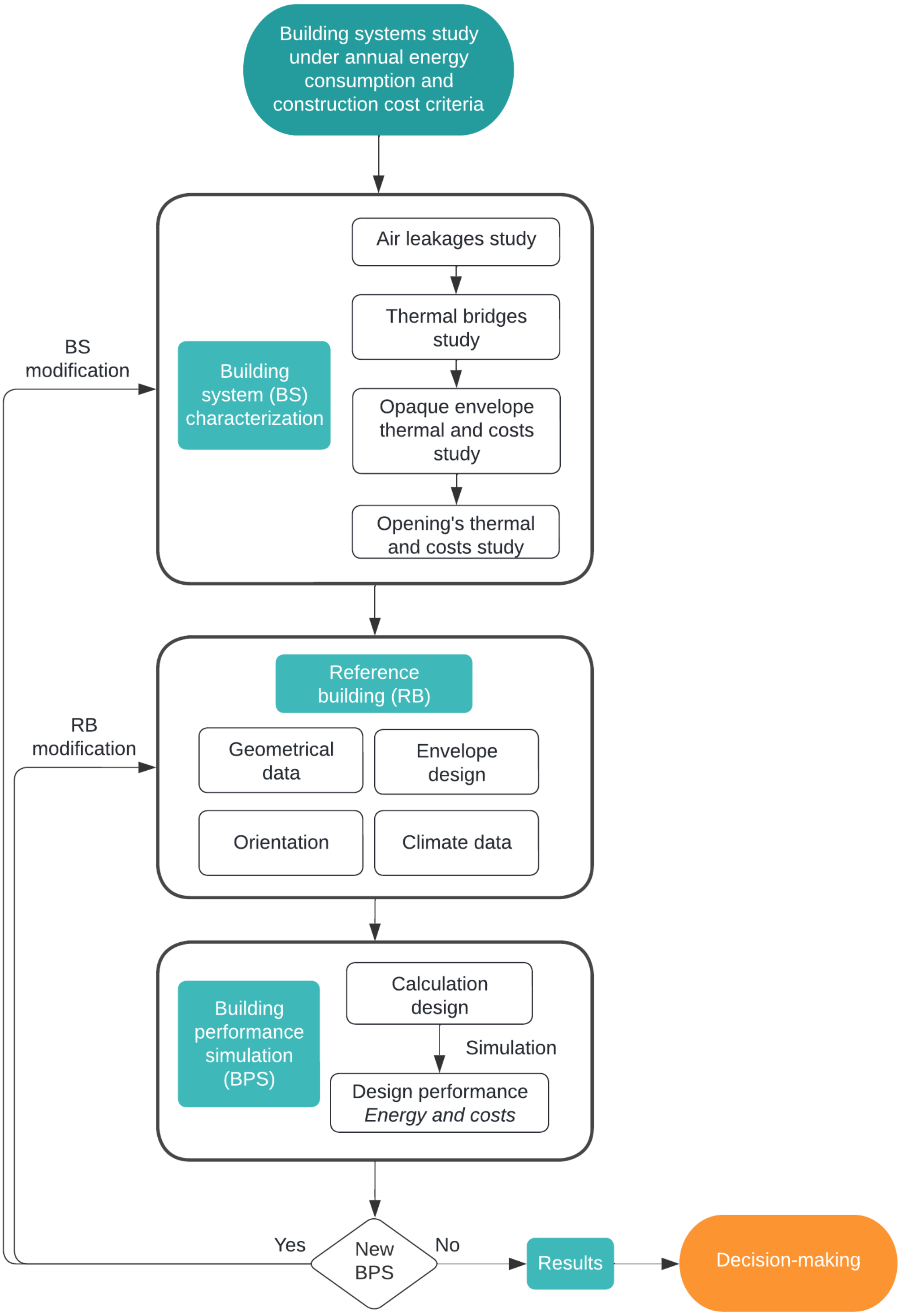


Figure 5-1. Chapter 5 contents

SketchUp (https://www.sketchup.com/es) and OpenStudio (https://openstudio.net/) have also been used to facilitate drawing and modelling as complementary tools to EnergyPlus. In order to perform this step, it was necessary to characterize, previously, all the variables that the EnergyPlus BPS environment uses to perform the simulations. These variables refer to the reference building (RB), the building system (BS) characterization and the simulation conditions (SC).

The reference building (RB) was defined by the geometrical data (e.g. length of a facade), the envelope design (e.g. position of the windows), the orientation and the climate data of the location of the building.

To define and model a building system in the BPS environment, it was necessary to characterize the air leakages, the thermal bridges, the opaque envelope and the openings. Therefore, the following was done:

- An experimental study of air permeability following the blower door procedure (Hsu et al. 2021) in different homes built by PMP.
- An analytical study of thermal bridges of the three building systems under study.
- A thermal and economic characterization of the opaque elements of three building systems.
- A thermal and economic characterization of the openings (assumed the same for the three building systems)

Simulation conditions (e.g., thermostats inside the home) were set following CTE-DB-HE regulations (Fomento 2019).

Next, the variables to be reported were clearly defined in the BPS environment. In this study, the main variables analysed were:

- Construction costs (€)
- Heating and cooling energy demands (kWh/m^2·year)
- Costs related to the power consumption of heating and cooling systems (€/year).

Cost studies were performed in parallel with the BPS environment simulations in a (.csv) file that has been specially implemented to do this task.

12 scenarios (Table 5-1) were analysed: 2 models of reference building (RB) in 2 different climates and, for each, the three building systems under study.

Scenarios	Reference Building (RB)	Location	Building system
1	RB1	Lleida	Prefabricated concrete modules (2D) with interior insulation technology
2	RB1	Lleida	Prefabricated concrete modules (2D) with exterior insulation technology
3	RB1	Lleida	Lightweight wood frame
4	RB1	Barcelona	Prefabricated concrete modules (2D) with interior insulation technology
5	RB1	Barcelona	Prefabricated concrete modules (2D) with exterior insulation technology
6	RB1	Barcelona	Lightweight wood frame
7	RB2	Lleida	Prefabricated concrete modules (2D) with interior insulation technology
8	RB2	Lleida	Prefabricated concrete modules (2D) with exterior insulation technology
9	RB2	Lleida	Lightweight wood frame
10	RB2	Barcelona	Prefabricated concrete modules (2D) with interior insulation technology
11	RB2	Barcelona	Prefabricated concrete modules (2D) with exterior insulation technology
12	RB2	Barcelona	Lightweight wood frame

Table 5-1. BPS scenarios

Reference buildings

<u>Geometrical data, envelope design and orientation</u>

The two reference buildings chosen for this study have geometries based on real projects carried out by PMP (https://pretaportercasas.com/).

As shown in Figure 5-2 and Figure 5-3, reference building 1 (RB1) and reference building 2 (RB2) have a clearly different living area and volume. Based on sales data and PMP's experience in the sector, two models that were chosen represent lower (97,2 m^2) and upper (271,92m^2) limits with respect to the living area. In addition, a model with a basement (RB2) was expressly chosen to analyse its behaviour.

As can be seen in Figure 5-2 and Figure 5-3, the area of windows on the south façade and/or window-to-wall ratio (WWR) is much higher in the case of RB2. The distribution of solar gains was expected to be clearly different in both cases. It is worth noting that an identical solar blind control was implemented in the two reference buildings. Therefore, solar gains were not expected to have a negative impact on the warmer times of the year.

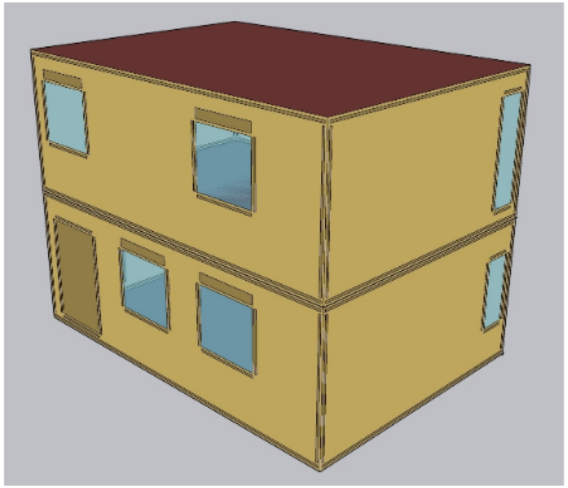
<u>Climate data</u>

The two reference buildings were located in the cities of Lleida (Spain) and Barcelona (Spain). These are two Mediterranean different climatic zones according to the CTE-DB-HE (Fomento 2019).

- Lleida - Climate zone D3 (Spain)
- Barcelona - Climate zone C2 (Spain)

These two climates were chosen to represent the most common climates where potential PMP customers reside.

Climate data was extracted from the official EnergyPlus data base, so weather files were downloaded directly from: (https://energyplus.net/weather.



Reference building data	
Location	Lleida/Barcelona
Floor area (m²)	97,9
Floor heigh (m)	3

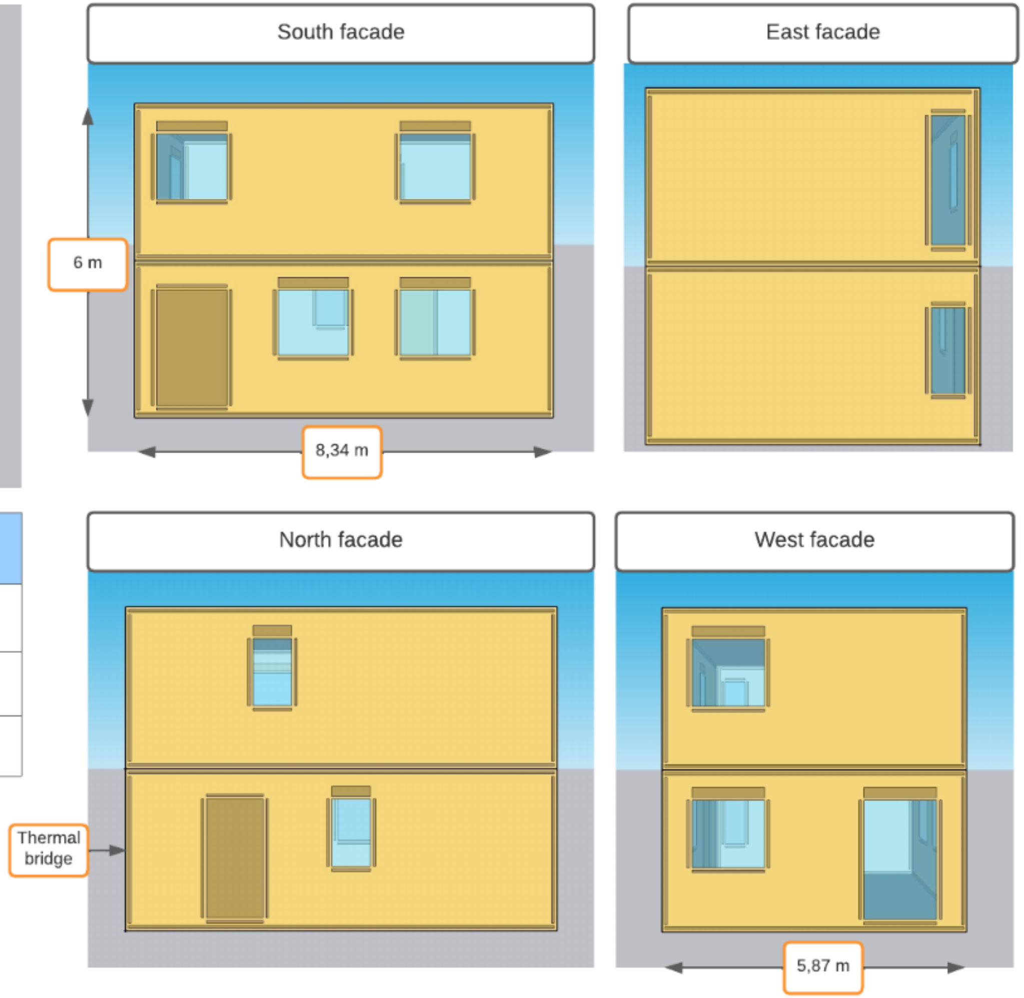
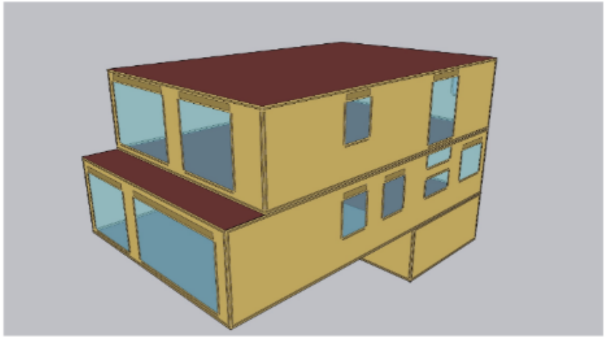
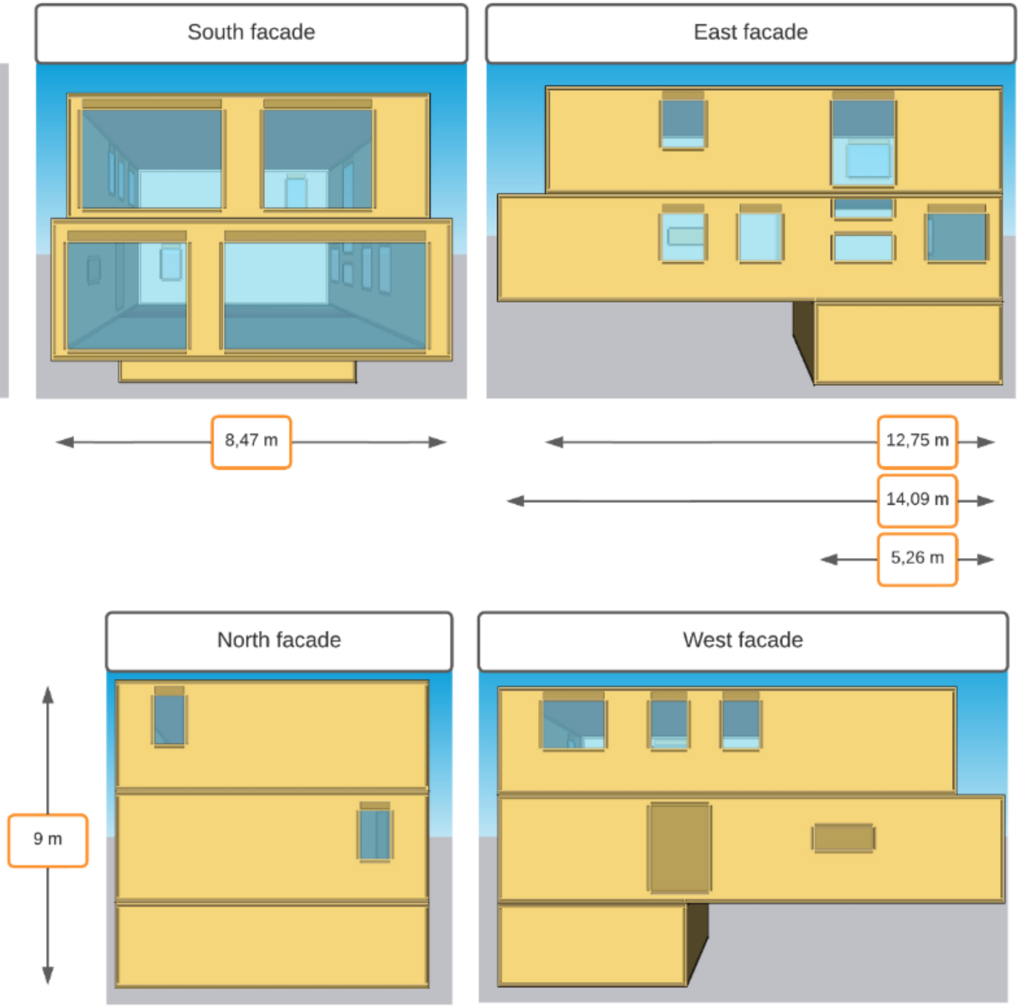


Figure 5-2. Reference building 1 (RB1)





Reference building data	
Location	Lleida/Barcelona
Floor area (m^2)	271,92
Floor heigh (m)	3

Figure 5-3. Reference building 2 (RB2)

Building system characterization

Air leakages study

Part of the energy losses of buildings during the colder seasons of the year, and part of the energy gains in the warmer seasons, are due to air infiltrations and/or air leakages. In order to properly evaluate the thermal behaviour of a house-building, it is necessary to characterize air leakages and indicate, in the BPS environment (https://energyplus.net/), the value of these air leakages expressed in AirChanges/Hour (ACH).

At the design stage of a building, it is not known exactly what air permeability it will have once it is built, as this value depends, in part, on the on-site construction process. The regulations followed in Spain to carry out the energy certifications of buildings, CTE-DB-HE (Fomento 2019), do not require measuring the air permeability of a building by a blower door test according to DIN EN ISO 9972: 2018-12 (ISO 9972: 2015), the CTE-DB-HE simply ask to calculate a value of air leakages according to design parameters (e.g., volume of the internal envelope). This is just a method of estimation and not a regulated experimental calculation of air leakages in buildings.

To characterize the air leakages of the PMP building system under a regulated experimental measurement method, an experimental blower door test (Hsu et al. 2021) was carried out following the procedure established in DIN EN ISO 9972: 2018-12 (ISO 9972: 2015) in 7 buildings built by PMP . The measurement procedure followed is summarized in Figure 5-4.

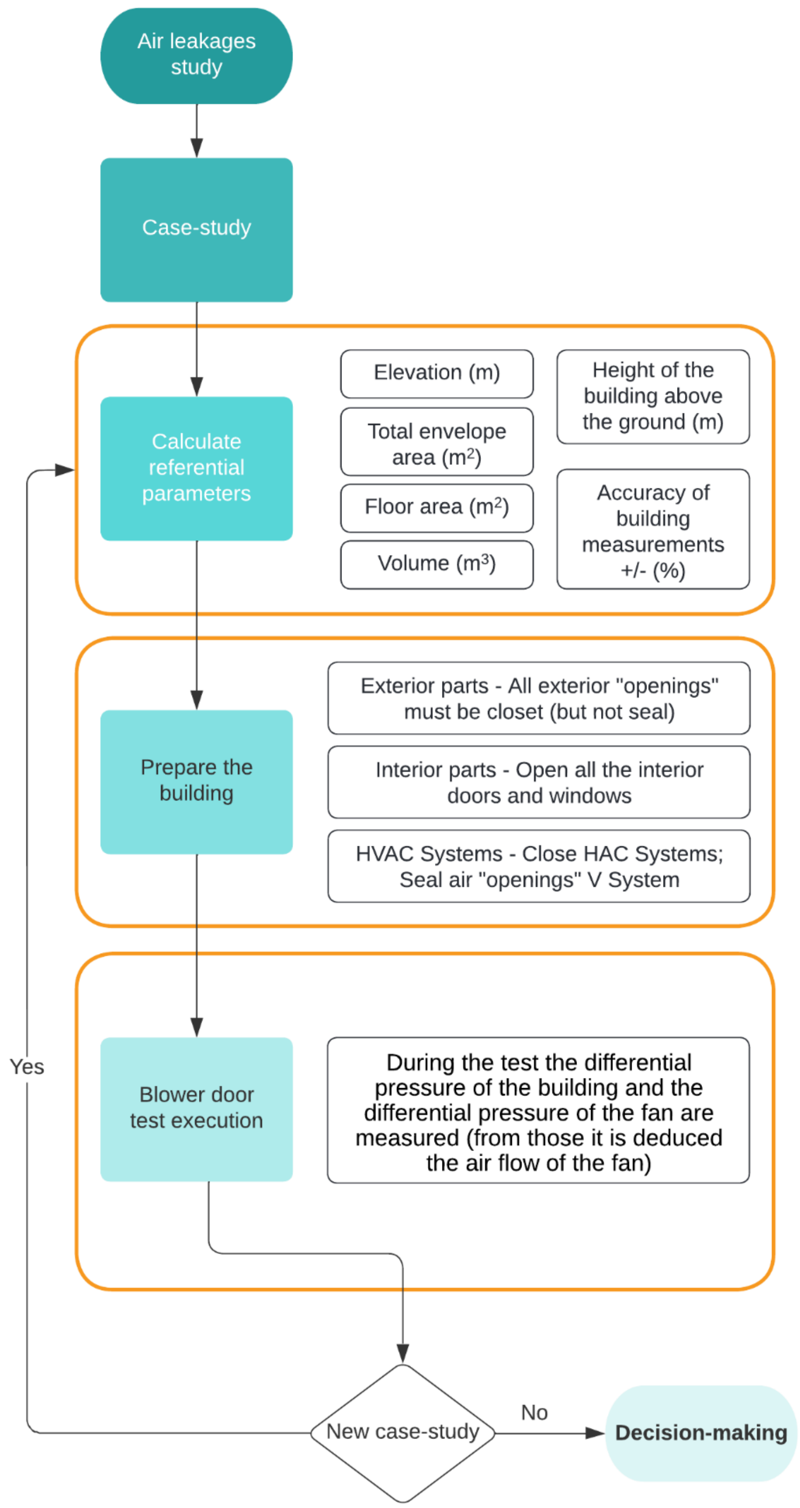


Figure 5-4. Blower door test procedure

The measuring equipment used was the Retrotec 5000 (Gauge-DM32-405039) from the manufacturer Retrotec (https://retrotec.com/).

The first step was to calculate the parameters that define the building under analysis (referential parameters) and enter them into the Retrotec's software (https://retrotec.com/). These parameters are: (1) elevation, (2) total envelope area, (3) floor area, (4) volume, (5) height of the building above the ground and (6) Accuracy of building measurements (Figure 5-4). It was also necessary to measure on-site and indicate:

- The indoor temperature during the test (ºC)
- Outdoor temperature during the test (ºC)
- The building exposure to the wind (High-Low)

Secondly, the building was prepared for the test by applying the measures in Figure 5-4:

- Close all the openings of the envelope
- Open all the interior doors and windows
- Close heating and air conditioning systems
- Seal air ventilation grilles of ventilation systems and kitchen’s fume hood and/or fireplace (Figure 5-5)

Figure 5-5. Sealing the kitchen fume hood

Next, the blower door frame was installed on the front door and cable connections were made between the fan, the computer, and the measuring device (Figure 5-6)

$(a)\ indoor's\ view$ $(b)\ outdoor'sview$

Figure 5-6. Fan installation of the blower door test

Finally, the test measurements started. There are two types of tests, blower door pressurisation and blower door depressurisation. The difference between them is the direction (in or out of the building) of air flow generated by the fan. Each tests lasts approximately 20 minutes. In this experimental study pressurisation tests were performed.

Figure 5-7 shows the results of one of the experimental tests performed throughout this study. The most important data of this analysis is indicated in red, which reports the result of the air permeability (ACH) of the house. On the one hand, the value of air leakages in measurement conditions where the differential of pressure between the interior and the exterior of the house is about 50Pa as indicated by the norm DIN EN ISO 9972: 2018-12 (ISO 9972: 2015). The value of air leakages under measuring conditions where the differential of pressure is 4 Pa had been regarded as a more precise indicator of the pressure level experienced by buildings under natural conditions than conventional steady-state measurements at 50 Pa (Sherman and Matson 2002). Hence, this was the value used to characterize air infiltrations in the BPS environment.

Figure 5-7 shows how the induced pressure evolves throughout the test. Initially, the base line representing the initial pressure differential was calculated before turning on the blower door fan (https://retrotec.com/). The baseline was also calculated before the end of the test.

During the test, a range of steady pressure differences across the building was created with the blower door fan, and the corresponding air flow rate through the fan was measured simultaneously for establishing the pressure-leakage relationship of the tested building (Hsu et al. 2021).

FanTestic	version:**5.11.79**	licensed to:**University of Lleida**
Test	By:**Adrià Mateo Fornés**	
Customer:	**PMP**	
Building	**El Catllar (Spain)**	

Building and Test	
Test file name:	El Catllar - v1
Building volume [m³]:	**324**
Envelope Area [m²]:	**414**
Floor Area [m²]:	**124**
Building Height (from ground	**625**
Building Exposure to wind:	**Highly exposed**
Accuracy of measurements:	**5%**

Results	
Air flow at 50 Pa, Q50[m³/h]	**959.80**
Air changes at 50 Pa,*n*50[/h]	**2.96**
Air flow at 4 Pa, Q4[m³/h]	**155.00**
Permeability at 4 Pa, Q4 Pa_surf[m³/h/m²]	**0.374**
Effective leakage area at 4 Pa, AL[cm²],	**278.5**
Effective leakage area at 4 Pa, AL[cm²]	**167.1**

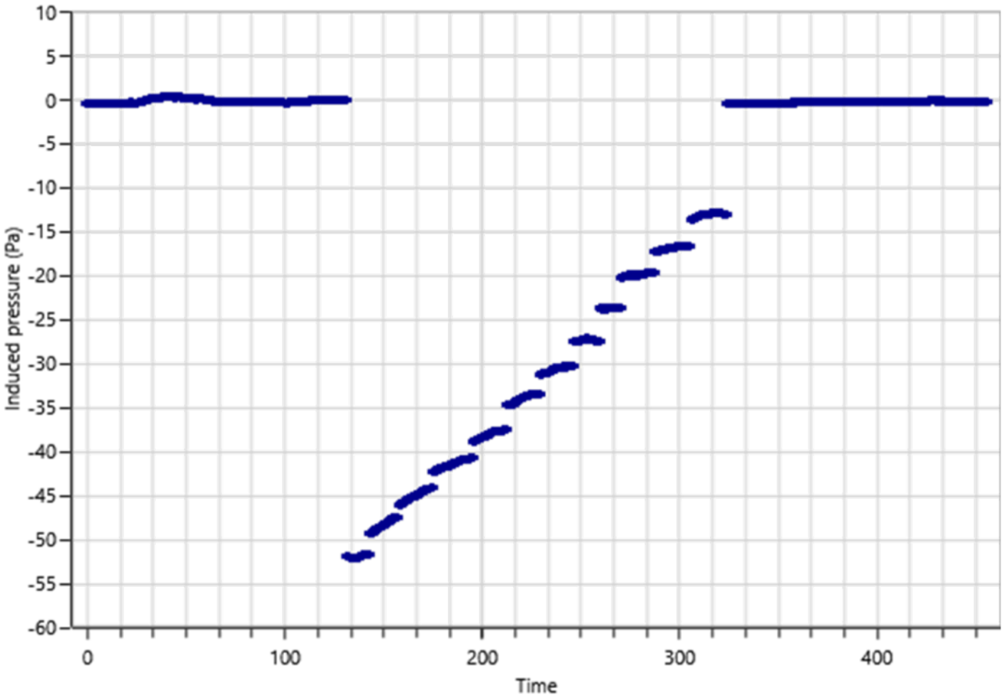


Figure 5-7. Blower door test example

In the example of the test in the Figure 5-7, corresponding to test number 3 (Table 5-2), the results were:

- n50 (Pa) = 2.96 (1/h)
- n4 (Pa) = 0,48 (1/h). Calculated from Figure 5-7 results: $(\frac{\text{Air flow at 4 Pa}}{\text{Building volume}})$

The regulations passivhaus (House and Weissensee n.d.) state that a home must have a n50 (Pa) lower than 0.6. Therefore, in this case the passivhaus regulations would not be complied with.

Table 5-2 shows the data and the results of the 7 tests that were performed, and their main characteristics. The climate zones refer to CTE-DB-HE regulations (Fomento 2019). The other data relating to the 7 case studies were attached to the table to assist in decision making as variables such as volume, compactness or the existence of a ventilation system were expected to have a significant impact on the results. Moreover, the opening's frameworks were from two different manufacturers. One aspect to be specified is that there is no direct relationship between these 7 case studies and the 12 scenarios described in Table 5-1. These case studies were done to experimentally calculate a specific air infiltrations value to be introduced after in the BPS environment (https://energyplus.net/) to simulate the 12 scenarios in Table 5-1.

Case-Study	Climate Zone *(CTE)*	Habitable Volume (m^3)	Habitable Area (m^2)	Envelope Area (m^2)	Air changes n50 Pa (-/h)	Air changes n4 Pa (-/h)	Opening's Framework	Garage	nº Floors	Compactness	Heating and Cooling Systems	Heat Recovery System
1	C2	**258**	**103**	357	**3,4**	**0,75**	A	No	2	0,72	Splits	Yes
2	D3	**364**	**143**	403	**2,7**	**0,39**	A	Yes	2	0,90	Radiant floor	Yes
3	C3	**324**	**124**	414	**2,7**	**0,43**	A	No	2	0,78	Radiant floor	No
4	C2	**562**	**221**	587	**2,1**	**0,18**	A	Yes	3	0,96	Ducts	Yes
5	D2	**319**	**118**	420	**3,0**	**0,53**	B	Yes	2	0,76	Radiant floor	Yes
6	C3	**352**	**141**	441	**2,9**	**0,44**	B	No	2	0,80	Ducts	No
7	C2	**368**	**147**	473	**3,4**	**0,54**	B	Yes	2	0,78	Ducts	Yes
Average			**142,37**		**2,89**	**0,47**						

Table 5-2. Blower door test results

In the Table 5-2 it can be seen that in the best case (case-study 4) the value n50 (50 Pa) was 2.1 and in the worst case (case-study 1 and case-study 7) 3.4. In all cases, the Spanish CTE regulations (https://www.codigotecnico.org/DocumentosCTE/AhorroEnergia.html) were complied with, but none of the 7 cases would accomplish the strictest regulations passivhaus (House and Weissensee n.d.) with in this area.

The average value of air infiltrations n50 (50Pa) was 2.89 (-/h) and n4 (4 Pa) was 0.47 (-/h). The building with a higher value of compactness had the lowest value of n50 (50Pa) and n4 (4 Pa). The building with a lower value of compactness had the highest value of n50 (50Pa) and n4 (4 Pa). It is clearly stated that the higher the compactness the lower the air infiltration.

With regard to carpentry manufacturers, with the exception of case-study 1, manufacturer A behaved better than manufacturer B.

There are no substantial differences between the heating and cooling equipment that affect the results. It is also not appreciated that other parameters such as the climate zone, the garage or the ventilation system clearly affect the results.

From the results obtained in Table 5, it was decided to use the value of n4 (4 Pa) of 0.4 (-/h) for the simulations in the EnergyPlus (https://energyplus.net/) BPS environment because case-studies 2 and 6 were the ones that best fit the average dimensions of a PMP House-building.

For the purposes of this study, it has been considered that the value of air permeability will be the same for the three building systems to be analysed. In fact, in the case of prefabricated concrete modules (2D) with exterior insulation technology building system and lightweight wood frame building system it was not possible to perform the experimental blower door tests.

Thermal bridges study

Thermal bridges play an important role in the thermal behaviour of buildings. During the cold seasons, thermal bridges represent energy losses throughout buildings. During the warmer seasons, they represent energy gains. In both cases, the impact on the thermal behaviour of the building is negative and increases the energy demand for heating and air conditioning of the buildings. Therefore, it is necessary to correctly characterize the behaviour of thermal bridges of a building system in EnergyPlus (https://energyplus.net/) BPS environment.

Unlike the previous study regarding air infiltrations, in order to characterize the thermal bridges, it is not necessary to make experimental studies of the finished house-building. In this study, the European standard UNE-SIO-10211 was followed to evaluate the thermal bridges of the three building systems under study (Figure 5-8).

The computing environment used was Therm (https://windows.lbl.gov/tools/therm/software-download).

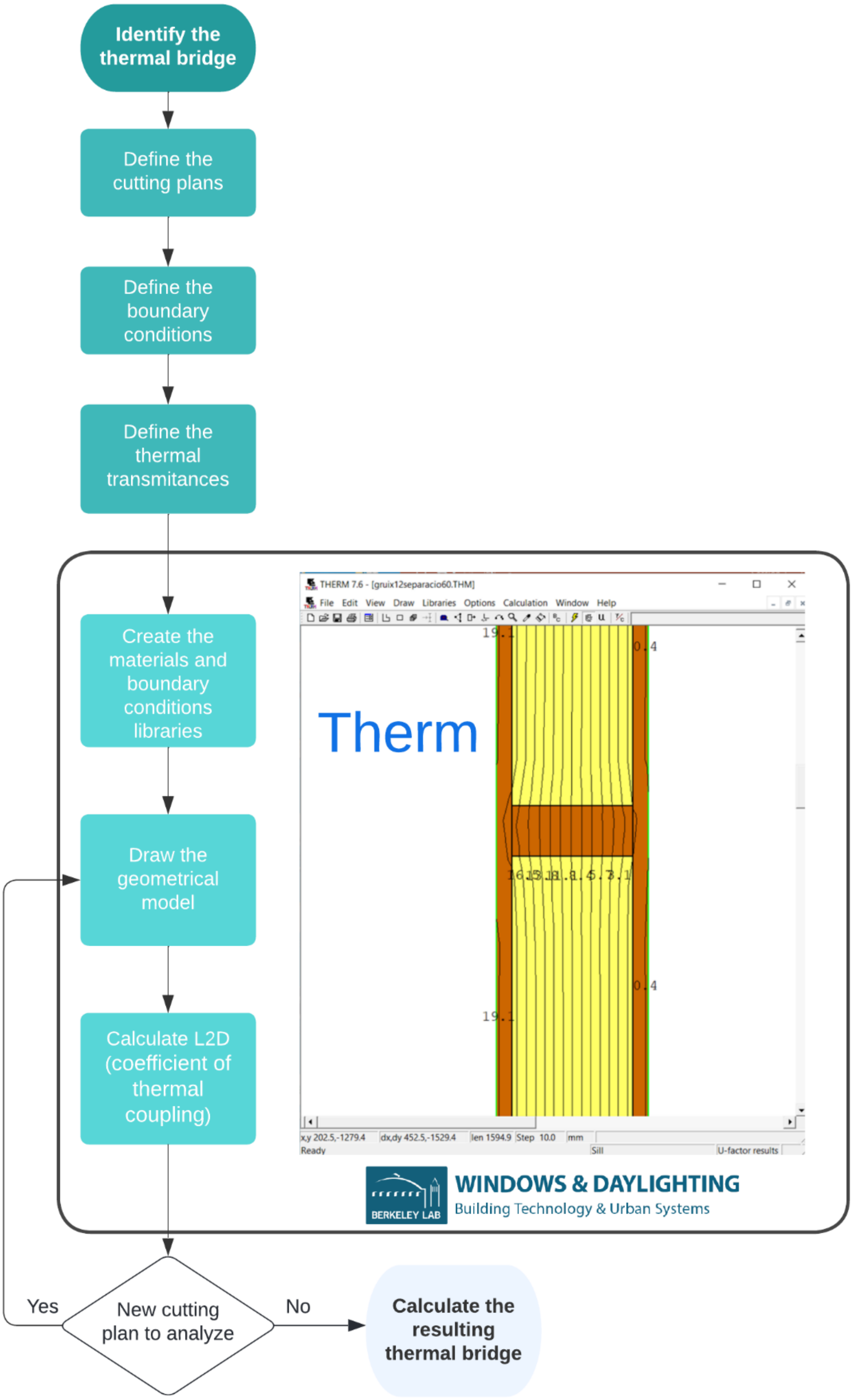


Figure 5-8. Thermal bridges study procedure

First, the following thermal bridges were identified: (1) windows, (2) doors, (3) wall-corners, (4) wall-roofs, (5) wall-bottom floor, and (6) wall-middle floor.

Second, the cutting plans for each thermal bridge were defined. The cutting planes determine the dimensions to be drawn in the Therm computing environment (https://windows.lbl.gov/tools/therm/software-download) to define the thermal bridge. The boundary conditions were then determined according to the CTE-DB-HE (Fomento 2019) regulations and the material libraries in the Therm computing environment were defined. The fundamental data to characterize the materials is their thermal conductivity (W/mK). From here each cutting plane was drawn and modelled, and the Therm (https://windows.lbl.gov/tools/therm/software-download) calculated the L2D parameter (coefficient of thermal coupling). Once all the cutting planes of all the thermal bridges were modelled and simulated, the values (Ψ) of each thermal bridge could be calculated according to the equation [*5-1*].

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j * l_j \qquad [5\text{-}1]$$

Where:

- L2D is the coefficient of thermal coupling obtained by the bidimensional calculation of the element (once applied the cutting plans).
- Uj is thermal transmittance of the unidimensional component j that spares the considered geometries.
- lj is the length of the bidimensional geometrical model where applied each U_j value.

For example, in the calculation of the wall-middle floor thermal bridge, the cutting plan can be seen in Figure 5-9 (a). Once the value of L2D and the conductivities of the wall and middle floor elements were calculated, in separated Therm files under the same boundary conditions as the cutting plane of Figure 5-9 (a), the wall-middle floor thermal bridge was calculated following equation [5-2].

$$\Psi_{Wall-middle\ floor} = L_{2D} - \sum_{j=1}^{N_j} U_j * l_j = 1{,}38\frac{W}{mK} - 0{,}95\frac{W}{mK} = 0{,}43\frac{W}{mK} \qquad [5\text{-}2]$$

Figure 5-9 (a) shows the boundary conditions that were defined. For the horizontal heat flow the Film Coefficient is 25 W/m^2K on the outside and 7.7 W/m^2K on the inside. In terms of vertical heat flow, the defined film coefficients are 10 W/m^2K and 5.5 W/m^2K according to CTE-DB-HE (Fomento 2019) regulations.

Figure 5-9 (a) also describes the building system under study. For example, the facade is defined by the prefabricated concrete modules (2D), the thermal insulation consisting of 12 cm of rock wool (λ = 0.035W/mK) and the finishing of plasterboard.

Finally, Figure 5-9 (b) shows how the temperature is distributed under the simulation conditions along the cutting plan (colour legend), and clearly identifies where the thermal bridge is and how its effect is spreaded along of construction.

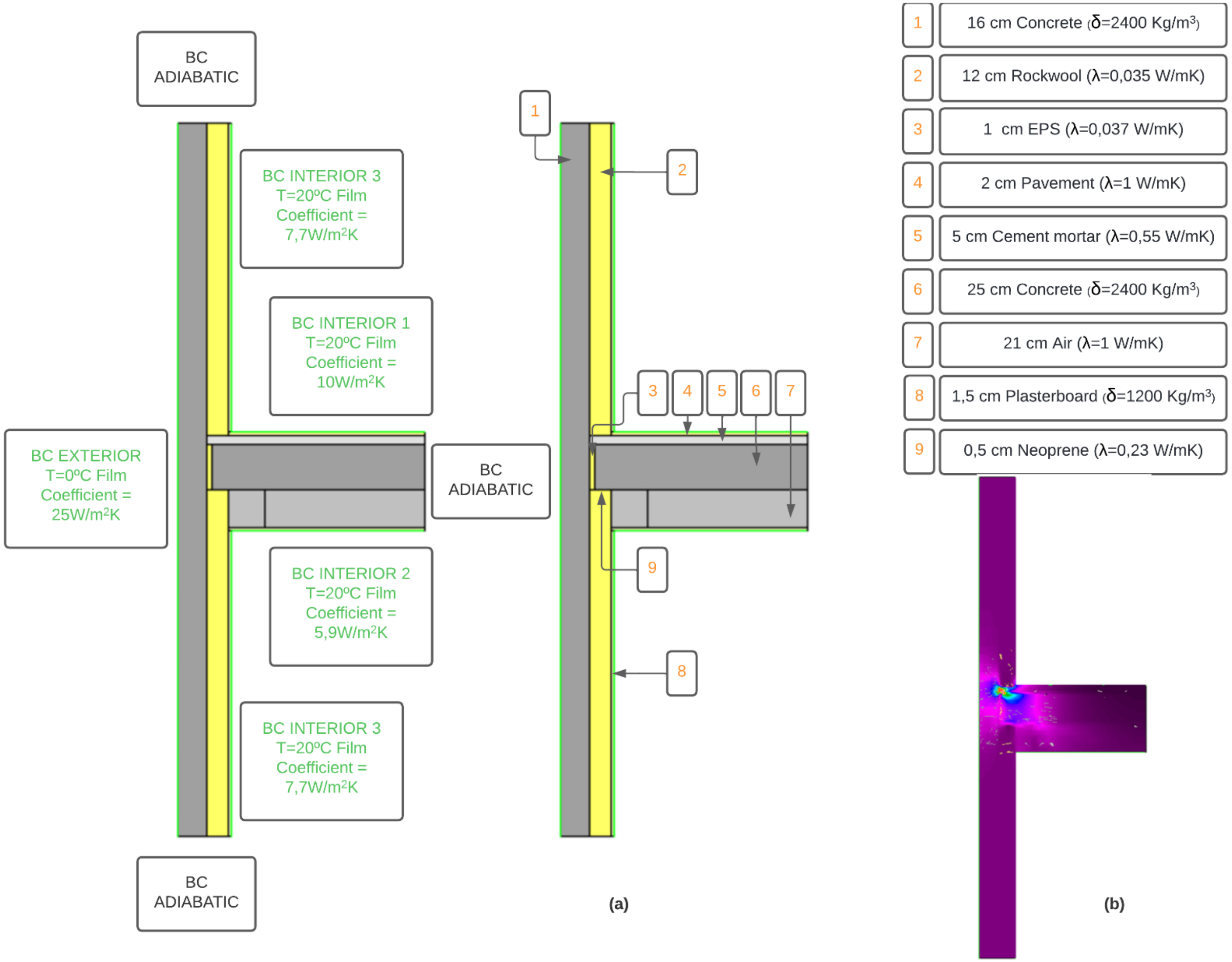


Figure 5-9. Wall-middle floor thermal bridge example (a) cutting plan and boundary conditions (b)Temperature distribution in the thermal bridge

The calculations of the 6 thermal bridges were carried out for the 3 building systems under study, and the results are summarized below in Table 5-3. These results are similar to the ones obtained by Ilomets et al. (2016), but in this case the building systems under analysis are IBS.

Thermal bridges Ψ (W/mK)			
	Building System		
	Prefabricated concrete modules (2D) with interior insulation technology (PMP)	Prefabricated concrete modules (2D) with exterior insulation technology	Lightweight wood frame
Windows	**0,3**	**0,3**	**0**
Doors	**0,1**	**0,1**	**0**
Wall-corners	**0,05**	**0,05**	**0**
Wall-roofs	**0,15**	**0**	**0**
Wall-bottom floor	**0,15**	**0**	**0**
Wall- middle floor	**0,43**	**0**	**0**

Table 5-3. Thermal bridges results

Unlike the previous air permeability study, the three building systems under study were represented in the simulations in the EnergyPlus (https://energyplus.net/) BPS environment by clearly different thermal bridges.

Opaque envelope thermal and costs study

The characteristics of the 3 industrialized building systems (IBSs) under study referring to the thermal behaviour (U-values) and costs, required to carry out the simulations in the EnergyPlus BPS environment, are detailed below (https://energyplus.net/). Table 5-4 summarizes all the thermal and economical characterization data of the three IBSs.

All cost data for all three envelopes were extracted from the manufacturers' databases.

Prefabricated concrete modules (2D) with interior insulation technology (PMP)

- Facade: 16 cm thick reinforced concrete wall facade with a 12 cm layer of rock (λ = 0,035W/mK) and a 15 mm plate plasterboard structure. Interior insulation layer.
  - Facade U-value (W/m^{2}K) = 0,27
  - Facade cost (€/m^2) = 128
- Floor: 25 cm reinforced concrete alveolar slab covered with 4 cm XPS (λ = 0,034W/mK), compression layer and 2 cm of ceramic pavement.
  - Floor U-value (W/m^{2}K) = 0,3
  - Floor cost (€/m^2) = 153
- Top-roof: 25 cm reinforced concrete alveolar slab covered with an outer layer of 4 cm XPS (λ = 0,034W/mK) and 12 cm interior false ceiling with rock wool (λ = 0,035 W/mK). The outer coating is gravel and the interior is plasterboard.
  - Top-roof U-value (W/m^{2}K) = 0,18
  - Top-roof (€/m^2) = 128

The concrete wall acts as an element of thermal inertia. However, the concrete layer of the wall is in contact with the exterior climate (because the insulant layer is internal). Studies demonstrate that this is not the best position of the element of inertia (concrete) as its virtues are not exploited efficiently enough (Bojic, Yik, and Sat 2001).

In addition, this IBS stands out for a high value of thermal bridges referring to the wall-middle floor compared to other thermal bridges as can be seen in Table 5-3.

The cost of the foundations was also assessed according to the database of PMP company, resulting on 16.5 €/m^2.

Prefabricated concrete modules (2D) with exterior insulation technology

There is only one difference between this IBS and the one previously characterized (PMP IBS), the position of the thermal insulation layer on the facade. In this case the position of the thermal insulation is in the outer layer of the concrete wall. The floor and top-roof have exactly the same composition as the PMP IBS system.

- Facade: 16cm thick reinforced concrete wall facade with a 12 cm layer of rock (λ = 0,035W/mK) and a 15 mm plate plasterboard structure. Outside insulation layer.
    - Facade U-value (W/m^{2}K) = 0,27
    - Facade cost (€/m^2) = 178
- Floor: 25 cm reinforced concrete alveolar slab covered with 4 cm XPS (λ = 0,034W/mK), compression layer and 2 cm of ceramic pavement.
    - Floor U-value (W/m^{2}K) = 0,3
    - Floor cost (€/m^2) = 153
- Top-roof: 25 cm reinforced concrete alveolar slab covered with an outer layer of 4 cm XPS (λ = 0,034W/mK) and 12 cm interior false ceiling with rock wool (λ = 0,035W/mK). The outer coating is gravel and the interior is plasterboard.
    - Top-roof U-value (W/m^{2}K) = 0,18
    - Top-roof (€/m^2) = 128

A remarkable feature of this building system with respect to PMP's IBS is that the wall-middle floor, wall-bottom floor and wall-roof thermal bridges are removed. In addition, the element of thermal inertia (concrete) is located in the inner layer, in contact with the internal environment of the home. According to previous studies, this is the most successful insulation position to take advantage of the thermal inertia of concrete as an element of energy efficiency (Bojic, Yik, and Sat 2001).

Therefore, this building system integrates thermal improvements compared to the PMP IBS.

The cost of the foundations is the same as the one in the PMP IBS, 16.5 €/m^2.

Lightweight wood frame

Lightweight wood frame building system is completely different from the previous ones. This system has been analysed as it is similar to that of some companies analysed in the chapter 3 study that have a better assessment of environmental sustainability.

- Facade: C24 flannel pine wood beams (5x16 cm), 16 cm XPS insulation (λ = 0,0042 W/mK) and OSB board finishes.
    - Facade U-value (W/m^{2}K) = 0,22
    - Facade cost (€/m^2) = 149
- Floor: The floor is similar to that of previous two IBSs. The difference affects the manufacturing process of the alveolar plate which in the previous cases is prefabricated and in this case is completely executed on-site. This difference only affects the cost, that is, in this case, more expensive.
    - Floor U-value (W/m^{2}K) = 0,3
    - Floor cost (€/m^2) = 177

- Top-roof: 12cm layer of XPS insulation (λ = 0,0042 W / mK), air chamber, pine wood and OSB coating.
  - Top-roof U-value (W/m^2K) = 0,18
  - Top-roof (€/m^2) = 173

In this case, foundations are smaller than that of concrete IBSs. However, it also requires the manufacture of a concrete or brick wall that is placed on the foundation and prevents the floor slab from coming into contact with the ground. The cost of this wall (0,8 m high and 0,2 m thick) is 100 €/m^2. According to the data provided by the PMP database, an extra cost of 9 €/m^2 has been estimated.

Opening's envelope thermal and costs study

The doors and windows were considered to be the same for the three industrialized building systems under study. It was considered in this way because it was interesting to see the impact that only the opaque envelope of the three IBSs has on the thermal behaviour and costs of a house-building. However, as seen in Table 5-4, the thermal bridges for windows and doors were different depending on the system.

Moreover, as said before, air leakages of buildings were considered the same.

		Prefabricated concrete modules (2D) with interior insulation technology (PMP)	Prefabricated concrete modules (2D) with exterior insulation technology	Lightweight wood frame
Top-roof	U-values (W/m^2K)	0,18	0,18	0,18
Facade		0,27	0,27	0,22
Floor		0,3	0,3	0,3
Top-roof	Costs (€/m^2)	128	128	173
Facade		128	178	149
Floor		153	153	177
Windows	U-values (W/m^2K)	1,4	1,4	1,4
	Costs (€/m^2)	1000	1000	1000
	SHGC glass factor (-)	0,6	0,6	0,6
Doors	U-values (W/m^2K)	2	2	2
	Costs (€/m^2)	1400	1400	1400
Thermal bridges Ψ (W/mK)	Windows	0,3	0,3	0
	Doors	0,1	0,1	0
	Wall-corners	0,05	0,05	0
	Wall-roofs	0,15	0	0
	Wall-bottom floor	0,15	0	0
	Wall-middle floor	0,43	0	0
Air leakages (ACH)		0,4	0,4	0,4

Table 5-4 Envelope thermal and economical characterization

Building performance simulation

BPS is the simulation of the behaviour, usually energetic, of a building in a computing environment (Sun, Liu, and Han 2020). Economic analysis is also often a part of BPS. The procedure followed to make a BPS is to create a calculation designs in the EnergyPlus environment (https://energyplus.net/), Sketchup (https://www.sketchup.com/es) and OpenStudio (https://openstudio.net/) and run the simulation, defining:

- The thermal envelope
- The costs of each of the envelope items
- The reference building
- Simulation conditions
- The study variables

A calculation design represents an analysis scenario. As summarized in Table 5-1, in this study 12 different scenarios were evaluated. Only the simulation conditions (Table 5-5) and the studied variables remain constant from one BPS to another.

The simulation conditions were:

- Internal loads: indoor energy gains due to lights, electric equipment and occupancy
- Ventilation
- Heating and cooling systems
- Schedules: allow to influence scheduling of many items (such as occupancy density, lighting, thermostatic controls, occupancy activity). In addition, schedules are used to control shading element density on the building (Reference 2021)

The study variables defined in EnergyPlus (https://energyplus.net/) were:

- Total heat gain energy infiltration zone
- Total heat loss energy infiltration zone
- Total internal heating energy zone
- Zone windows total heat gain energy
- Zone windows total heat loss energy
- Surface inside face conduction heat transfer energy

Using these study variables, it was assessed:

- Energy demand for heating systems and air conditioning systems for a whole year (kWh/m^2 per year)
- Annual costs related to the use of heating systems and air conditioning systems (€/year)
- Construction costs (€), which include manufacturing, transport and execution items.

Note that the cost analysis was done in parallel with the thermal analysis performed by the EnergyPlus (https://energyplus.net/) calculation engine. Costs were calculated in a file (.csv) implemented specifically to perform this task. It also includes an analysis of the following parameters that also affect the sustainability, quality and comfort of buildings:

- The parameter (K) (W/m^2K) of the Spanish state regulations on energy efficiency of buildings CTE-DB-HE (Fomento 2019)
- The potential for surface condensation in the thermal envelope according to CTE-DB-HE (Fomento 2019)

- The number of hours with temperatures outside the comfort thresholds defined by CTE-DB-HE (Fomento 2019).

All the operations required to calculate these variables and parameters based on EnergyPlus results were entered into automated file (.csv) algorithms.

Shading controls	May 1st – October 31th, if solar radiation incident on a window > 25W/m^2
Internal loads	People activity (W/m^2) = 90 People occupancy (m^2/person) = 28 Lighting (W/m^2) = 4.4 Electric equipment (W/m^2) = 4.4
Ventilation	Summer nights (ACH) = 3 Occupancy (m^3/s/person) = 0.00022
Heating and cooling systems	Ideal load air systems
Schedules *[hours of the day, extremes included]*	Occupancy (%) = 100 [1-7, 21-23]; 80 [8, 14-15,20]; 50 [9,13,16,19]; 30[17], 20 [10-12] Lighting (%) = 100 [18-23]; 50 [17]; 30 [8-16]; 10 [1-7] Equipment (%) = 100 [18-23]; 50 [17]; 30 [8-16]; 10 [1-7] Cooling set point (ºC) = 27 [1-12]; 25[15-23] Heating set point (ºC) = 17 [1-6]; 20[7-23]

Table 5-5. Simulation Conditions

Results and discussion

Although other parameters were calculated, only those most relevant to decision-making are included in Table 5-6. It should be added that all the 12 scenarios evaluated comply with the minimum requirements required by the CTE-DB-HE regulations (Fomento 2019).

In view of the results in Table 5-6, it is clear that there is a more energy-efficient system throughout the use phase of homes, with lower demand in all the scenarios assessed, the Prefabricated concrete modules (2D) with exterior insulation technology. As stated in previous studies (Bojic, Yik, and Sat 2001) this exterior insulation building systems make better use of the thermal inertia of concrete while allowing the reduction of thermal bridges. For example, between scenarios 1 and 2, a 25% reduction in heating and cooling demand was achieved, only by modifying the position of the thermal insulation, from the layer in contact with the indoor environment to the layer in contact with the outside environment. However, this solution increased the construction cost by about 8700 € in those scenarios. Given that the annual savings are approximately 166 €, the return on the initial investment would not be given until 52 years. Similar results were obtained by analysing the other scenarios comparing these two building systems. Therefore, although Prefabricated concrete modules (2D) with exterior insulation technology building system is an energy-efficient solution, it was not advisable to PMP to apply it according to cost criteria. However, in more extreme weather conditions where energy demand is higher, the impact in terms of costs will also be greater and the return on initial investment will be more affordable. However, at the time of the study, it was not the subject of PMP to study scenarios for these climates as they were out of the company's scope.

The results of the study also show a better thermal performance of the Lightweight wood frame building system compared to the PMP system, but worse than the Prefabricated concrete modules (2D) system with exterior insulation technology. This concludes that concrete systems with external insulation have a higher potential for energy efficiency during the use phase of homes than a wooden system with similar characteristics in the Mediterranean studied climates.

Table 5-6 reflects that, in general, the reference building 1 (RB1) has a higher demand than the reference building 2 (RB2). This is due to the design of the enclosure and the relationship between the energy gains and losses throughout the envelope. Better management of solar energy gains, a larger living space and the presence of a liveable basement were the main features of RB2 that favour its better energy-performance.

Scenarios	Reference building (RB)	Location	Building system	Total demand (kWh/m² year)	Heating and cooling costs (€/year) *(1)	Construction costs (€)
1	RB1	Lleida	Prefabricated concrete modules (2D) with interior insulation technology	**43,1**	548,0	**42171,4**
2	RB1	Lleida	Prefabricated concrete modules (2D) with exterior insulation technology	**33,2**	422,2	**50880,3**
3	RB1	Lleida	Lightweight wood frame	**35,5**	452,1	**50711,8**
4	RB1	Barcelona	Prefabricated concrete modules (2D) with interior insulation technology	**43,1**	548,0	**42171,4**
5	RB1	Barcelona	Prefabricated concrete modules (2D) with exterior insulation technology	**33,2**	422,2	**50880,3**
6	RB1	Barcelona	Lightweight wood frame	**35,5**	452,1	**50711,8**
7	RB2	Lleida	Prefabricated concrete modules (2D) with interior insulation technology	**26,0**	330,6	**118459,3**
8	RB2	Lleida	Prefabricated concrete modules (2D) with exterior insulation technology	**20,2**	256,4	**127807,9**
9	RB2	Lleida	Lightweight wood frame	**20,6**	262,2	**129141,3**
10	RB2	Barcelona	Prefabricated concrete modules (2D) with interior insulation technology	**21,1**	269,0	**118459,3**
11	RB2	Barcelona	Prefabricated concrete modules (2D) with exterior insulation technology	**16,5**	209,7	**127807,9**
12	RB2	Barcelona	Lightweight wood frame	**17,6**	223,9	**129141,3**

Table 5-6. Main results

(*) The simile in euros is made taking into account an electrical equipment with an efficiency of 90% and an energy cost of 0,13 €/kWh.

Chapter 6. Industrialized house-building design customization under heating, cooling and initial investment costs criteria

Methodology and chapter structure

The aim of this chapter is to develop a time-efficient design procedure in terms of human and computing resources that allows the design of homes to be customized under the criteria of energy costs and initial investment costs. The procedure should allow PMP company to offer clients the opportunity to purchase a custom product that is specifically designed to be sustainable in energy-cost terms.

Many studies based on parametric analysis using BPS environments aim to design a building by optimizing the design variables according to the building objectives (Gou et al. 2018; Sun, Liu, and Han 2020; Zhao and Du 2020). In other words, the objective is to design the building that best fits specific requirements.

Zhao and Du (2020) proposed a multi-objective optimization method using the NSGA-II algorithm and a BPS environment defined by EnergyPlus (https://energyplus.net/) and DesignBuilder (https://www.designbuilder-lat.com/). The aim of that research is to design windows and shading configuration considering energy consumption and thermal comfort. To do this, the design variables that define windows and shadings are parametrized in the BPS environment. After, the BPS environment execute the simulations and, with the results, optimization algorithms find the recommended parameters of windows and shadings. Those parameters define the optimal design that meets the building objectives.

In general, parametric studies always follow the same steps (Figure 6-1). A reference building (RB) is first defined in a BPS environment. The reference building (RB) is a basic design that will be modified during the analysis to create multiple designs of buildings (calculation designs). The RB is defined by: (1) geometrical data (e.g., floor heigh), (2), orientation, (3) envelope design (e.g., wall insulation layer) and (4) climate data. In the RB the decision variables are selected and modelled with arrays of parameters. For example, in the Zhao and Du (2020) study, one decision variable is the Window inside layer material, which is a variable used by EnergyPlus (https://energyplus.net/) to calculate the energy gains and losses through the window.

The BPS environment is capable of creating as many calculation designs as possible combinations of parameters. For example, if 2 decision variables are selected and each is modelled with an array of 3 parameters, the BPS environment will generate 2^3=9 calculation designs. Each calculation design, which represents a building with a different performance, is calculated automatically. Finally, the BPS environment store the results in a database that can be consulted to draw the conclusions of the study.

This procedure is done to identify the calculation design that has a performance closer to that defined by the building objectives. And so, what is the combination of parameters recommended for designing the building. However, this is not an easy task when the building objectives are multiple and the analysis include many parameters of different decision variables. For this reason, the parametric analysis is complemented by optimization algorithms, as they allow, once the simulations have been performed, to look for the combinations of dominant parameters and, therefore, the optimal design solutions.

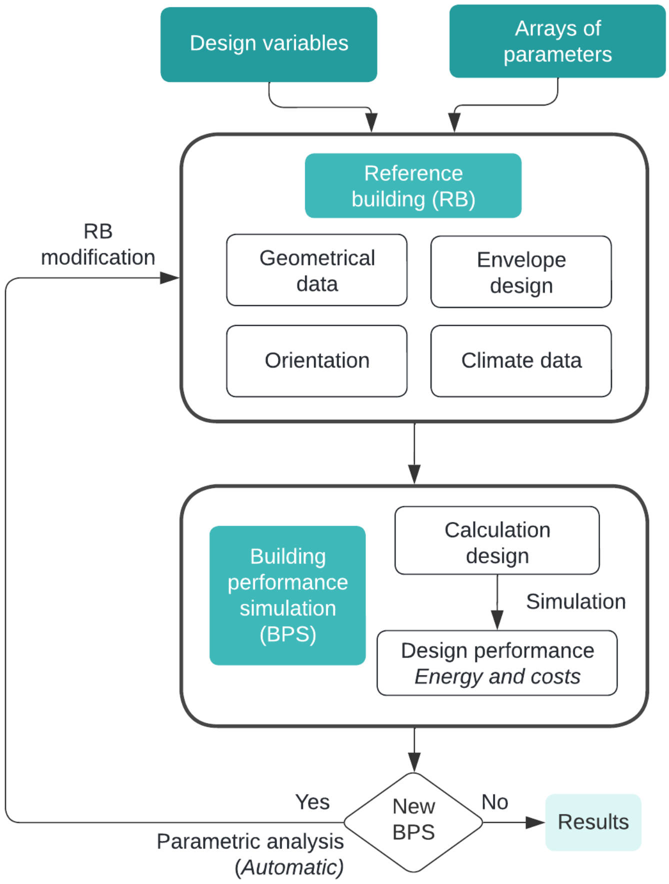


Figure 6-1. Parametric analysis

These approaches all have the same barriers that prevents them from being implemented in the industry, are not time-efficient, and require excessive human and computer resources (Touloupaki and Theodosiou 2017). In fact, the computing resources (memory space and computation time) are proportional to the volume of the study carried out. When parameterizing many design variables, the required machinery resources increase exponentially. For this reason, a company in the IHB sector that receives requests from potential customers every day interested in building a home cannot afford to do such a laborious and complex design study. First of all, because today the speed of response is increasingly valued for customers (Chonko and Jones 2005). And secondly because this work involves an increase in cost proportional to the hours needed to do the study.

To overcome these issues, a design procedure has been developed that integrates 4 cornerstones: (1) template, (2) configurator, (3) result viewer and (4) customer-oriented decision-making. The template and the configurator significantly reduce human and machinery resources required to perform the analysis and therefore increase the speed of the study. The result viewer allows customer-oriented decision-making based on heating, cooling and initial investment costs criteria.

The procedure developed is based on the following 6 stages (Figure 6-2):

- **Catalogue**: the first step is to create a finite catalogue of building elements (opaque and transparent) that the construction company offers to its customers to integrate into the design of their home. For example, different models of windows, with specific thermal, aesthetic and economic characteristics. This catalogue does not need to be updated by each customer and can therefore be reused until the construction company decides to modify the items to be offered.

- **Briefing**: the next step is a meeting between technicians and customers to agree on the minimum requirements for the building to be designed (e.g., total useful area and thermal zones). In addition, the constructive elements of the catalogue that the client wishes to introduce in the study must also be selected. In case the customer wants to test different types of buildings and compactness it will also be possible but will require a longer study time (e.g., same useful area but distributed on one or more floors).
- **Template and configurator**: the study is then adapted to the client's needs using the Template and editing the data according to the agreed decisions. The way to do it is simple and standard. The procedure is complemented by a user manual addressed to the different technical profiles: designer, architect and / or engineer. This step does not take more than 1 hour.
- **Calculation**: it takes about 2 to 6 hours, depending on the final number of solutions to be calculated and the performance of the computer itself. The more construction elements to combine, the longer the study time. In any case, the calculation process is performed by the BPS environment automatically. It does not, therefore, require human resources. The BPS input used consists of Sketchup (https://www.sketchup.com/es), OpenStudio (https://openstudio.net/), EnergyPlus (https://energyplus.net/) and JEPlus + (http://www.jeplus.org/wiki/doku.php) working in parallel.
- **Result viewer**: with the results of the study the result viewer is prepared. To do this, the results file (.csv) is manually entered into an implemented (.csv) file to decode the information and calculate the initial investment costs and the annual heating and cooling costs of each calculation design automatically (there are as many calculation designs as possible combinations of parameters). With the results, a Matlab script is executed that generates the result viewer, a graph that shows the initial investment costs and the annual heating and cooling costs of all the Calculation Designs studied. This step is done by any technician in approximately 30 minutes.
- **Decision-making**: finally, clients view the results of the evaluation of all the calculation designs in the result viewer. Each calculation design represents a potential house-building design that customers and technicians have to value. Customers can observe the architectonic design of each house-building, the initial investment and its annual heating and cooling energy performance during the use phase. Thus, the PMP client can participate in the customization of the houses under energy-cost criteria.

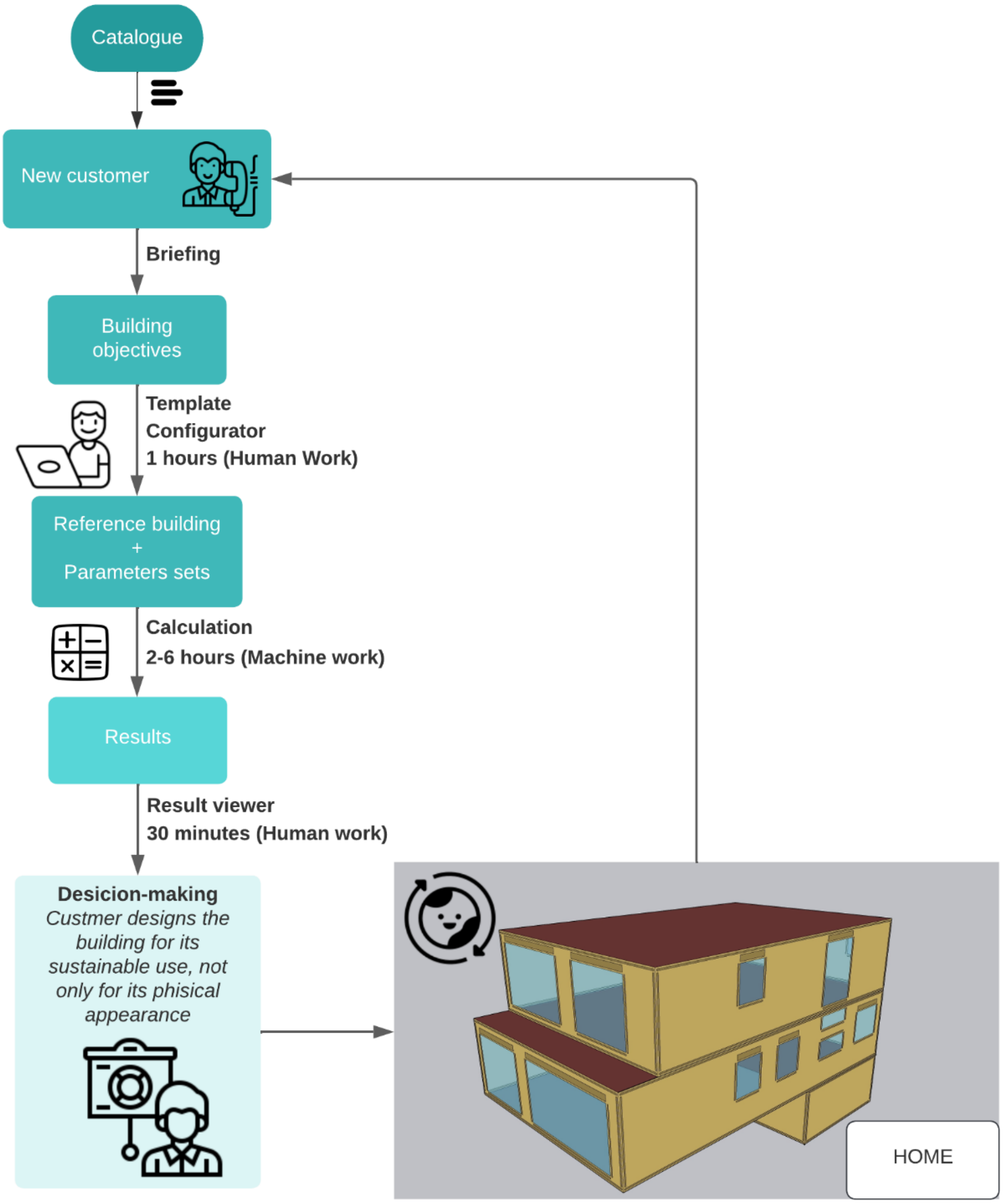


Figure 6-2. Improved design procedure

Improved design procedure

To design environmentally sustainable buildings under heating, cooling and initial investment costs criteria, the complete building life cycle must be considered in decision-making, therefore also including the use of the building (operational phase). The proposed procedure is used in the initial design and has a high impact on the thermal behaviour of the building through the operational phase. In addition, it will allow assessing multiple design solutions and highlighting the ones with high energy-performances. The resulting design procedure adjusts to the needs of the industry offering a fast and efficient process with respect to the necessary human and machinery resources that adds value to the product allowing customer participation (Fang, Palmatier, and Evans 2008).

Catalogue

The catalogue is the set of construction elements (e.g., windows, facades, doors, roofs and floors) characterized by specific aesthetic, thermal and economic properties that the construction company offers to clients to customize their homes.

This catalogue shows the basic information of each construction element to the customer (e.g. images, geometric data and prices). At the same time, it contains the technical data to characterize each building element in the BPS environment of the EnergyPlus (https://energyplus.net/). The values needed to characterize the construction elements in EnergyPlus are obtained from studies such as those carried out in chapter 4 (opaque envelope thermal and costs study and opening's thermal and costs study).

To calculate the thermal transmittances (W/m^2K) of the elements, Therm software (https://windows.lbl.gov/tools/therm/software-download) was used. Other important factors in defining the energy gains and losses through the Opaque Envelope and/or Opening's (e.g., glass solar factor) are characterized via the datasheets of manufacturers.

The catalogue can be reused as many times as the construction company considers appropriate. If the company wants to modify the catalogue, it will have to do the necessary studies again to characterize the construction elements to be incorporated and/or modified.

Briefing

The briefing consists of a meeting between technicians and customers where the information needed to carry out the design of the home is gathered (building objectives). It is a very important stage because it is the first time where the customer has the opportunity to express its needs and start customizing their home (Oliveira and Melhado 2011).

At this stage, customers have the opportunity to use not only aesthetic criteria and/or defining the building's needs program.

Template

The template is a simplification and standardization of a reference building (RB) which contains the design aspects and the simulation conditions already defined (Figure 6-3).

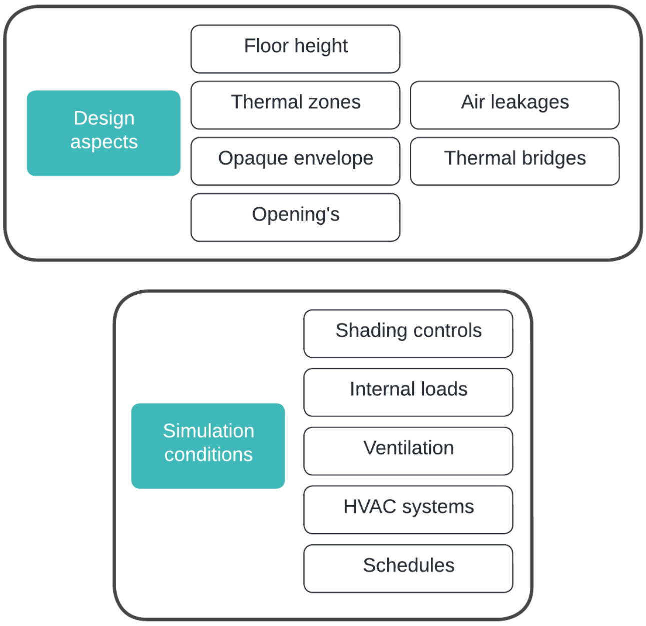


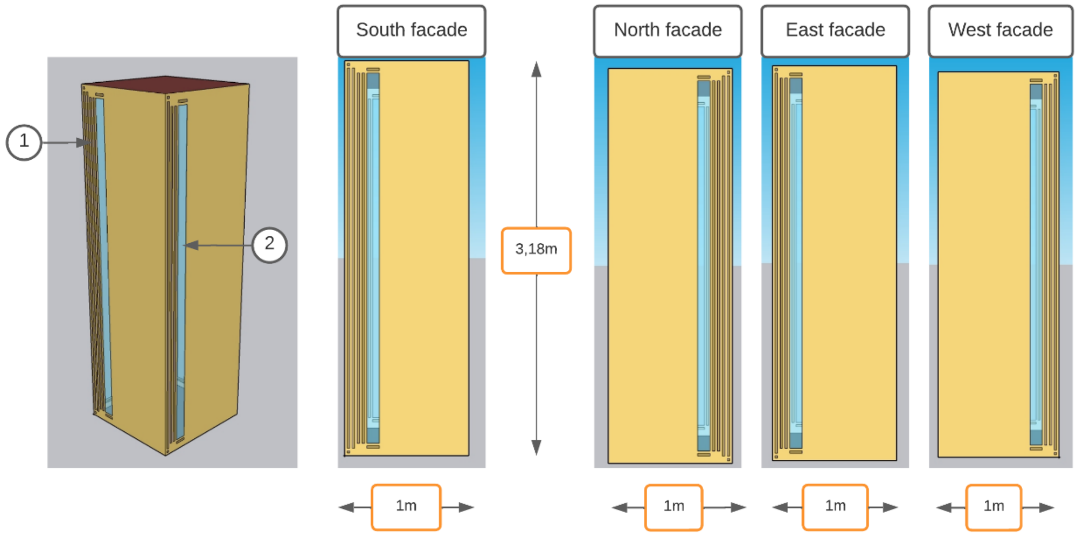
Figure 6-3. Template data

The template is drawn in Sketchup (https://www.sketchup.com/es) and modelled with the BPS environment of the EnergyPlus (https://energyplus.net/).

As shown in the Figure 6-4, the template is a closed 3D space defined by a thermal envelope (opaque envelope, opening's, thermal bridges and air infiltrations) that delimits a thermal zone characterized by simulation conditions. A thermal zone represents a set of specific simulation conditions that apply to a specific space (e.g., temperature thermostats throughout the year). In the case of the Figure 6-4 template, as there is only one space, there is only one thermal zone. The simulation conditions are: (1) shading controls (characterization of window shading devices), (2) internal loads (characterization of thermal energy gains inside the space due to the activity of people, lighting and electrical equipment), (3) ventilation (characterization of the air renewal necessary to maintain healthy conditions inside the space), (4) heating and cooling systems and (5) schedules (used to define time-dependent study variables, for example the temperature of thermostats throughout the year). One thing to note is that the template does not contain the entrance door (Figure 6-4). This will need to be drawn on the template quickly and simply in (https://www.sketchup.com/es) as explained below (template edit). This consideration has been given to facilitate the subsequent editing of the template.

The template is defined containing the information to generate the spaces which represent a different thermal zone each: ground floor, middle floor, top floor, ground floor parking, basement and underground parking. These elements can be chosen and assembled to create the model according to the customer preferences. For example, to create a detached single-family building with a ground floor only one 3D space is needed (Figure 6-4), the ground floor, represented by a single thermal zone.

It is not necessary to define the output variables (variables indicated to the BPS environment to calculate and report) in the template. In fact, the template is specifically defined to contain the minimum data needed to define calculation designs so that the calculation engine (EnergyPlus) can perform the simulations more quickly (requiring less design space). In addition, the only output variables required by the defined procedure (Figure 6-2) are the heating demand and the cooling demand, which EnergyPlus (https://energyplus.net/) always calculates automatically.



Example Model: single-family house-building (1 floor, no basement)		
Thermal bridges	Included	1
Windows	Included	2
Entrance door	Not included	

Figure 6-4. Template example

Template edit

Using the template, the dimensions of the geometric elements can be easily adapted to the owner needs directly in Sketchup (https://www.sketchup.com/es). To adjust the template to the needs defined by the client during the briefing session (e.g., useful area) and create the reference building Figure 6-5 steps must be followed.

- Step 1. Double-click on the space.
- Step 2. Double-click on the surface to be moved (north, south, east or west façade of the building) in order to increase the interior volume of the space and adjust it to the customer's needs defined during the briefing.
- Step 3. Select the Move tool.
- Step 4. Select the vertex of the surface, indicate the direction of movement and write the distance needed in the selected facade to obtain the usable area agreed with the customer (Briefing). Then, select a second surface to move (facade perpendicular to the one moved in the previous step) and repeat the same done with the previous facade.
- Step 5. Only necessary in the case of wanting to include another space (e.g., two-storey house). Generate the new space by copying and pasting the space shown in Figure 6-5. The properties are edited in the same way as in the previous steps. Then, indicate the thermal zone of the new space using the OpenStudio (https://openstudio.net/) inspector tool (e.g., in the case of a garage, the thermal zone has specific living conditions). Click on the new space, click (right button), select OpenStudio inspector (Figure 6-5, OpenStudio inspector:5.1) and, in the display of the thermal zones select the desired one. At this point assemble the spaces with the move tool (Figure 6-5 (3)) and indicate with a click on the tool (Figure 6-5, Match surfaces:5.2) that the two spaces in contact are part of the same building.

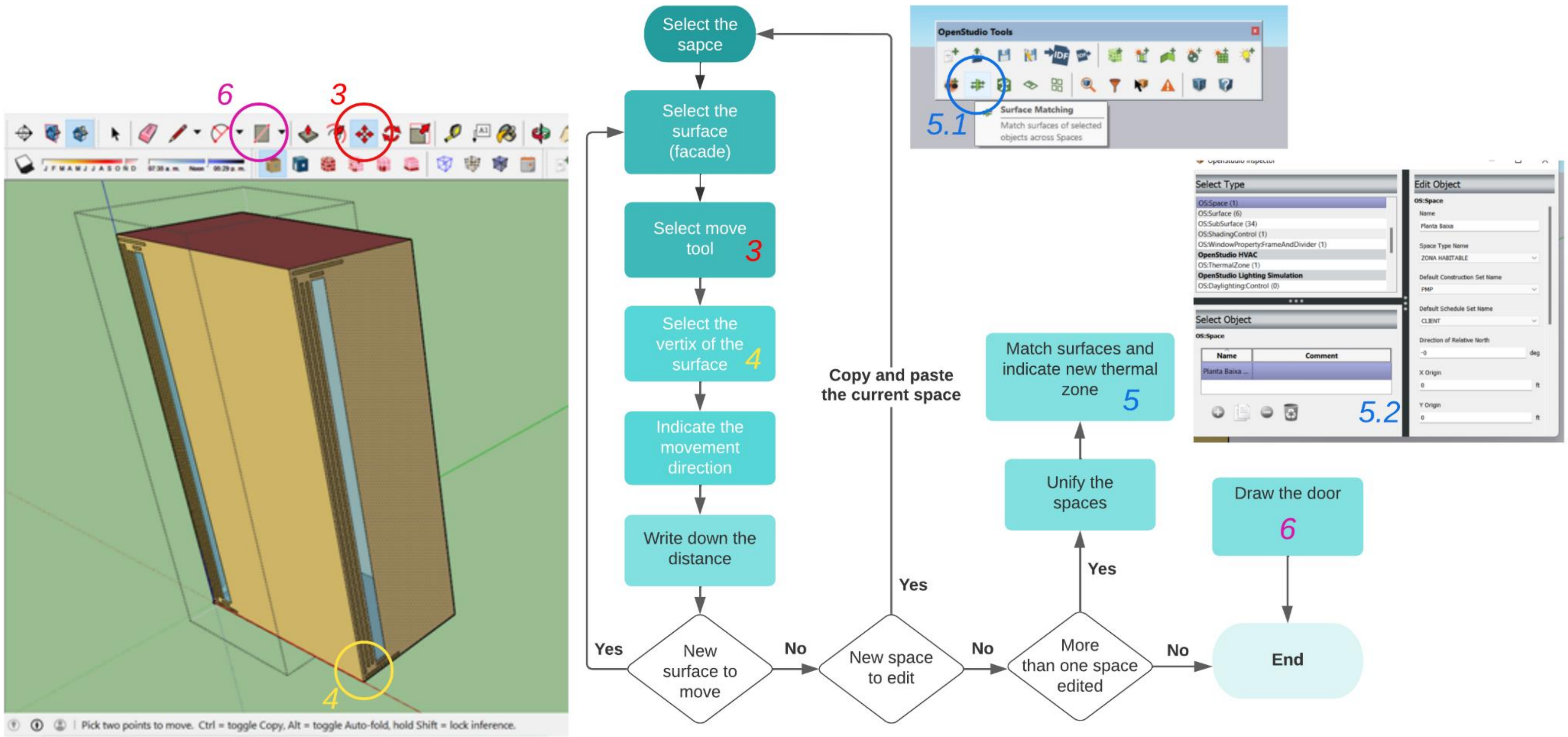


Figure 6-5. Template edit

- Step 6. Draw the door. Double click on the space, click on the surface (facade) and draw the door with the agreed measurements. (Figure 6-5, Shapes:6).

As a side note, thermal bridges and windows are edited using the configurator directly in Energy Plus EP-Launch (https://energyplus.net/) in the post template-editing phase.

The great contribution that allows the template, is a reduction of time to draw and model the reference building in comparison with the creation of a blank project in the BPS environment. In fact, editing the template takes less than 15 minutes while creating a reference building based on a blank project is a laborious task that can lead to a working day for a technician specialized in the BPS environment.

The template, and the subsequent calculation design generated, are simplified building models in the BPS environment (Negendahl 2015). The procedure facilitates faster and more efficient decision-making, although the simplifications that have been introduced make both the physical models that are generated and the results obtained significantly different from reality. However, decision-making in the early stages of design remains valid and useful as the goal is to compare and identify the calculation design that best fits the needs of users. In later stages in a House-building project it is essential to obtain the energy certification following the procedure set out in the regulations. For example, in Spain the requirements of the CTE-DB-HE in energy efficiency must be met (Fomento 2019). At this stage, the study model can be designed with all the details. However, the calculation engine is the same (EnergyPlus) and in the case of energy simulations small geometric details have minimal influence on the final results of simulations. In addition, EnergyPlus itself also incorporates certain simplifications in its calculation algorithms (Berkeley et al. 2021; Crawley et al. 2001).

Fenestration surface

The fenestration surface is simplified. Only a unique rectangular element is modelled per facade and floor (Figure 6-4). This fenestration element has an area equivalent to a certain combination of windows. Different window types are defined into the configurator. For example, a combination of three windows "type A" with an area of 1,04 m^2 and a window "type B" with an area of 1,82 m^2 (Figure 6-6). The thermal and economic properties of each window are defined in the configurator.

It has been determined that the solar gains and the energy losses throughout windows are the same in the real model with multiple fenestration surfaces and in the edited template where there is a unique fenestration surface of equivalent area.

It should be noted that in the context of building performance simulations (BPS), where gains and losses through the different elements of the thermal envelope are analysed, to later calculate the demands for heating and cooling, this simplification does not have a significant impact on the results.

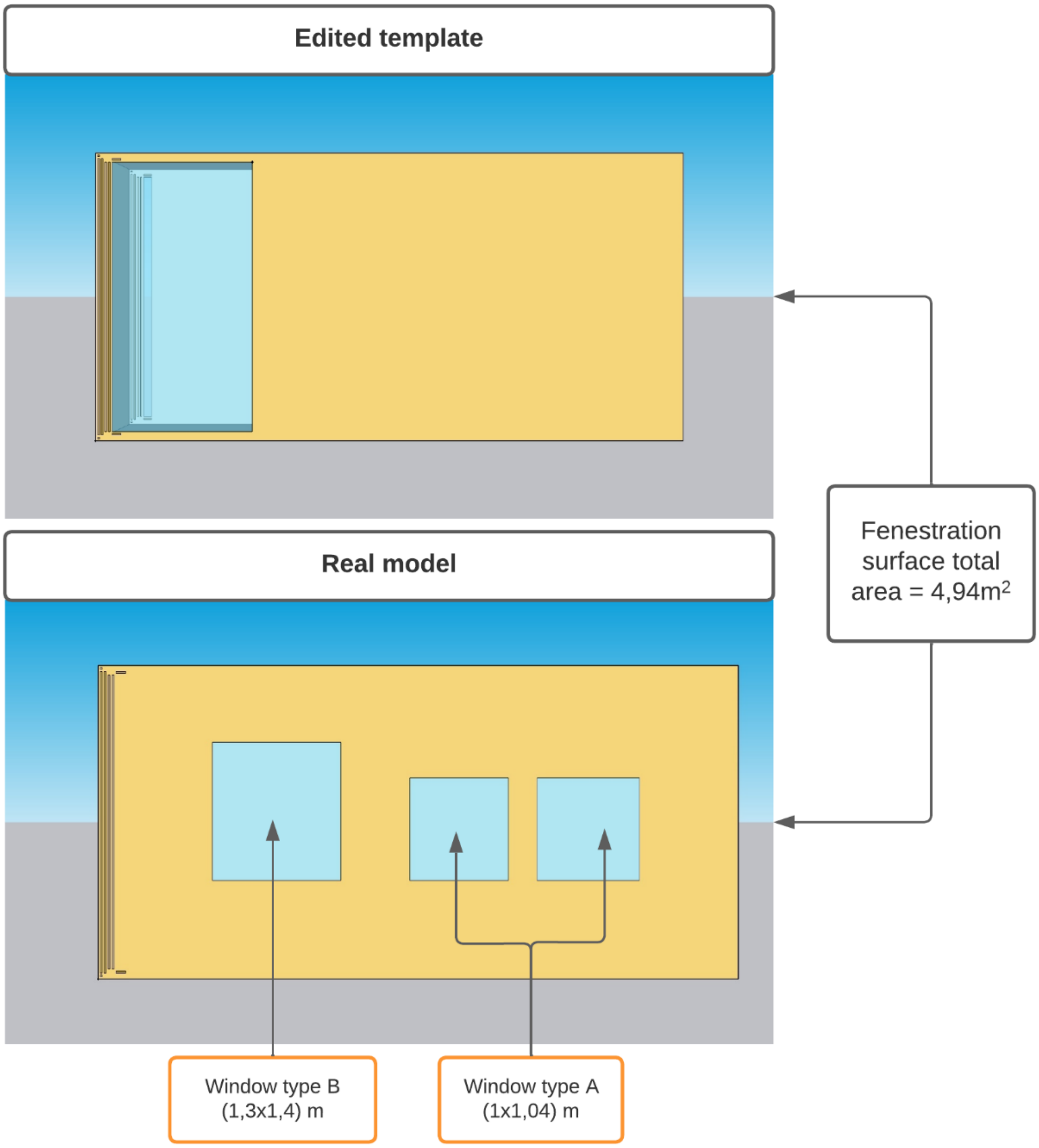


Figure 6-6. Fenestration surface in the template

Thermal zones

A thermal zone represents a set of specific simulation conditions that apply to a specific space. One consideration that has no effect on the final results is that the defined spaces do not contain partitions walls inside. Only in the case of defining a building with two or more spaces (e.g. a house with a ground floor and parking), doing Step 5 of the template edit (Figure 6-5) the BPS environment will generate the partition wall and/or ceiling between the two spaces. It is assumed that all the rooms that a space can contain will have the same temperature.

Simulation conditions

Simulation conditions are standardized. The simulation conditions are: (1) shading controls, (2) internal loads, (3) ventilation, (4) heating and cooling systems and (5) schedules. It means that their values remain constant throughout the computing process done by the BPS environment calculation engine.

Thermal bridges

Thermal bridges are all modelled by drawing rectangular areas since EnergyPlus does not allow linear elements to be modelled. Therefore, instead of introducing a linear thermal transmittance Ψ (W/mK), a thermal resistance value R (m^2K/W) is defined as equation [6-1] shows where t (m) is thickness of the rectangle referring to the thermal bridge.

$$R\ (m^2K/W) = t\ (m)\ /\ \Psi\ (W/mK) \qquad [6\text{-}1]$$

All the thermal bridges of the windows are simplified in four rectangular geometries that contain the same average value (Figure 6-7). The dimensions of the rectangles are adjusted to the reference building by terms of the configurator as is detailed below.

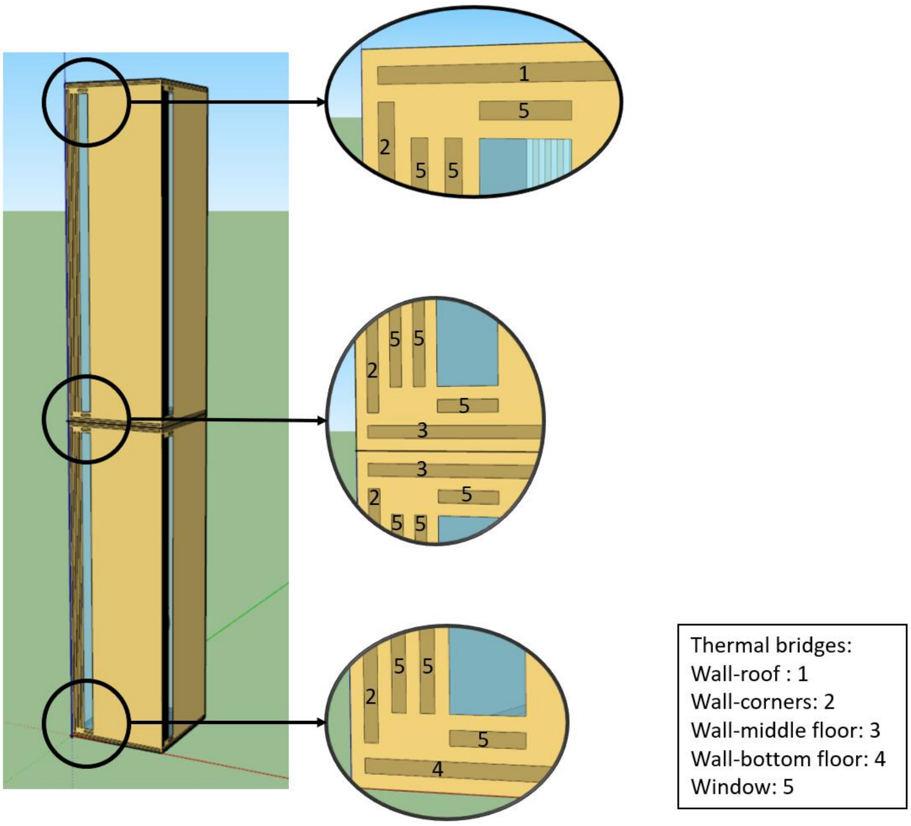


Figure 6-7. Thermal bridges in the template

Heating and cooling systems

Ideal air loads are assigned to the conditioned zones (Sun, Liu, and Han 2020). According to this technique, it is accepted that, each thermal zone is connected to an air handling unit having infinite capacity that can perform both heating and cooling with 100% operation efficiency (Acar, Kaska, and Tokgoz 2021). Ideal air loads are used to calculate the energy demand for heating and cooling.

After the demand calculation by the BPS environment, the energy consumption is calculated in a consecutive procedure in which the designed result viewer, that will be explained later, is used.

Configurator

The configurator (Figure 6-8) limits the number of calculation designs to simulate, reducing the computational memory space needed. In addition, it serves to enter in the reference building generated from the Template in the BPS environment the data referring to the constructive elements (e.g., windows, facades, doors, roofs and floors) that the client has chosen from the catalogue in order to customize his house.

The configurator, unlike the catalogue, informs the BPS environment of the parameters that must be entered in each design variable under study (Figure 6-8). It is in charge of the parametric design. For example, in Figure 6-8 one of the configured construction elements is the type of exterior walls. There are three types of walls with different U-Values. The decision variable which defines them is the rockwool thermal transmittance (P7). Hence, an array of three values {0.032, 0.035, 0.037} (W/m^2K) is introduced in this variable to represent the three types of walls. This part of the process is done in the JEPlus environment (http://www.jeplus.org/wiki/doku.php). After all the parameters have been entered into the JEPlus environment, the program will automatically generate and simulate the calculation designs.

One detail to consider is that in this part of the process the dimensions of the rectangles that represent the thermal bridges in the reference building are also adjusted in the ".idf" file. This file is the one that contains the reference building created from the template. Doing so is very simple, just search in the ".idf" file for the name of the thermal bridge (wall-middle floor, wall-bottom floor and wall-roof) and change the coordinates according to the dimensions of the space. The names are always the same so it is very fast to find them in the ".idf" file. The wall-corners thermal bridge does not need to be modified. The thermal bridges of the windows are modelled with the same vector that the window itself. Just look up the thermal bridge decision variables (coordinates) and enter the same parameter vector that was entered to model the windows (Figure 6-9).

A Java script that reads JEPlus has also been implemented to automatically generate two (.csv) files including the demands of each of the calculation designs, one file for the cooling demand and the other for the heating demand (Figure 6-8). The result viewer will use these two files in the next step.

A regular parametric study must not only first generate a reference building from a blank project but also program after the parametric design in the BPS environment. This is laborious and has a cost related to the technician's working hours.

This stage of the procedure (configurator) can be done in up to 45 minutes. Thus, the great contribution of the procedure presented is that it allows to model a parametric study according to the client needs of customization in, at most, 1 hour of time.

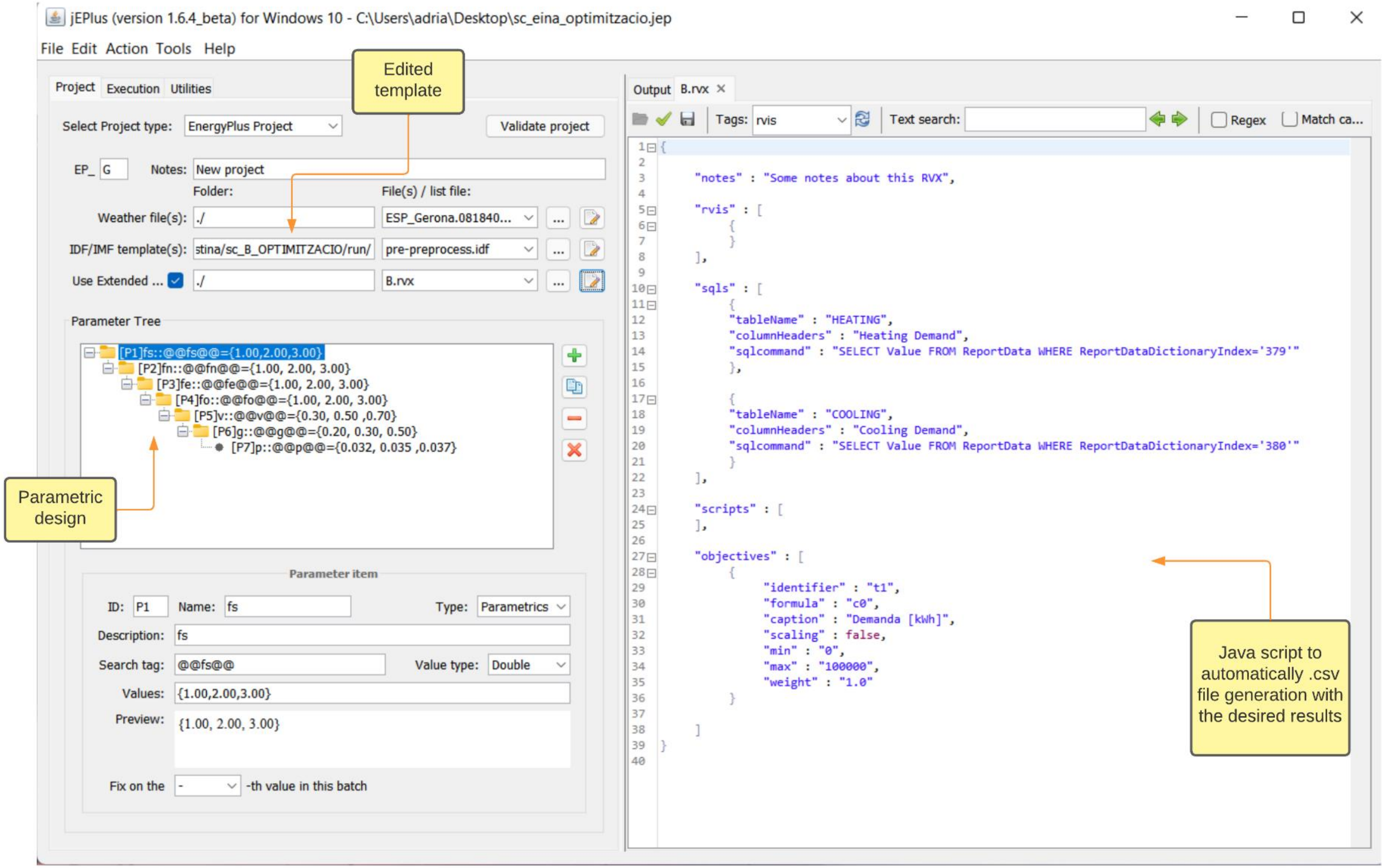


Figure 6-8. Configurator in JEPlus

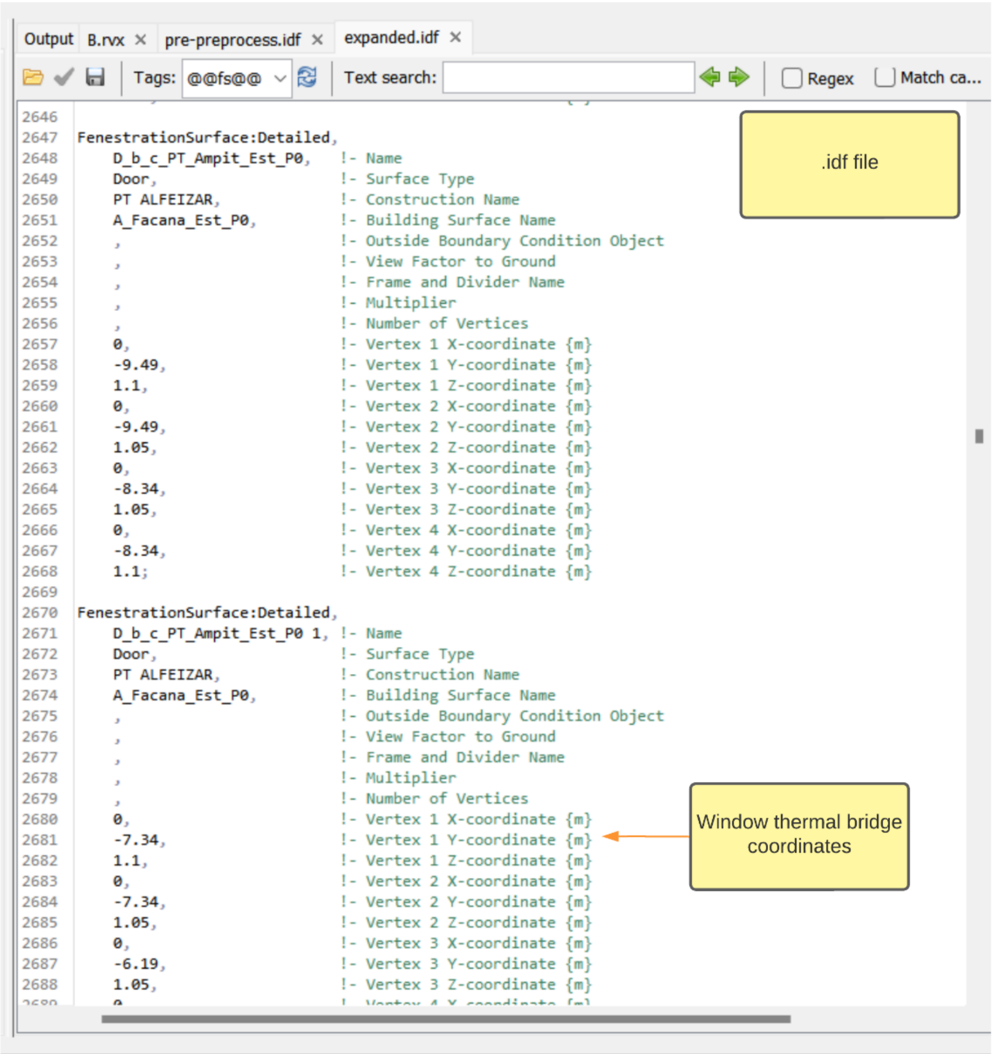


Figure 6-9. Thermal bridges in the configurator

Result viewer

The evaluation process of the multiple designs is conducted using EnergyPlus computation engine (https://energyplus.net/). As the computational memory space needed is reduced thanks to the template and the configurator, the computational time is also reduced.

The result viewer integrates two stages:

- First, an implemented (.csv) file like the one in Figure 6-10 is used, where the simulation results are entered. These results are created by JEPlus (http://www.jeplus.org/wiki/doku.php) in a folder like the one shown in the Figure 6-8. This file is responsible for decoding the results of EnergyPlus (https://energyplus.net/) and parametric designs. In addition, it is responsible for calculating costs related to the initial investment and annual energy consumption. This (.csv) file must be edited by a company technician by entering the main data of the study agreed in the briefing. This can be done in about 20 minutes.
- Then a script (Figure 6-11) implemented in Matlab (https://es.mathworks.com/) is responsible for graphing the results intuitively and with a legend that allow clients to know the relevant information of each design.

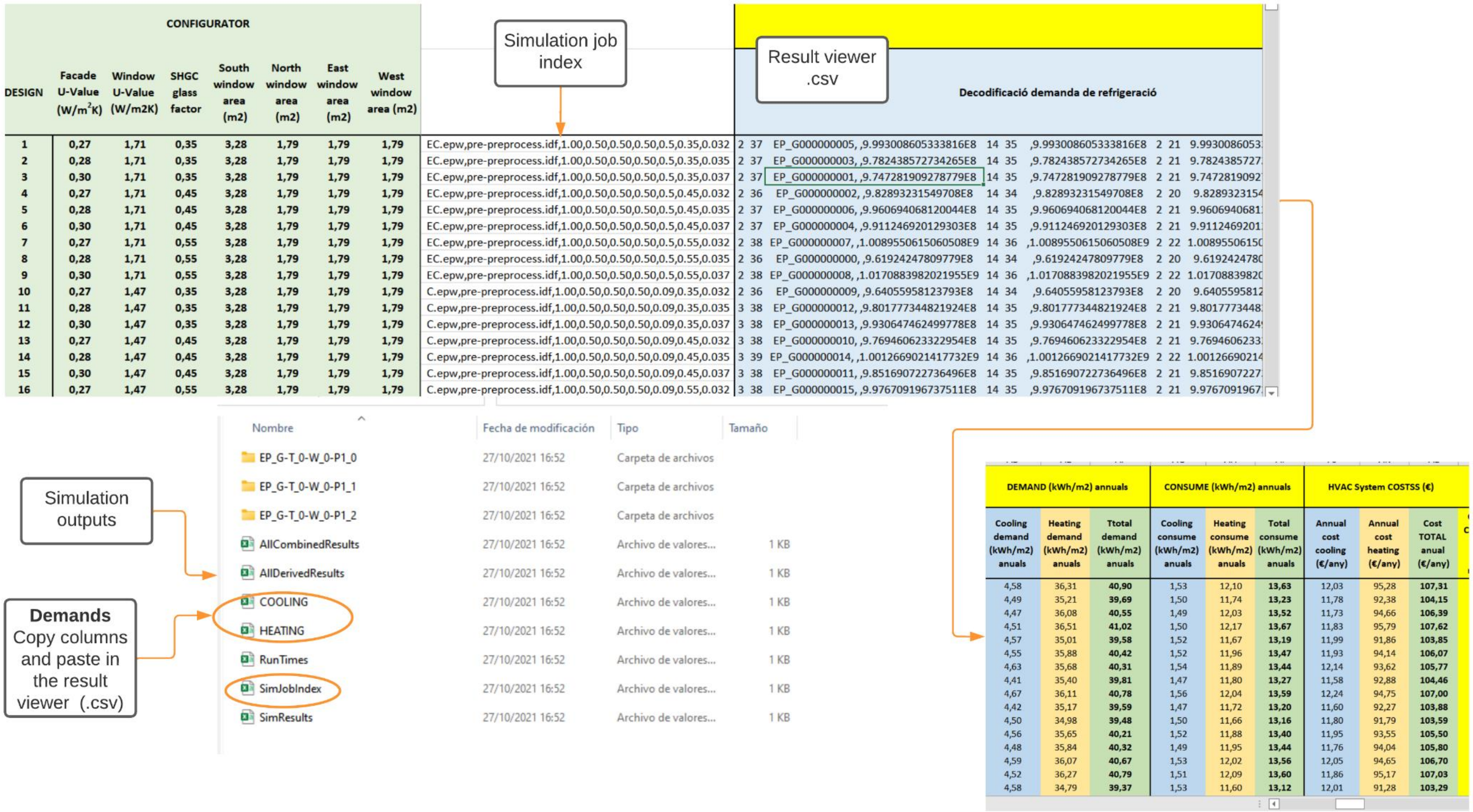


Figure 6-10. Result Viewer (.csv)

```
fig = figure('DeleteFcn','doc datacursormode');
dades=xlsread('matlab2');
designnumber=round(dades(:,1),1);
annualcosts=round(dades(:,2),1);
initialinvestment=round(dades(:,3),1);
demand=round(dades(:,4),1);
lifecyclecosts=round(dades(:,5),1);
roockwoollambda=round(dades(:,6),3);
glassgfactor=round(dades(:,7),2);
glassconductivity=round(dades(:,8),2);
WWRsouth=round(dades(:,9),2);
WWRnorth=round(dades(:,10),2);
WWReast=round(dades(:,11),2);
WWRwest=round(dades(:,12),2);

A=[designnumber, annualcosts, initialinvestment, demand, lifecyclecosts, roockwoollambda,
glassgfactor, glassconductivity, WWRsouth, WWRnorth, WWReast, WWRwest];

%Make a color index for the LCC
nc = 16;
offset = 1;
c = lifecyclecosts - min(lifecyclecosts);
c = round((nc-1-2*offset)*c/max(c)+1+offset);

scatter(initialinvestment,annualcosts,10,lifecyclecosts, 'filled')
ax = gca;
ax.FontSize = 15;
xlabel('Initial investment (€)')
ylabel('Heating and cooling systems annual costs (€)')

datacursormode on

dcm_obj = datacursormode(fig);
set(dcm_obj,'UpdateFcn',{@myupdatefcn,A})

function txt = myupdatefcn(~,event_obj,A)
pos = get(event_obj,'Position');
ind = get(event_obj, 'DataIndex');
a1=num2str(A(ind,1));
a2=num2str(A(ind,2));
a3=num2str(A(ind,3));
a4=num2str(A(ind,4));
a5=num2str(A(ind,5));
a6=num2str(A(ind,6));
a7=num2str(A(ind,7));
a8=num2str(A(ind,8));
a9=num2str(A(ind,9));
a10=num2str(A(ind,10));
a11=num2str(A(ind,11));
a12=num2str(A(ind,12));

txt = {
       ['DESIGN SOLUTION: ',a1],...
       ['RESULTS: '],...
       ['a. Initial investment (€): ',a3],...
       ['b. Heating and cooling systems demand for energy (kWh/m2): ', a4],...
       ['c. Heating and cooling systems annual costs (€/year): ', a2],....
       ['d. Life-cycle costs (LCC) (€): ', a5],...
       ['DECISION VARIABLES: '],...
       ['1. Window length (v1) South wall (m): ', a9],....
       ['2. Window length (v2) North wall (m): ', a10],....
       ['3. Window length (v3) East wall (m): ', a11],....
       ['4. Window length (v4) West wall (m): ', a12],....
       ['5. Glass conductivity (v5) (W/mK): ', a8],....
       ['6. Solar transmittance (v6) (-): ', a7],....
       ['7. Roockwool conductivity (v7) (W/mK): ', a6],....
       };
End
```

Figure 6-11. Result viewer Matlab script (.m)

Customer-oriented decision making

Decision-making is traditionally focused only on the needs program, materials and finishes, and the architectonic configuration of the building. The suggested new approach includes sustainability criteria in customer-oriented decision-making that will have connotations in the thermal performance of the building during the use phase (operational phase).

The suggested procedure has two levels of customer integration in early design. First, customers, with the advice of technicians, select the construction elements they want to incorporate into the building's configurator (e.g. the types of exterior walls). Second, decision makers and customers can decide together the final building configuration (e.g. number and size of openings according to the building orientation and building distribution), in early design.

A graphic representing the energy-cost performances of multiple building configurations evaluations is presented to them. It is important to highlight that in this procedure the energy-cost performances refer to the costs of the following items:

- House-building execution costs (EC), which are equivalent to the initial investment of the building that customers have to make.
- Heating and cooling systems use costs (UC), which are linked to the energy consumption in heating and cooling during a year. UC are a measure of how sustainable is the building during its use.
- Heating and cooling systems maintenance costs (MC), which depend on the heating and cooling system equipment.
- Life-cycle costs (LCC) represented in equation [6-2], which are supposed to be in a 50 years cycle according to the CTE (https://www.codigotecnico.org), are a measure of capital costs.

$$LCC = Initial\ investment + 50\ (UC + MC) \qquad [6\text{-}2]$$

Other costs (e.g. water consumption or lighting) are not contemplated. In the resulting chart, each point represents a building with a unique configuration. It is considered that the way owners use the heating and cooling systems is the same in all the cases. In this graphic, clients can see how some day-zero expensive solutions can become profitable in the considered 50 years life-cycle thanks to a more sustainable design under energy-consumption criteria, and in a lot of cases even many years before. Ideally, solutions close to the origin of the graph are preferable. However, the procedure scope is not to calculate the optimal solution as other methods do (Acar, Kaska, and Tokgoz 2021). The objective is that customers realize the energy-cost pros and cons of each solution. In fact, the graphic is interactive, so that customers can click on each of the points and see what the characteristics of that building configuration are. Thus, after preferable solutions are identified in the bottom-left area of the chart, clients can decide which of them is the one that best fits their needs.

Finally, in Figure 6-12 the summary of the whole process in a more developed way than in Figure 6-2 is presented. In this way you can get a quick and at the same time more detailed view of the designed procedure.

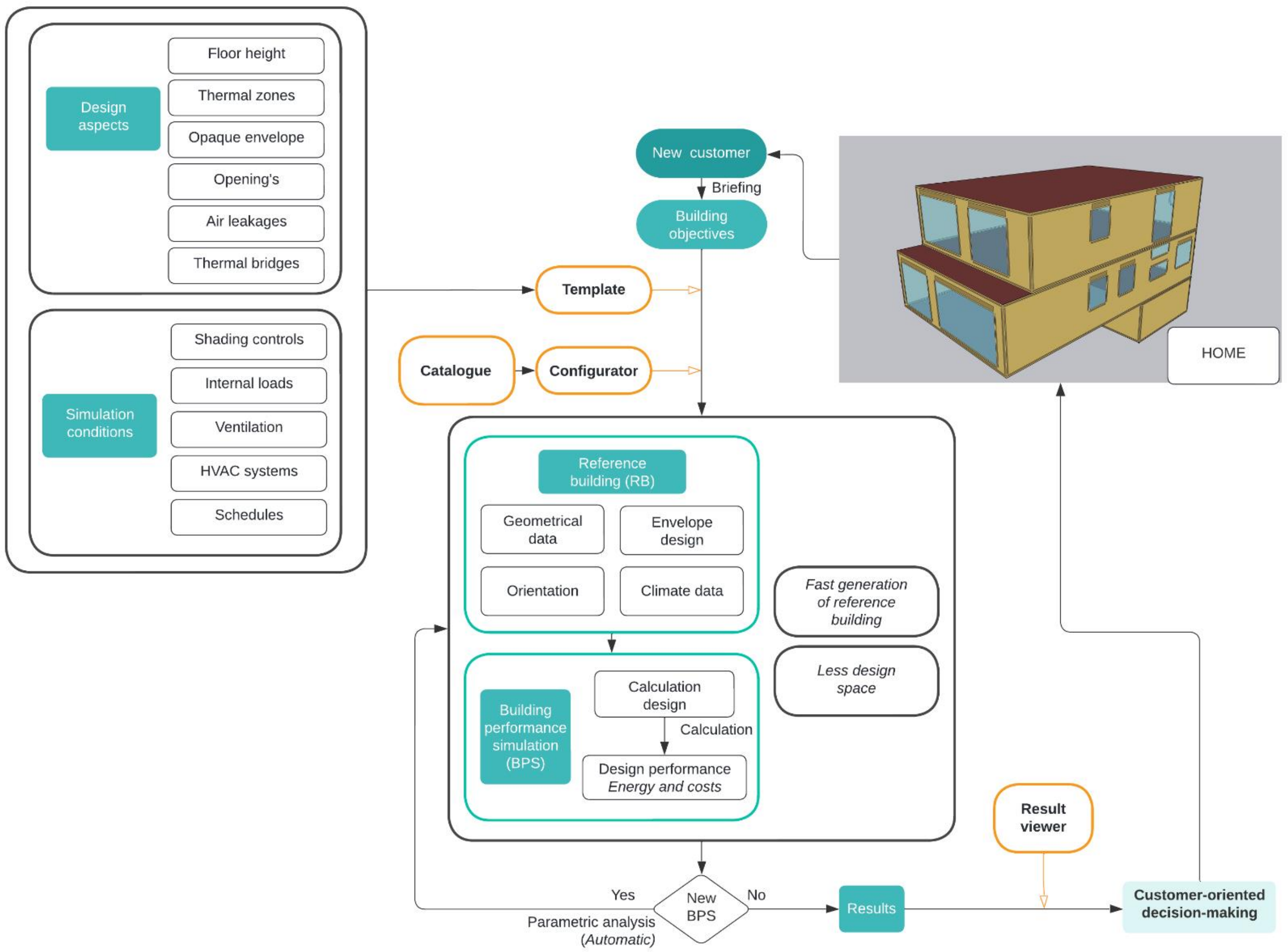


Figure 6-12. Detailed improved design procedure

Case-study

In order to put into practice, the suggested improved process, it has been applied to a PMP Prêt-à-Pôrter cases (https://pretaportercasas.com) case-study.

It is important to highlight that, previous to the case-study:

- The template was created and adapted to the PMP company.
- In parallel, PMP defined the building elements to introduce in the configurator.

The design objectives are to find a building design with low initial investment costs, low annual energy consumption costs and customer-oriented. The main requirements of the customer are the location, the orientation, the number of building storeys and the floor area, represented in Table 6-1 along with the rest of the defined design aspects.

Design aspect	Description	
Location	Lleida	
Orientation	The building main facade is oriented to South	
Building storeys	2	
Heights	3,18m/storey	
Floor area	$70m^2$	
Thermal zones	Ground floor and first floor, both conditioned	
Opaque envelope	Top-roof	U-value = 0,18 W/m^2K
	Exterior walls	U-value = PARAMETRIC
	Floor	U-value = 0,30 W/m^2K
Windows	U-value	**PARAMETRIC**
	SHGC glass factor	**PARAMETRIC**
	WWR	**PARAMETRIC**
Thermal bridges	Windows	Ψ=0,1 (W/mK)
	Doors	Ψ=0,05 (W/mK)
	Wall-corners	Ψ=0,05 (W/mK)
	Wall-roof	Ψ=0,1 (W/mK)
	Wall-bottom floor	Ψ=0,1 (W/mK)
	Wall-middle floor	Ψ=0,2 (W/mK)
Ventilation	Summer nights (ACH) = 3	
	Occupancy (m^3/s/person) = 0.00022	
Air leakages	0.048 m^3/s (constant)	

Table 6-1. Case-study design aspects

These variables (Table 6-1) can be modified later, if necessary, in subsequent studies. The other design aspects are set by PMP company (thanks to the chapter 5 building system analysis) and building regulations in Spain CTE (https://www.codigotecnico.org). Moreover, the Simulation Conditions (Table 6-2) are defined according the same normative (CTE DB-HE).

Simulation conditions	Description	
Shading controls	May 1st - October 31th, if solar radiation incident on a window > 25W/m²	
Heating and cooling systems	Ideal loads air system	
Internal loads	People activity	90W/m²
	People occupancy	28m²/person
	Lighting	4,4W/m²
	Electric equipment	4,4W/m²
	Summer nights	3ACH
	Occupancy	0,00022m³/s/person
Schedules *[hours of the day, extremes included]*	Occupancy (%) = 100 [1-7, 21-23]; 80 [8, 14-15,20]; 50 [9,13,16,19]; 30[17], 20 [10-12]	
	Lighting (%) = 100 [18-23]; 50 [17]; 30 [8-16]; 10 [1-7]	
	Equipment (%) = 100 [18-23]; 50 [17]; 30 [8-16]; 10 [1-7]	
	Cooling set point (ºC) = 27 [1-12]; 25[15-23]	
	Heating set point (ºC) = 17 [1-6]; 20[7-23]	

Table 6-2. Case-study simulation conditions

During the briefing step clients also choose from the catalogue the construction elements they want to include in the study. In the current case-study the construction elements selected from the catalogue where the ones shown in Table 6-3 (configurator). As mentioned, the catalogue contains user-level information (e.g. window types) and the configurator contains technical data for modelling catalogue items in the template. The window-to-wall ratio (WWR) is the way to define the area of the windows of each facade according to the user's choice by catalogue.

Design aspect	Decision variable	Description
WWR South wall	Window length (v1)	[4 5 6] (m)
WWR North wall	Window length (v2)	[1 2] (m)
WWR East wall	Window length (v3)	[1,4 2,1] (m)
WWR West wall	Window length (v4)	[1,4 2,1] (m)
Windows U-value	Glass conductivity (v5)	[0,1 0,2 0,3] (W/mK)
Windows SHGC glass factor	Solar transmittance (v6)	[0,50 0,60] (-)
Exterior walls U-value	Rockwool thickness (v7)	[0,08 0,1] (m)

Table 6-3. Case-study decision variables and parameters

Windows and exterior walls types are the elements that will be combined to generate the multiple calculation designs to evaluate.

To generate the reference building, the template is edited (Figure 6-13).

- First, the geometric elements ground floor and top floor are selected and assembled.
- Then, the sizes of these geometric elements are defined according to the customer requirements.
- After, the sizes of the wall-roof, wall-middle floor and wall-bottom floor thermal bridges are also adjusted.

Once the reference template is modelled, the multiples calculation designs are generated in JEPlus (http://www.jeplus.org/wiki/doku.php) by introducing the decision variables values referring to the construction elements previously chosen by clients (Table 6-3). In total there are 288 different design configurations. Notice that thanks to the template, this step was done in just ten minutes.

Then, the calculation runs and the multiple designs energy-cost performances are evaluated and represented in the resulting graphic of Figure 6-14 to support decision-making. Notice that this process lasts about one hour 30 minutes.

In the Figure 6-14 each of the 288 designs is represented by a point. Ideally, points close to the origin represent preferable building designs under heating, cooling and initial investment costs criteria. At first glance it can be rule out those solutions that are far from optimal. In this way, the range of possibilities is greatly reduced.

Then, customers can select each of the near to preferable buildings design and decide the one that better fits their needs. In this case study the clients have chosen the design solution "number 5" (Figure 6-14). Customers can see the main characteristics of the solution in the legend.

As a result, owners customized the geometry and the envelope configuration of the building in an energy-cost efficient way. Each client is able to participate in making decisions that affect the architectural design and thermal behaviour of their home during the use phase (operational phase).

It is important to highlight the important reduction of human and computational working time in this case-study thanks to the new design procedure. The reference building generation time is reduced about 3000% (from 5 hours to 10 minutes). Moreover, the complete assessment of 288 different building design lasts about one hour 30 minutes.

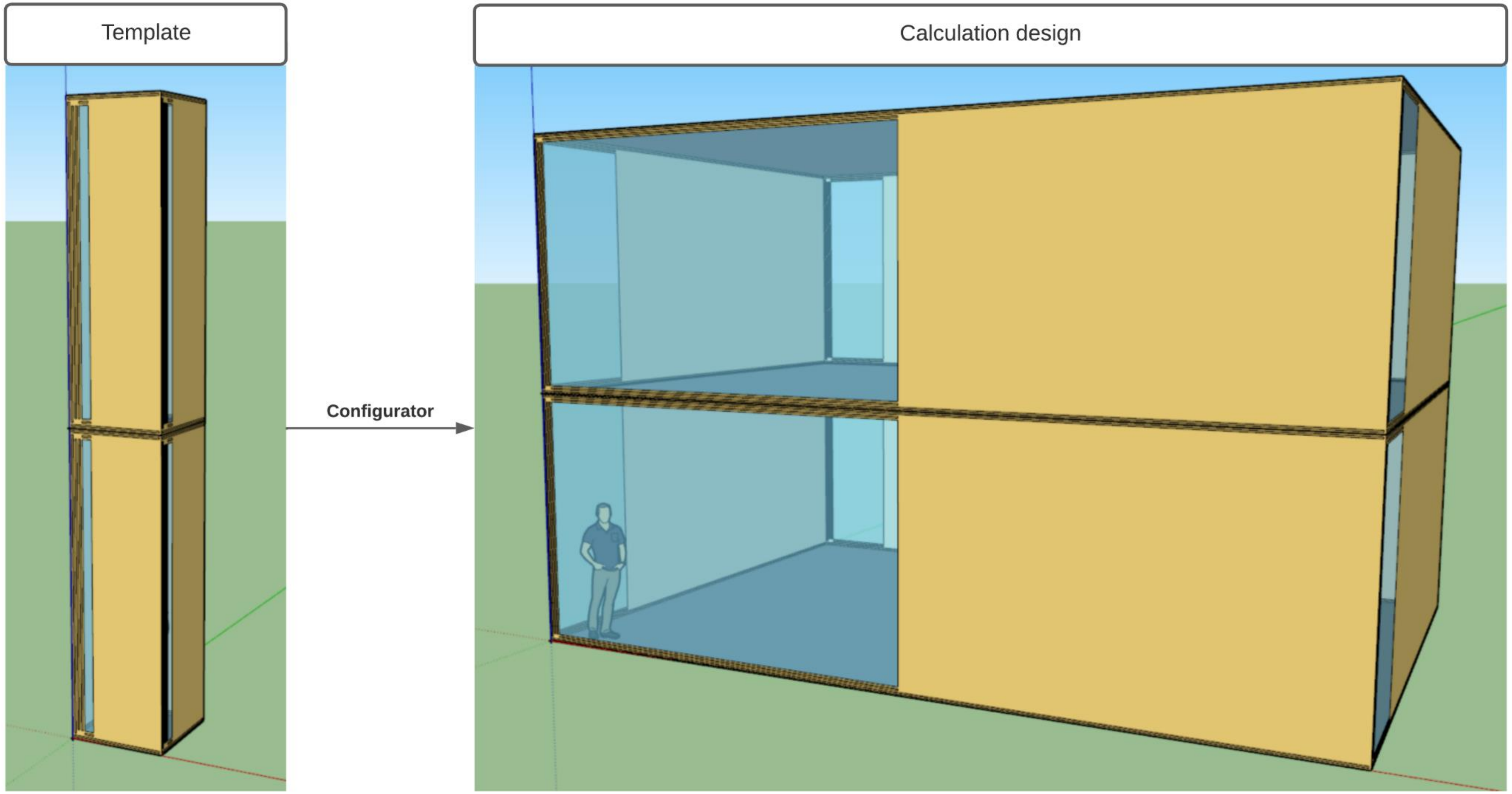


Figure 6-13. Case-study

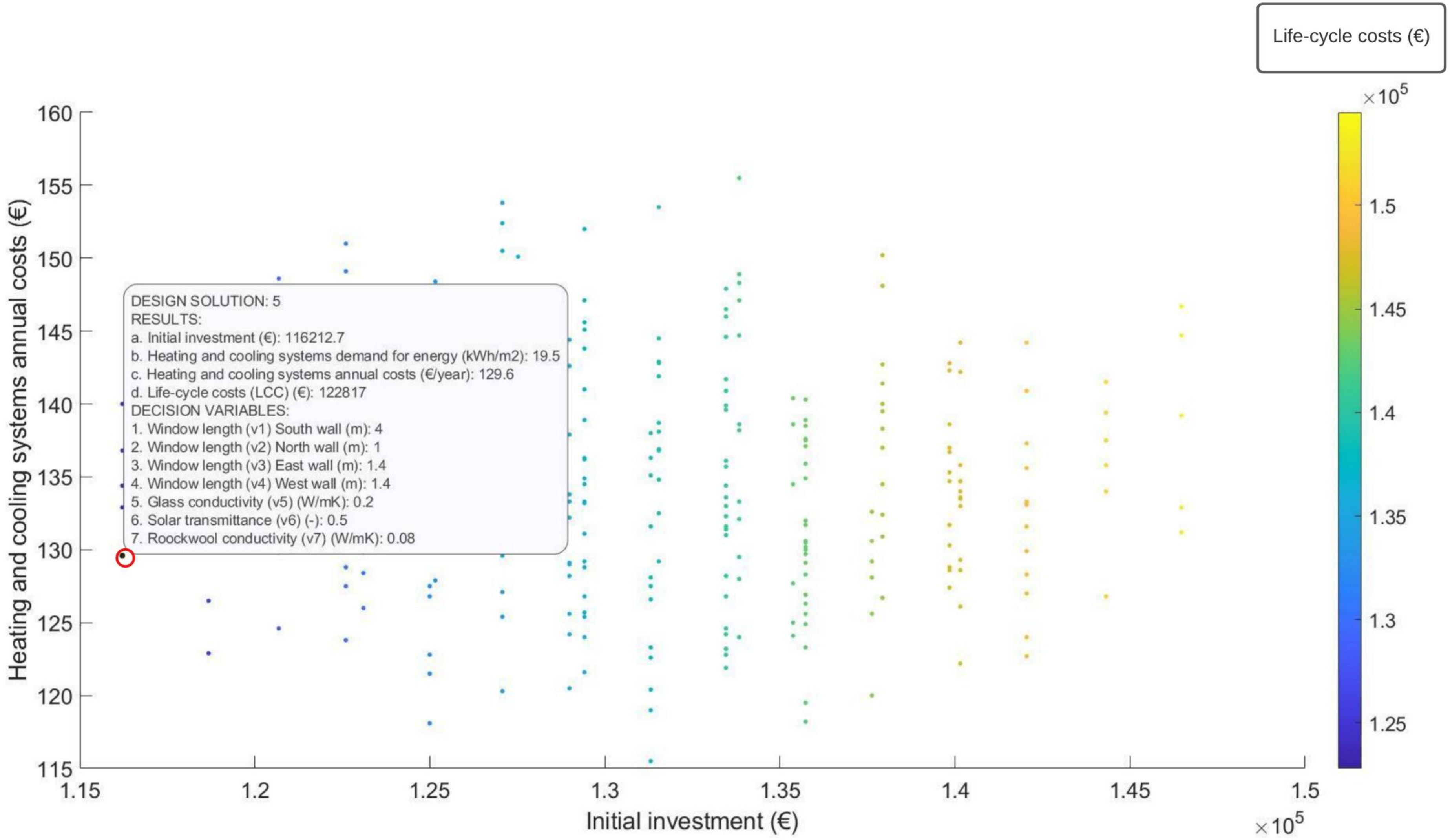


Figure 6-14.Result viewer

Discussion

The house-building design process has been improved by a new suggested procedure that has also been adjusted to the PMP building system singularities. It allows decision makers and customers to make efficient decisions in early design to balance costs, sustainability and customization (Figure 6-15). An advantage of an early decision-making is that production process can start earlier. It means that the delivery time of real projects is reduced. This is not only a benefit on time but also a benefit on indirect costs.

This design process can be useful for those IHB companies that produce single-family houses and which building objectives include customization, and that receive requests from potential customers every day. An important virtue is that the procedure allows a fast custom-oriented study in a market context where speed of response is increasingly valued by customers (Chonko and Jones 2005).

In general, the procedure contributes to the design of house-buildings with reduced energy demand during the use (operational phase) and, at the same time, its associated costs. It also makes customers aware of the importance of sustainable practices in house-buildings use and guides them towards the choice of thermally efficient housing (Figure 6-14).

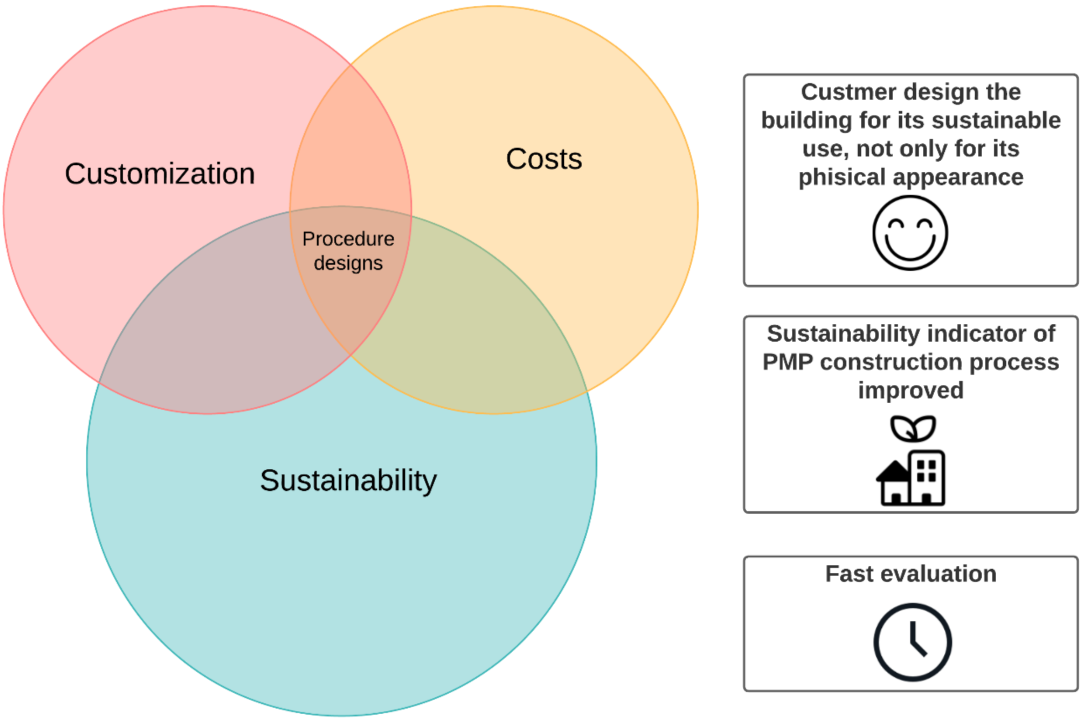


Figure 6-15. Improved design procedure benefits

Chapter 7. Conclusions

This thesis presents a design process that allows to customize industrialized house-buildings (IHB) under heating, cooling and initial investment costs criteria. It is important to highlight that the process is specially implemented to reduce design resources and time. The process has been adapted to the singularities of the industrialized building system (IBS) of the company PMP Prêt-à-Porter Cases (Lleida - Spain), which is based on the prefabrication of concrete modules (2D) or panels.

- A first approach of an historical review that characterizes the IHB design stage was developed, through an established analysis criteria that allows to compare the main features in a homogeneous and continuous way. A IHB design stage timeline has been implemented, showing the evolution of key factors and parameters over four historical periods instead of simply listing and describing isolated events as in previous historical reviews in the field of house-building industrialization
- The industrialization index was established as a new key parameter to characterize an industrialized building system (IBS) never used before in previous studies. It was defined as the ratio of a complete house-building that is manufactured, taking into account foundations, structure, skin, fit-out and services. Based on this parameter, it appears that it is possible to design an IBS with both high productivity and high customization by increasing the industrialization index of panelised (2D) building systems. This appear to be relevant contribution as so far no one had considered the importance of the industrialization index and the possibility of achieving high productivity in the IHB industry with panelised (2D) building systems. Thus, one of the future challenges of the IHB industry is to design flexible building systems (2D) with a high industrialization index that ensure high productivity and high customization (e.g. including piping in flexible panels).
- The results obtained in the IHB design stage state of the art show a clear trend of building systems as well as design strategies towards sustainability and customization, being 2D modules the best option for the improvement of both.
- The PMP IBS leaded in customization (I1), fire safety (I2) and acoustic comfort (I3). However, an area for improvement identified was the industrialization index (P8), which could lead to both a delivery time (I5) and price (I6) reduction. Moreover, a clear margin for improvement in environmental impact (I4) was found. Thus, the thermal transmittance of walls (P5) and the CO_2 emissions in fabrication phase (P6) could be improved.
- In Lleida and Barcelona climates, Lightweight wood frame building system has a better thermal performance compared to the PMP system, but worse than the Prefabricated concrete modules (2D) system with exterior insulation technology. Concrete systems with external insulation have a higher potential for energy efficiency during the use phase of homes than a wooden system with similar characteristics in the Mediterranean studied climates. However, with the current low demands of new house-buildings in Mediterranean climates under building regulations such as the CTE-DB-HE (Fomento 2019), modifying the building system does not appear as a cost-effective strategy for PMP (https://pretaportercasas.com/).
- Current house-building design parametrization and/or optimization approaches are not time-efficient, and require excessive human and computer resources, preventing them from being implemented in the industry. Indeed, an IHB firm, that receives requests from potential customers every day, cannot afford to do such a laborious and complex design study.

- A time-efficient design process in terms of human and computing resources that allows customization of housing under criteria of heating and cooling energy consumption, and initial investment costs has been developed, integrating 4 cornerstones: (1) template, (2) configurator, (3) result viewer and (4) customer-oriented decision-making.
- Throughout a case-study, an important reduction of human and computational working time was achieved thanks to the developed design procedure. The reference building generation time is reduced about 3000% (from 5 hours to 10 minutes), and the complete assessment of 288 different building design lasts about 1 hour 30 minutes.
- This procedure allows decision makers and customers to make efficient decisions in early design to balance costs, sustainability and customization. It appears to be useful for those IHB companies that produce single-family houses and receive potential customers every day and which building objectives include customization. In general, it contributes to reduce the energy demand during the use (operational phase) of homes and its associated costs. At the same time, it allows users to be aware of the environmental and economic benefits that the proper design and use of house-buildings can entail. Another advantage of an early decision-making is that production process can start earlier. It means that the delivery time of real projects is reduced. This is not only a benefit on time but also a benefit on indirect costs.
- According to the experimental results, the average value of air infiltrations n50 (50Pa) for the PMP IBS was 2.89 (-/h) and n4 (4 Pa) was 0.47 (-/h). In general, the higher the compactness of the building, the lower the air infiltration.
- To date, there are not many studies that provide air infiltration and thermal bridges data of IHB systems, so it is hoped that the results obtained can be compared with future studies to contribute to the evolution of the industrial fabric of the sector.

Future works

The remaining identified trends (high industrialization index and high standardization index) may be the starting point for future research projects in this field. One of the improvement proposals for industrialized building systems (IBS) based on 2D modules or panels, as in the case of PMP, is to redesign the production system to manufacture modules with more building elements and thus increase the industrialization index. The aim of this improvement is to reduce the costs and time of execution of construction. In general, these IBSs successfully industrialize and assemble, non-load-bearing walls, load-bearing walls, and slabs representing the floor, roof, and horizontal partitions. However, other tasks such as those related to the execution of MEP and/or the insulation of surfaces are still carried out completely on-site. This traditional component of the process negatively affects productivity. It is proposed to design a modular system that can be integrated with an IBS based on the prefabrication of 2D modules, which will guarantee a higher industrialization rate. For example, standardizing parts that contain pipes and mechanisms of the MEP that have an assembly process based on that from structural panels.

In another direction, based on the developed design procedure, it could be programed a web application where users can play and test different home design options and view their heating and cooling consumption and cost indicators. It could serve as a potential innovative marketing tool to attract customers. It is true that this application should not contain exactly all the design and calculation procedures, as it would be overly complex. One proposal would be to design this application by introducing a pre-calculated database defined based on doing a certain volume of case studies similar to the one presented in this thesis.

Bibliography

Books

Arieff, A., & Burkhart, B. (2002). Prefab. Gibbs Smith.

Blake, F., & Sorkin, M. (1998). Moshe safdie: Habitat ’67, montreal. Testo & Immagine.

Cooke, B., & Walker, G. (1994). European construction: Procedures and techniques. Palgrave.

Decker, J., & Chris, C. (2005). Quonset Hut: Metal Living for a Modern Age. Princeton

Architectural Press.

Finnimore, B. (1989). Houses from the factory: System building and the Welfare State 1942-74. Rivers Oram Press.

Neder, F. (2008). Fuller houses. r. buckminster fuller’s dymaxion dwellings and other domestic adventures. Lars Mu¨ller.

Papers

Acar, Ugur, Onder Kaska, and Nehir Tokgoz. 2021. “Multi-Objective Optimization of Building Envelope Components at the Preliminary Design Stage for Residential Buildings in Turkey.” *Journal of Building Engineering* 42(March): 102499. https://doi.org/10.1016/j.jobe.2021.102499.

Ågren, Robert, and Robert D. Wing. 2014. “Five Moments in the History of Industrialized Building.” *Construction Management and Economics* 32(1–2): 7–15.

Akmam Syed Zakaria, Sharifah, Thayaparan Gajendran, Timothy Rose, and Graham Brewer. 2018. “Contextual, Structural and Behavioural Factors Influencing the Adoption of Industrialised Building Systems: A Review.” *Architectural Engineering and Design Management* 14(1–2): 3–26. http://dx.doi.org/10.1080/17452007.2017.1291410.

Arbor, Ann. 2009. “IMPACT OF INSULATION ON BUILDING ENERGY CONSUMPTION Jong-Jin Kim and Jin Woo Moon.” : 674–80.

Attia, Shady et al. 2021. “Overview and Future Challenges of Nearly Zero Energy Buildings (NZEB) Design in Southern Europe.” *Energy & Buildings* 155(2017): 439–58. https://doi.org/10.1016/j.enbuild.2017.09.043.

Aye, Lu et al. 2012. “Life Cycle Greenhouse Gas Emissions and Energy Analysis of Prefabricated Reusable Building Modules.” *Energy & Buildings* 47: 159–68. http://dx.doi.org/10.1016/j.enbuild.2011.11.049.

Badir, Y.F., M.R.A. Kadir, and A.H. Hashim. 2002. “Industrialized Building Systems Construction in Malaysia.” *Journal of Architectural Engineering* 8(1): 19–23.

Baldwin, Andrew et al. 2009. “Designing out Waste in High-Rise Residential Buildings: Analysis of Precasting Methods and Traditional Construction.” *Renewable Energy* 34(9): 2067–73. http://dx.doi.org/10.1016/j.renene.2009.02.008.

Barlow, James et al. 2003. “Choice and Delivery in Housebuilding: Lessons from Japan for UK Housebuilders.” *Building Research and Information* 31(2): 134–45.

Barlow, James, and Ritsuko Ozaki. 2005. “Building Mass Customised Housing through

Innovation in the Production System: Lessons from Japan." *Environment and Planning A* 37(1): 9–20.

Berkeley, Lawrence et al. 2021. "EnergyPlus Essentials."

Boafo, F.E., J.-H. Kim, and J.-T. Kim. 2016. "Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways." *Sustainability (Switzerland)* 8(6).

Bojic, M., F. Yik, and P. Sat. 2001. "Influence of Thermal Insulation Position in Building Envelope on the Space Cooling of High-Rise Residential Buildings in Hong Kong." *Energy and Buildings* 33(6): 569–81.

Cao, Jianpeng, David F. Bucher, Daniel M. Hall, and Jerker Lessing. 2021. "22. Cross-Phase Product Configurator for Modular Buildings Using Kit-of-Parts." *Automation in Construction* 123: 103437. https://doi.org/10.1016/j.autcon.2020.103437.

Chonko, Lawrence B, and Eli Jones. 2005. "The Need for Speed : Agility Selling Author (s): Lawrence B . Chonko and Eli Jones Source : The Journal of Personal Selling and Sales Management , Vol . 25 , No . 4 (Fall , 2005), Stable URL : Https://Www.Jstor.Org/Stable/40472226 REFERENCES Linked Re." 25(4): 371–82.

Crawley, Drury B. et al. 2001. "7. EnergyPlus: Creating a New-Generation Building Energy Simulation Program." *Energy and Buildings* 33(4): 319–31.

Fang, Eric, Robert W. Palmatier, and Kenneth R. Evans. 2008. "Influence of Customer Participation on Creating and Sharing of New Product Value." *Journal of the Academy of* Marketing Science 36(3): 322–36.

Finnimore, B. (1989). Houses from the factory: System building and the Welfare State 1942-74. Rivers Oram Press.

Ghaffarianhoseini, Ali et al. 2017. "Building Information Modelling (BIM) Uptake: Clear Benefits, Understanding Its Implementation, Risks and Challenges." *Renewable and Sustainable Energy Reviews* 75(September 2016): 1046–53.

Gibb, Alistair G. F. 2001. "Standardization and Pre-Assembly- Distinguishing Myth from Reality Using Case Study Research." *Construction Management and Economics* 19(3): 307–15. http://www.tandfonline.com/doi/abs/10.1080/01446190010020435.

Gosling, Jonathan et al. 2016. "Defining and Categorizing Modules in Building Projects: An International Perspective." *Journal of Construction Engineering and Management* 142(11).

Gou, Shaoqing et al. 2018. "2. Passive Design Optimization of Newly-Built Residential Buildings in Shanghai for Improving Indoor Thermal Comfort While Reducing Building Energy Demand." *Energy and Buildings* 169: 484–506. https://doi.org/10.1016/j.enbuild.2017.09.095.

He, Qiong et al. 2021. "A Cost-Effective Building Retrofit Decision-Making Model – Example of China's Temperate and Mixed Climate Zones." *Journal of Cleaner Production* 280: 124370. https://doi.org/10.1016/j.jclepro.2020.124370.

Hegazy, By Tarek, Essam Zaneldin, and Donald Grierson. 2001. "Improving design coordination for building projects": 322–29.

House, The Swimming, and Lake Weissensee. "Passivhaus Primer : Airtightness Guide Airtightness and Air Pressure Testing in Accordance with the Passivhaus Standard - A Guide for the Design Team and Contractors This Primer Is an Aid to Understanding the Key Principles."

Hsu, Yun-sheng et al. 2021. "Evaluation of the Indoor Pressure Distribution during Building

Airtightness Tests Using the Pulse and Blower Door Methods.” *Building and Environment* 195(December 2020): 107742. https://doi.org/10.1016/j.buildenv.2021.107742.

Huang, Beijia et al. 2021. “Contribution and Obstacle Analysis of Applying BIM in Promoting Green Buildings.” *Journal of Cleaner Production* 278: 123946. https://doi.org/10.1016/j.jclepro.2020.123946.

Hvam, Lars et al. 2017. “A Framework for Determining Product Modularity Levels.” *Advances in Mechanical Engineering* 9(10): 1–14.

Jaillon, L., C. S. Poon, and Y. H. Chiang. 2009. “Quantifying the Waste Reduction Potential of Using Prefabrication in Building Construction in Hong Kong.” *Waste Management* 29(1): 309–20. http://dx.doi.org/10.1016/j.wasman.2008.02.015.

Jaillon, L., and C.S. Poon. 2009. “The Evolution of Prefabricated Residential Building Systems in Hong Kong: A Review of the Public and the Private Sector.” *Automation in Construction* 18(3): 239–48.

Jonsson, Henric, and Martin Rudberg. 2014. “Classification of Production Systems for Industrialized Building: A Production Strategy Perspective.” *Construction Management and Economics* 32(1–2): 53–69.

Henric Jonsson, Martin Rudberg, (2017) "KPIs for measuring performance of production systems for residential building: a production strategy perspective", Construction Innovation , Vol. 17 Issue: 3, doi: 10.1108/CI-06-2016-0034 Permanent

Kamali, Mohammad, and Kasun Hewage. 2016. “Life Cycle Performance of Modular Buildings: A Critical Review.” *Renewable and Sustainable Energy Reviews* 62: 1171–83. http://dx.doi.org/10.1016/j.rser.2016.05.031.

Kyrö, Riikka, Tuuli Jylhä, and Antti Peltokorpi. 2019. “Embodying Circularity through Usable Relocatable Modular Buildings.” *Facilities* 37(1–2): 75–90.

Larsen, Maria Stoettrup Schioenning et al. 2019. “Mass Customization in the House Building Industry: Literature Review and Research Directions.” *Frontiers in Built Environment* 5(October): 1–12.

Lessing, Jerker, and Staffan Brege. 2018. “Industrialized Building Companies’ Business Models: Multiple Case Study of Swedish and North American Companies.” *Journal of Construction Engineering and Management* 144(2): 05017019. http://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0001368.

Li, Zhengdao, Geoffrey Qiping Shen, and Xiaolong Xue. 2014. “Critical Review of the Research on the Management of Prefabricated Construction.” *Habitat International* 43: 240–49. http://dx.doi.org/10.1016/j.habitatint.2014.04.001.

Lin, Zhongjie. 2011. “Nakagin Capsule Tower: Revisiting the Future of the Recent Past.” *Journal of Architectural Education* 65(1): 13–32.

Lou, E.C.W., and K.A.M. Kamar. 2012. “Industrialized Building Systems: Strategic Outlook for Manufactured Construction in Malaysia.” *Journal of Architectural Engineering* 18(2): 69–74.

Mao, Chao, Qiping Shen, Wei Pan, and Kunhui Ye. 2015. “Major Barriers to Off-Site Construction: The Developer’s Perspective in China.” Journal of Management in Engineering 31(3): 04014043. http://ascelibrary.org/doi/10.1061/%28ASCE%29ME.1943-5479.0000246.

Mateo, A., Barrau, J., Miedes, A., Forne, J. O., & Perez, G. (2019). Customized cost-efficient building skin design for industrial housing adri`a. In 14th conference on advanced building skins (pp. 446–454). Zentralstr. 44 CH-6003 Lucerne, Switzerland.

Nadim, Wafaa, and Jack S. Goulding. 2010. "Offsite Production in the UK: The Way Forward? A UK Construction Industry Perspective." *Construction Innovation* 10(2): 181–202.

Negendahl, Kristoffer. 2015. "Automation in Construction Building Performance Simulation in the Early Design Stage : An Introduction to Integrated Dynamic Models." *Automation in Construction* 54: 39–53. http://dx.doi.org/10.1016/j.autcon.2015.03.002.

Ochoa, Carlos E, Myriam B C Aries, Evert J Van Loenen, and Jan L M Hensen. 2012. "Considerations on Design Optimization Criteria for Windows Providing Low Energy Consumption and High Visual Comfort." *Applied Energy* 95: 238–45. http://dx.doi.org/10.1016/j.apenergy.2012.02.042.

Oliveira, Luciana Alves, and Silvio Burrattino Melhado. 2011. "Conceptual Model for the Integrated Design of Building Façades." *Architectural Engineering and Design Management* 7(3): 190–204.

Pe, Luis. 2008. "A Review on Buildings Energy Consumption Information ´." 40: 394–98.

Peltokorpi, Antti, Hylton Olivieri, Ariovaldo Denis Granja, and Olli Seppänen. 2018. "Categorizing Modularization Strategies to Achieve Various Objectives of Building Investments." *Construction Management and Economics* 36(1): 32–48. http://doi.org/10.1080/01446193.2017.1353119.

Perez, G., & Perini, K. (2018). Nature based strategies for urban and building sustainability. Elsevier Inc.

Rudberg, Martin, and Joakim Wikner. 2004. "Mass Customization in Terms of the Customer Order Decoupling Point." *Production Planning and Control* 15(4): 445–58.

Segerstedt, Anders, and Thomas Olofsson. 2010. "Supply Chains in the Construction Industry." *Supply Chain Management: An International Journal* 15(5): 347–53.

Sharafi, Pezhman et al. 2018. "Identification of Factors and Decision Analysis of the Level of Modularization in Building Construction." 24(2): 1–12.

Simo Ilomets, Kalle Kuusk, Leena Paap, Endrik Arumägi & Targo Kalamees

(2016): Impact of linear thermal bridges on thermal transmittance of renovated apartment

buildings, Journal of Civil Engineering and Management.

Su, Xing, and Xu Zhang. 2016. "A Detailed Analysis of the Embodied Energy and Carbon Emissions of Steel-Construction Residential Buildings in China." *Energy and Buildings* 119: 323–30. http://dx.doi.org/10.1016/j.enbuild.2016.03.070.

Sun, Cheng, Qianqian Liu, and Yunsong Han. 2020. "3. Many-Objective Optimization Design of a Public Building for Energy, Daylighting and Cost Performance Improvement." *Applied Sciences (Switzerland)* 10(7).

Touloupaki, Eleftheria, and Theodoros Theodosiou. 2017. "5. Performance Simulation Integrated in Parametric 3D Modeling as a Method for Early Stage Design Optimization - A Review." *Energies* 10(5).

Wang, Weimin, Radu Zmeureanu, and Hugues Rivard. 2005. "13. Applying Multi-Objective Genetic Algorithms in Green Building Design Optimization." *Building and Environment* 40(11): 1512–25.

Zhao, Jing, and Yahui Du. 2020. "Multi-Objective Optimization Design for Windows and Shading Configuration Considering Energy Consumption and Thermal Comfort: A Case

Study for Office Building in Different Climatic Regions of China.” *Solar Energy* 206(September 2019): 997–1017. https://doi.org/10.1016/j.solener.2020.05.090.

Other documents

Commission, T H E European. 2016. “The European Commission,.” (9): 46–57.

Eurostat, Statistics. 2022. *Energy Consumption in Households*.

Fomento, Ministerio de. 2019. “DB-HE.” : 1–50.

Fomento, Ministerio de. 2019 (b) . “DB-SI.” : 1–129.

Fomento, Ministerio de. 2019 (c). “DB-HR.” : 1–129.

Sherman and Matson. 2002. “Air tightness of new U.S. houses: A preliminary report”. Lawrence Berkeley National Laboratory. URL http://energy.lbl.gov/ie/pdf/LBNL-48671.pdf

Reference, Input-output. 2021. “Input Output Reference.”