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Modular standardization criteria applied in multi-story residential buildings in Cross-Laminated Timber (CLT)

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Abstract: Multi-storey residential buildings in cross-laminated timber are emerging as a sustainable and profitable option with industrialization possibilities, that open the way to new paradigms in construction. In this new building model, the standardized modulation results in an efficient strategy to integrate design and manufacturing platforms. However, the application of this strategy requires the study and development of methodologies that achieve the necessary design flexibility to obtain adequate levels of production and customization. Based on this, this work analyzes the modularity conditions observed in five buildings built between 2002 and 2016, in order to study the standardization criteria implemented. To achieve this, an analysis is made of the underlying modularity in the design and the conditions of variation or repetition presented. In this sense, the use of different modularity criteria was observed between the first experiences developed and the most recent buildings, given by the technological progress of recent years. The research allows us to approach the understanding of the modularity conditions associated with these buildings, as a contribution to the development of methodologies that optimize the design for manufacturing and assembly

Key words: modularity; industrialized construction; Cross-Laminated-Timber; multi-storey residential buildings, DfMA

1 Introduction

The construction of multi-residential buildings using cross-laminated timber as the primary structural material began in Europe in the first decade of the 2000s with a few low-rise buildings. Since then, this construction technology has evolved rapidly, enabling the construction of taller buildings such as the Stadthaus – a nine-storey building built in England in 2009; the eight-story Holz 8, built in Germany; and the 10-story Forté, built in Australia in 2012.

The construction of these buildings gave rise to a new paradigm in the global construction industry, introducing a sustainable and industrialized technology that positions wood as the only carbon-negative material on the planet capable of supporting high-rise construction (Smyth, 2018) and that can also enhance construction efficiency through industrialization.

Given the prefabricated nature of these buildings, their design process could incorporate Design for Manufacturing and Assembly (DfMA) methodologies—originally used in industrial manufacturing (Staub-French et al., 2018)—which have been proposed for adaptation to the construction industry. Under this methodology, both off-site prefabrication and on-site assembly of each construction component are taken into account from the outset of the design process (Gao et al., 2018) (Gao et al., 2019).

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In this process, product modularity—understood as the breakdown of a product into building blocks (modules), joined by specific interfaces and managed according to manufacturing criteria (Erixon, 1996)—is fundamental (Shafiee et al., 2020a). However, even though modularity is a key requirement for the design and construction of industrialized buildings, there remains a lack of understanding regarding its application and general management (Da Rocha et al., 2015). In the specific field of buildings constructed with cross-laminated timber, modularity strategies could address general industrialization requirements, whether through panelization (2 dimensions) or volumetric elements (3 dimensions) (Koppelhuber et al., 2017). However, given the novelty of this technology, there have been no studies to date on the modularity of high-rise buildings constructed with this material (Dorrah and El-Diraby, 2019). In this regard, it is considered that design efficiency for manufacturing and assembly must take into account modularity criteria that allow for both design customization (variation in solutions) and the standardization of building components (repetition of elements). The latter is intended to reduce the total number of parts, which in turn reduces manufacturing time and improves efficiency (Kremer, 2018) (Shafiee et al., 2020a).

Construction standardization is an important strategy that enables the subsequent reuse of the design; it refers to a situation in which multiple construction components are replaced by a single one that can perform the functions of all of them (Pakkanen et al., 2016) and can be reused subsequently. In this way, modularization includes definitions of modules and interfaces to reduce complexity in a company's operations. Based on the above, this research aims to study the conditions of modularity and underlying standardization in existing multi-residential buildings constructed with CLT, with the goal of providing insights that contribute to improving the design processes for the manufacturing and assembly of these buildings, drawing on the practical experience gained from constructions already completed using this technology.

To conduct the research, five buildings constructed in different countries were selected as case studies; these demonstrate the application of this technology and are supported by documentation. Based on this, the study began by analyzing and categorizing the observed modular patterns at both the architectural-spatial and structural (walls) levels, with particular emphasis on repetition criteria. The analysis was based on a study of typical floor plans, defined as those with the highest degree of repetition within the building. To determine the wall modularities, a methodology based on reverse engineering was applied, which involved deducing the dimensions of these elements based on ideal conditions. Finally, the relationship between the observed modular repetition criteria and the achieved design flexibility was determined.

2 Method

The research focuses on studying the modularity conditions of existing buildings. This was done by analyzing their typical floor plans, defined as those that recur most frequently within the building.

Based on this, an exploratory methodology was adopted, supported by an online literature search using web search engines, with the aim of identifying buildings that met the required characteristics in a global context. To this end, keywords in Spanish and English related to the research topic were used, leading to various sources of information—such as research articles, online magazines, digital catalogs, and videos—which provided the basic information required for the study, including floor plans, construction details, photographs, and images, among others.

Since the typical floor plans of the buildings constituted one of the main sources of study, they were digitized using commercial computer-aided design software, based on images obtained through the methods described above. For this purpose, a standard stair tread width of 300 mm was used as a baseline, with an estimated margin of error of approximately +/- 5 to 10 mm per meter, which was considered acceptable for the purposes of the research, given that the proposed method of analysis focuses on proportions rather than exact measurements. Based on this information, the various

functional modulations observed at the architectural-spatial level were identified and categorized, with these being defined as spatial units with independent functions. The conditions of their repetition were then evaluated. The data were presented in a summary table (Table 3), with the identified module categories serving as independent variables and the following as dependent variables:

1. Total number of modules: Referring to the total number of modules by category observed in the typical floor plan.
2. Number of module types: Refers to the number of distinct module types observed by category.
3. Module types: This indicates the coding defined for each module type by category. This coding is established solely to improve the visualization of the data in the table, with module types identified by the letter "T," e.g., T1, T2, T3…Tn, according to the types observed.
4. Repetitions by module type: Refers to the number of repetitions observed for each module type.
5. Mirror repetition: This refers to whether the repetition is symmetrical or exact, with the word "YES" used for the former and "NO" for the latter.
6. Percentage of module repetition: This takes into account the ratio of repeated modules to the total number of modules observed.

Finally, Table 3 presents average values for module types, repetition by module type, and the percentage of module repetition.

It should be noted that mirror symmetry, observed in the repetition of some modules, was considered valid, while acknowledging that, although it represents a condition of structural equality in terms of dimensions, shapes, and quantity of material, it may involve certain variations in the location and configuration of utility installations.

Second, the conditions of variability or repetition observed in walls were analyzed (Table 4). Consequently, since the information obtained online did not provide precise data on measurements and configuration conditions, a reverse-engineering process was applied to each case study. This allowed for the deduction of logical dimensions and configurations of panelized walls (2-dimensional) based on ideal design, manufacturing, and assembly conditions applicable to this type of building. In this way, for each typical floor plan, different types of walls (panels) were identified following an initial categorization that distinguished interior walls from exterior walls. These structural elements were coded to then proceed with an evaluation of their repetition patterns. It should be noted that for this initial methodological approach, only interior walls were quantified. The data were compiled in a table (Table 4), taking into account the types of interior walls observed as independent variables and the number of repetitions per wall type observed in each case study as dependent variables. To facilitate the visualization of the data in the table, a nomenclature was established that allows for the identification of module types by category using the letter "T," such as T1, T2, T3…Tn, depending on the types of walls observed. Finally, the following dependent variables were quantified: 1) total number of walls; 2) total number of wall types; 3) average number of repetitions per wall type; 4) highest repetition value; 5) percentage of unique walls; 6) percentage of repeating walls.

2.1 Case studies

As mentioned, the research is based on a study of a group of multi-residential CLT buildings, ranging from 4 to 8 stories in height, that reflect global technological expertise and capabilities across different contexts and years of construction. To select these buildings, an online search was first conducted between November and December 2020, during which seventeen cases were identified that met the required criteria for use, number of stories, and construction technology. Based on this, the buildings were listed according to their name, year of construction, location, use, number of stories, and construction technology. The categories included mixed-use, primarily residential, and hybrid CLT/concrete

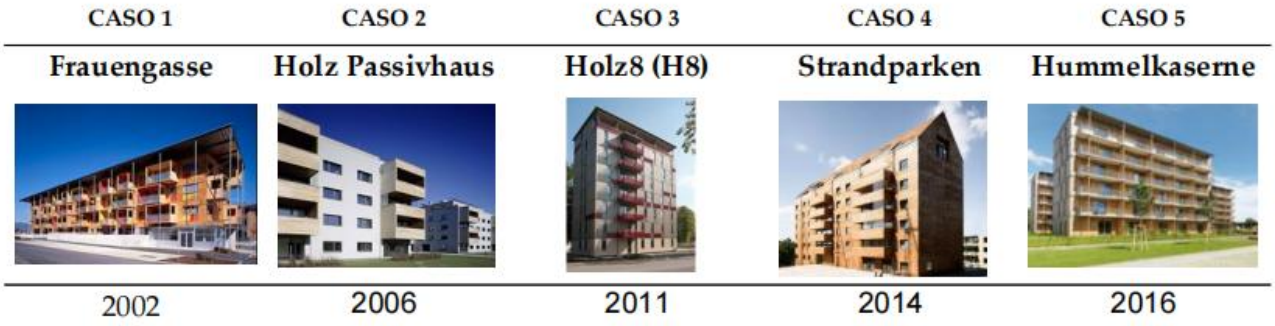
systems, with CLT as the primary structural material (Table 1).

Table 1. Initial list of buildings

No.	Building Name	Year	Location	Use	No. of Floors	Construction Technology
01	Frauengasse	2002	Judenburg, Austria	Residential	4	CLT Panels
02	Holz Passivhaus	2006	Vienna, Austria	Residential	5	CLT Panels
03	Limnologen	2009	Växjö, Sweden	Residential	8	CLT Panels
04	Stadthaus	2009	London, England	Residential	9	CLT Panels
05	Holz8 (H8)	2011	Bad Aibling, Germany	Residential	8	Hybrid CLT Panels / Concrete
06	Forte	2012	Melbourne, Australia	Residential / Commercial	10	Hybrid CLT Panels / Concrete
07	Fernpassstrasse	2012	Munich, Germany	Residential	4	CLT Panels
08	Wagramerstrasse	2013	Vienna, Austria	Residential	7	Hybrid CLT Panels / Concrete
09	Pentagon II	2013	Oslo, Norway	Residential	8	Hybrid CLT Panels / Concrete
10	Cenni di Cambiamento	2013	Trieste, Italy	Residential	9	CLT Panels
11	Panorama Giustinelli	2013	Trieste, Italy	Residential	7	Hybrid CLT Panels / Concrete
12	Strandparken	2014	Vlugtenburg, Sweden	Residential	8	CLT Panels
13	The Jules Ferry Tower	2014	Saint-Dié-des-Vosges, France	Residential	8	CLT Panels
14	Puukuokka	2015	Jyväskylä, Finland	Residential	6–8	CLT Panels
15	Hummelkaserne	2016	Graz, Austria	Residential	6	CLT Panels
16	Kanalen Brygge	2020	Tønsberg, Norway	Residential	5	CLT Panels
17	Bike and Ride	2020	Vienna, Austria	Residential	6	CLT Panels

From this first group, five buildings were selected (Table 1) and (Table 2) representing approximately 30% of the initially identified buildings, taking into account that they constituted a representative variety in terms of height, shape, functional configuration, and evolution over time. This number was considered sufficient for an initial methodological approach. Although few in number, they reflect the world's leading experience and technological capabilities in this field, making their analysis relevant. It should be noted that a key selection criterion was the year of construction, so that the buildings would illustrate evolution over time (Table 2), as well as the quantity and quality of documentation they provided, such as floor plans, construction details, and manufacturing and assembly processes.

Table 2. Case studies and construction years



2.1.1 Description of the case studies

Freuengasse Residences: Built in 2002 in Judenburg, Austria, this four-story building consists of three apartment blocks with separate entrances. Although it is primarily residential, its first floor is designated for commercial use. It has a

total of 22 apartments. This building was constructed almost entirely of CLT panels, with the exception of the stairwells, which were built of concrete.

The total project covers an area of 1,800 m² and involved a total investment of 2,400,000 €, resulting in an estimated total investment of approximately 1,333 €/m². ("Hagmüller Architekten ZT GmbH," n.d.) ("Multi-residential CLT in Judenburg, Austria | WoodSolutions," n.d.)

Holz Passivehaus Residences: Located on Mühlweg in Vienna, this complex consists of seventy residential units distributed across six five-story buildings, constructed to the Passive House standard and designed with an environmentally friendly concept. The entire complex was built using CLT. The semi-basement and first-floor levels, along with the central vertical circulation core, were constructed of concrete. The remaining floors were constructed of CLT.

The entire project was developed on a 6,750 m² site, with an investment of 11,000,000 €. The total investment cost is estimated at approximately 1,630 €/m². ("Sozialer Wohnbau, Holz-Passivhaus am Mühlweg, 1210 Wien - Haus der Zukunft," n.d.)

Holz 8: This building was constructed in Bad Aibling, Germany. It has eight stories with a total of 16 apartments (2 per story). Its main structure was built using CLT with a concrete vertical circulation core. The building was constructed using high levels of industrialization, which allowed for an on-site assembly time of three and a half weeks. The project covers a total area of 1,309 m² and had a total investment cost of 2,500,000 €, resulting in an estimated total investment cost of approximately 1,533 €/m². ("Holz 8 - Residential and Office Building, DE: dataholz.eu," n.d.)

Strandparken: Located in Stockholm, Sweden. It consists of four 8-story buildings with attic floors, each containing 31 apartments, two of which were constructed entirely of CLT.

The project was built on a total area of 9,920 m² and involved a total investment of 200 million Swedish kronor (approximately 19,670,000 €), resulting in an estimated total investment cost of approximately 1,982 €/m². ("Strandparken | ByggfaktaDOCU.se," n.d.)

Hummelkaserne Residences: Located in Graz, Austria. It is a residential complex consisting of four six-story buildings with a total of 92 apartments designed to passive house standards. It was built almost entirely with CLT panels, with the exception of the vertical circulation and access core.

The total project covered an area of 5,695 m² and required an investment of 4,850,000 €, resulting in an estimated total investment cost of approximately 851 €/m². (Guttmann, n.d.)

3 Results

In the cases studied, underlying modular patterns were observed at the architectural-spatial and structural levels, with categories identified based on size and functionality that follow a principle of hierarchical composition, where larger modules are composed of and configured from smaller modules. The identified module categories are (Figure 1): 1- Residential core, defined as a functional unit that houses several residential units and consists of an independent vertical circulation core; 2- Vertical circulation core and common access; 3- Residential unit or dwelling; 4- Enclosed compound. In each category, depending on the case study, different conditions of repetition or variation were observed, determined by the level of architectural flexibility noted. One condition of repetition observed was mirror symmetry. Within the category of enclosures, the following module typologies were identified based on function: 1-Living-dining room; 2- Living-dining-kitchen; 3- Kitchen; 4- Bedrooms; 5- Bathrooms; 6- Balconies.

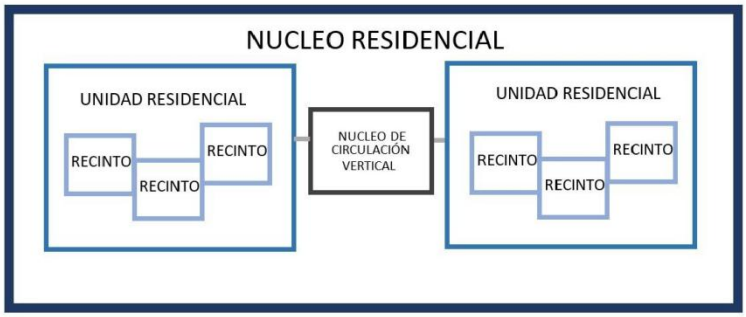


Figure 1. Observed module categories. Source: author's own work



Figure 2. Case 1. Frauengasse residences. Modulation of residential units

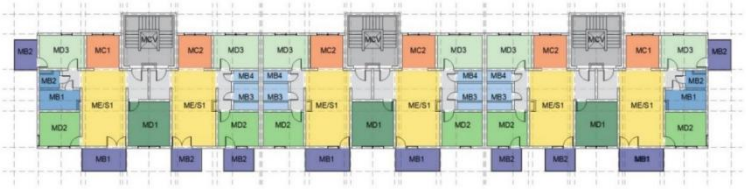


Figure 3. Case 1. Frauengasse residences. Spatial modulation. Source: author's own work

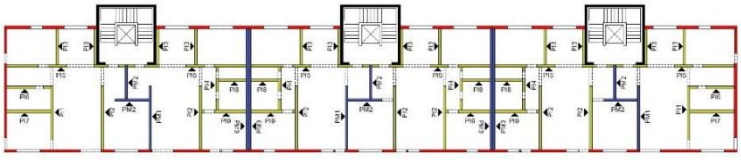


Figure 4. Case 1. Frauengasse residences. Modulation of interior walls. Source: author's own work



Figure 5. Case 2. Passivhause residences. Modulation of residential units. Source: author's own work

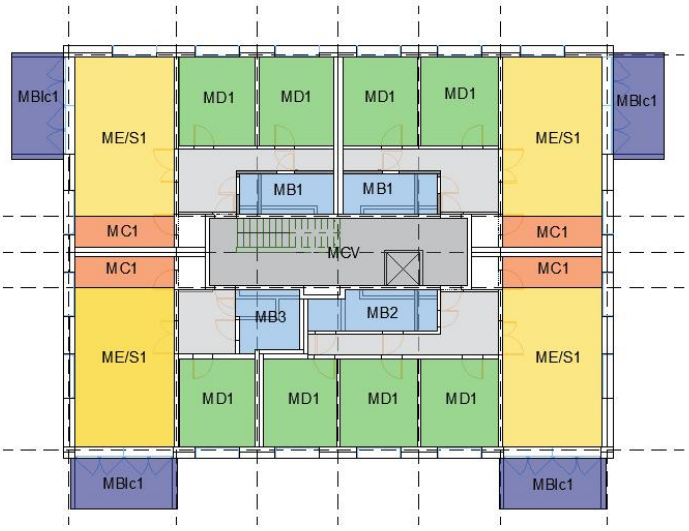


Figure 6: Case 2. Passivhause residences. Spatial modulation. Source: author's own work

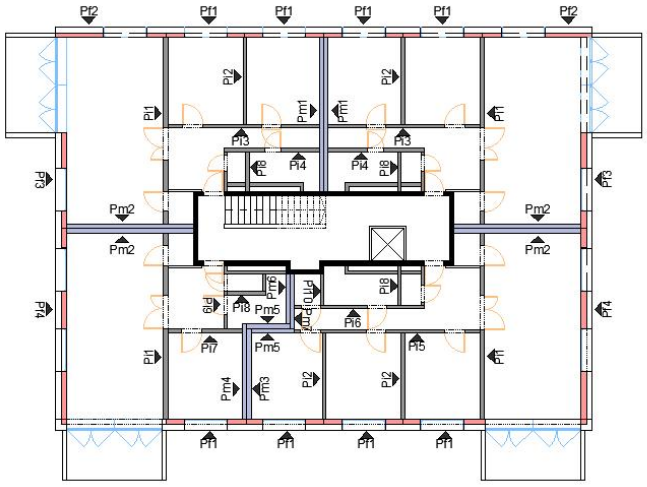


Figure 7. Case 2. Passivhaus residences. Modulation of interior walls. Source: author's own work

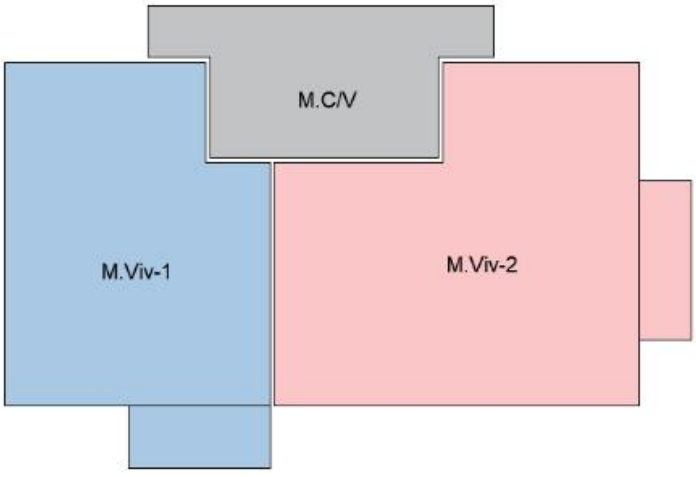


Figure 8. Case 3. Holz 8 residence. Modulation of residential units. Source: author's own work



Figure 9. Case 3. Holz 8 residence. Spatial modulation. Source: author's own work

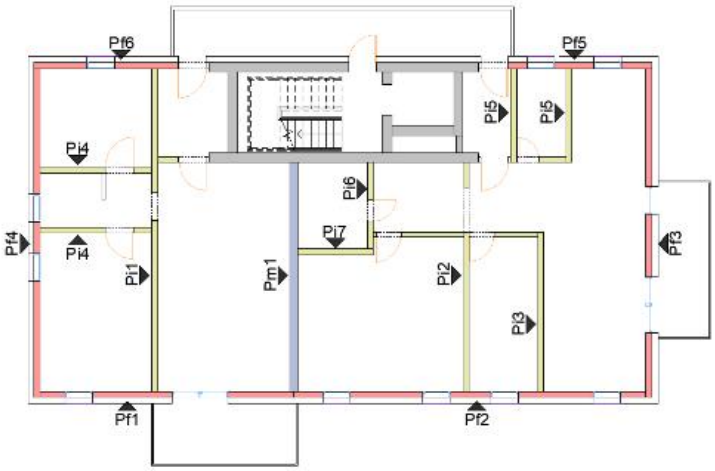


Figure 10. Case 3. Holz 8. Modulation of interior walls. Source: author's own work

3.1 Results by case

Case 1: Frauengasse

The entire building consists of three identical residential core modules, joined lengthwise. Each module features independent vertical circulation modules constructed of concrete, all sharing the same characteristics in terms of form and functional configuration (Figure 2). Regarding the residential units, two distinct types were observed, each repeated three times, for a total of six. Of these, only one appears as a mirror image. As for the rooms, there is a consistent repetition of the kitchen and living/dining room modules in each of the six residential units. Similarly, there is a high pattern of repetition in the bedroom, bathroom, and balcony modules (Figure 3) (Table 3).

With regard to the interior walls, a total of 56 walls were identified, comprising 12 distinct types (Figure 4) (Table 4), with an average repetition of 4.7, where 12 is the highest repetition value and 2 is the lowest. The percentage of repeated walls is 100% (Table 4).

The building consists of a single residential core comprising four residential units based on three distinct module types. Of these, one is mirrored to complete the total of four units arranged around a central vertical circulation core constructed of concrete (Figure 5). It features a very regular layout with a high degree of repetition in the rooms, with variations observed only in the bathrooms, which follow three distinct module types, one of which is repeated in a mirrored

configuration (Figure 6) (Table 3).

With regard to interior walls, a total of 33 wall types were identified in this building, with 17 distinct types having an average repetition rate of 1.94, where 4 is the highest repetition value and 2 the lowest. Likewise, there are 9 unique walls within the typical floor plan, and 73% of the walls are repeated (Table 4).

Case 3: Holz 8

The Holz 8 building consists of a single residential core comprising two distinct residential units, served by a lateral vertical circulation core (Figure 8). Each residential unit features a completely unique layout of rooms with no repetitions (Figure 9).

As for the interior walls, in the typical floor plan—which is quite small—a total of 10 walls are identified, with only 2 being repeated. In other words, there is a high degree of wall variation, with 60% unique walls compared to 40% repeating walls, for an average of 1.24 (Figure 10) (Table 4).

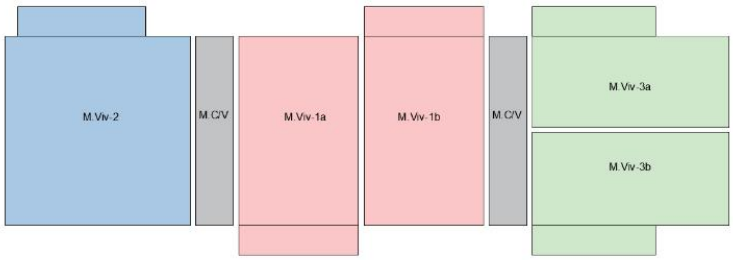


Figure 11. Case 4. Strandparker residential building. Modulation of residential units. Source: author's own elaboration

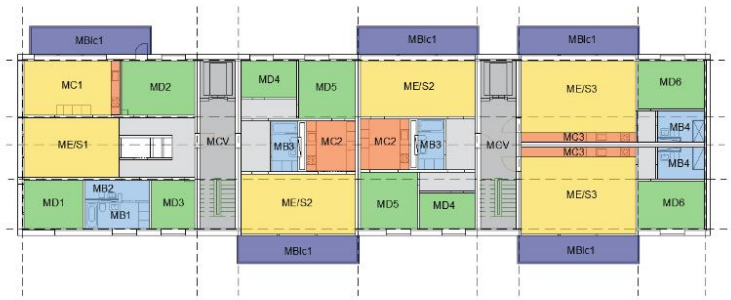


Figure 12. Case 4. Strandparker residential building. Spatial modulation. Source: author's own elaboration

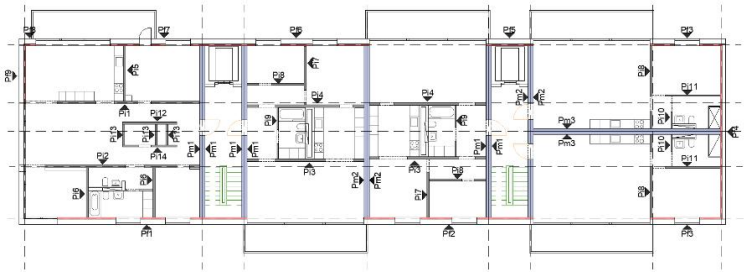


Figure 13. Case 4. Strandparker residential building. Modulation of interior walls. Source: Author's own elaboration

Case 4: Strandparker

The entire building comprises two modules corresponding to separate residential cores, joined lengthwise. Each module features a vertical circulation core located transversely within the overall volume (Figure 11) with identical chara-

-cteristics. This building exhibits a very limited modular repetition pattern (Table 3). With regard to the housing units, there are three distinct types, two of which are mirrored, resulting in a total of five units per typical floor. The repetition of spaces is very limited, reflecting a high degree of design flexibility (Figure 12) (Table 3). A consistent modular repetition pattern is observed only in the balconies.

As for the interior walls, a total of 34 walls and 17 wall types were identified. Furthermore, the maximum repetition value is 6 and the minimum is 2, with the latter being the most common value, observed in 10 of the 17 total module types. The percentage of unique walls is 15%, compared to 85% for repeating walls, but with a low repetition rate, as noted above (Table 4).



Figure 14. Case 5. Hummelkazerne residential building. Modulation of residential units. Source: author's own elaboration



Figure 15. Case 5. Hummelkazerne residential building. Spatial modulation. Source: author's own elaboration

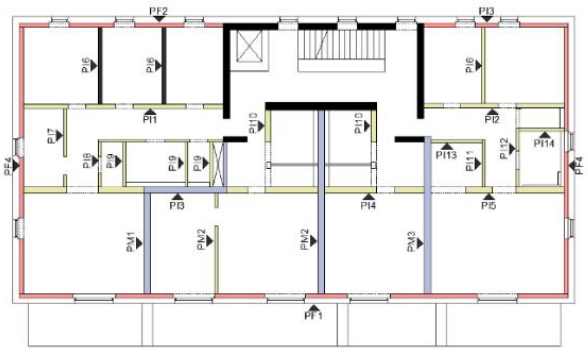


Figure 16. Case 5. Hummelkazerne residential building. Modulation of interior walls. Source: author's own elaboration

Case 5: Hummelkaserne

This building features a single residential core containing four distinct types of residential units. These units, in turn,

are composed of various types of room modules (Figure 14). The vertical circulation core is positioned laterally within the floor plan but is integrated into the overall volume. A very low pattern of repetition is observed in most of the room modules, with the exception of the balconies, which exhibit constant repetition. Of the total of seven bedrooms in the entire building, one particular module type is repeated three times and another only twice (Table 3). In the bathrooms, only two types of modules are observed, one of which is repeated as a mirror image and the other is repeated identically but rotated by 90° (Figure 15).

With regard to interior walls, a low pattern of repetition is observed (Figure 16). A total of 22 walls and 16 distinct wall types were identified, with a maximum repetition value of 3 and a high number of unique walls. Overall, unique walls account for 55% of the total, compared to 45% for repeating walls (Table 4).

Table 3. Architectural-spatial modulation conditions by case. Author's own work

T=Tipo de módulo		Caso 1 Frauengasse						Caso 2 Holz-Passivhaus						Caso 3 Holz 8						Caso 4 Strandparker						Caso 5 Hummelkaseme					
Categorías de Módulos		Total de Módulos	Cantidad de tipos de Módulos	Tipo de módulo	Repeticiones de tipos de módulo	Repetición en espejo	% Repetición de módulos	Total de Módulos	Cantidad de tipos de Módulos	Tipo de módulo	Repeticiones de tipos de módulo	Repetición en espejo	% Repetición de módulos	Total de Módulos	Cantidad de tipos de Módulos	Tipo de módulo	Repeticiones de tipos de módulo	Repetición en espejo	% Repetición de módulos	Total de Módulos	Cantidad de tipos de Módulos	Tipo de módulo	Repeticiones de tipos de módulo	Repetición en espejo	% Repetición de módulos	Total de Módulos	Cantidad de tipos de Módulos	Tipo de módulo	Repeticiones de tipos de módulo	Repetición en espejo	% Repetición de módulos
Nucleo Residencial		3	1	T1	3	NO	100%	1	1	T1	1	NO	0%	1	1	T1	1	NO	0%	2	2	T1	1	NO	0%	1	1	T1	1	NO	0%
																						T2	1		0%						
Nucleo de Circulación Veitical		3	1	T1	3	NO	100%	1	1	T1	1	NO	0%	1	1	T1	1	NO	0%	2	1	T1	2	NO	100%	1	1	T1	1	NO	0%
Unidad Residencial		6	2	T1	3	SI	50%			T1	2	SI	50%	2	2	T1	1	NO	0%			T1	2	SI	50%			T1	1	NO	0%
				T2	3	SI	50%	4	3	T2	1	NO	0%			T2	1	NO	0%	4	3	T2	1	NO	0%	4	4	T2	1	NO	0%
										T3	1	NO	0%									T3	1	NO	0%			T3	1	NO	0%
																												T4	1	NO	0%
Recintos	Living																			1	1	T1	1	NO	0%						
	Living/Comedor	6	1	T1	6	NO	100%							2	2	T1	1	NO	0%	2	1	T1	2	SI	100%	4	2	T1	2	NO	50%
																T2	1	NO	0%									T2	2	NO	50%
	Cocina	6	2	T1	2	SI	33%							2	2	T1	1	NO	0%	2	1	T1	2	SI	100%			T1	1	NO	0%
				T2	4	SI	67%									T2	1	NO	0%							3	3	T2	1	NO	0%
																												T3	1	NO	0%
	Living/Comedor/ Cocina							4	1	T1	4	SI	100%							2	1	T1	2	SI	100%						
	Dormitorios	15	3	T1	3	SI	20%	8	1	T1	8	SI	100%			T1	1	NO	0%			T1	1	NO	0%			T1	1	NO	0%
				T2	6	SI	40%							4	4	T2	1	NO	0%			T2	1	NO	0%	7	4	T2	1	SI	0%
				T3	6	SI	40%									T3	1	NO	0%	9	6	T3	1	NO	0%			T3	3	SI	43%
																T4	1	NO	0%			T4	2	SI	22%			T4	2	NO	0%
																						T5	2	SI	22%						
																						T6	2	SI	22%						
	Baños	12	4	T1	2	NO	17%			T1	2	SI	50%			T1	1	NO	0%			T1	1	NO	0%			T1	2	NO	50%
				T2	2	NO	17%	4	3	T2	1	NO	0%	3	3	T2	1	NO	0%	3	4	T2	1	NO	0%	4	2	T2	2	SI	50%
				T3	4	NO	33%			T3	1	NO	0%			T3	1	NO	0%			T3	2	SI	0%						
				T4	4	NO	33%															T4	2	SI	0%						
	Balcones	10	2	T1	4	NO	40%	4	1	T1	4	NO	100%	2	1	T1	2	NO	100%	4	1	T1	4	NO	100%	5	1	T1	5	NO	100%
				T2	6	NO	60%																								
Promedio de tipos de módulos		2,00						1,57						2,00						2,10						2,25					
Promedio de repetición según tipo de módulo		3,81						2,36						1,06						1,62						1,61					
Promedio de porcentaje de repetición de módulos		50%						36%						6%						29%						19%					

4 Discussion

The analysis conducted in each case study was performed at both the architectural-spatial modulation level and the structural modulation level—specifically regarding walls—taking into account that the design of industrialized buildings requires modular coordination between the dimensions of spaces and the dimensions of structural components (Jensen et al., 2015). In the design process, this coordination is usually established through the use of grid systems for laying out the base design—which define the location and size of structural elements—or by considering maximum distances between structural components (Habraken, 2008). In this regard, it is worth note that in none of the cases studied was the use of a regular grid (i.e., with equal and repetitive measurements in every direction) observed as the basis for defining a standard modulation of spaces and structural elements. In these cases, the configuration and sizing of spaces and walls in general respond to flexible schemes constrained by the distances between supports or the maximum spans that the floor slabs can withstand, as well as the functional width of the rooms. This treats the facade walls as load-bearing walls, so that the location and layout of interior walls on the floor plan become flexible, responding solely to the distribution of interior spaces. Regarding modular standardization at the architectural-spatial level, a variety of applications are observed depending on each case. However, it is important to note that in only two of the buildings (Frauengasse and Holzpassivhause) was a high degree of repetition in modular dimensions observed (Table 3).

With regard to residential units or apartments, a common intention was observed to ensure a diversity of options per typical floor plan, likely driven by the real estate market. In these cases, the highest number of repetitions observed by

module type was 2 (Table 3), most of which were achieved through mirror repetition (axial symmetry). Only two cases without repetitions of residential units were observed: Holz 8 and Hummelkaserne (Table 3).

With regard to vertical circulation modules, various configurations were observed. These correspond to concrete cores arranged in three ways: 1) central; 2) lateral-longitudinal; 3) transverse-intermediate. In cases where they are repeated, they are identical in dimensions but positioned differently.

As for the rooms, the most frequently repeated categories in all cases were common-use spaces such as the living-dining room, kitchen, bedrooms, and balconies (Table 3), with the exception of the Strandparker, where a high pattern of repetition was observed only for balconies. It is important to note that the repeated use of room layouts is more common in lower-rise buildings (Table 5). This appears, first, to be a factor associated with reducing construction costs (since these are residential blocks in lower-income suburbs), and second, it may result from the fact that, as the number of floors increases, spatial and structural standardization (in this case, walls) within a single typical floor plan becomes less relevant to construction, and the focus shifts to repetition across floors. However, it is important to highlight the case of the Hummelkaserne, which was built somewhat more recently (in 2016). In this building, the architectural-spatial design does not follow criteria of repetitive floor plans; instead, the floor plan features a fairly flexible design. This could stem from technological advances in the design and manufacturing processes of these buildings in recent years, which allow for greater diversity at similar costs.

Regarding the structural modulation of walls, the criterion applied in all cases was the two-dimensional configuration of panels (panelization); in none of the buildings were strategies involving volumetric modules (prefabricated three-dimensional elements) applied. As mentioned earlier, one of the current challenges in industrialized construction is to reduce and standardize as many of the required building components as possible, while simultaneously ensuring design autonomy and customization (Viana et al., 2017) (Viklund, 2017) (Kremer, 2018). In this regard, Case 4 (Strandparker) featured a flexible floor plan; however, it also had the second-highest average repetition of wall types (Table 4) (Table 5), leading to the conclusion that, among the cases studied, this one applies the best combination of modularity for mass customization. Based on this, the least efficient cases were Fraunegasse and Holz 8. The former had little design flexibility and a high level of wall repetition, while the latter had total flexibility but very little repetition. However, it is important to note that Holz 8, even though it does not feature a high degree of repetition of wall modules, is eight stories tall (Table 5), which reinforces the evidence of a repetition criterion associated with the number of stories, rather than with the typical floor plan.

Table 4. Modular standardization of interior walls by case. Author's own work

Cantidad de repeticiones por tipo de muro según caso	Tipos de muro interior																	Total de muros	Total de tipos de muro	Promedio de repetición por tipos de muro	Valor de repetición mayor	Cantidad de muros únicos	Porcentaje de muros únicos	Porcentaje de muros con mas de una repetición
Caso 1	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**						56	12	4,67	12	0	0	100%
Frauengasse	6	7	2	2	2	4	4	12	4	4	3	6												
Caso 2	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	33	17	1,94	4	9	27%	73%
Holz Passivhaus	4	4	2	2	1	1	1	4	1	1	2	4	1	1	2	1	1							
Caso 3	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**										10	8	1,25	2	6	60%	40%
Holz 8	1	1	1	2	2	1	1	1																
Caso 4	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	34	17	2,00	6	5	15%	85%
Strandparken	1	1	2	2	1	2	2	2	2	2	2	1	3	1	6	2	2							
Caso 5	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**		22	16	1,38	1	12	55%	45%
Hummelkaserne	1	1	1	1	1	3	2	1	1	3	2	1	1	1	1	1								

Table 5. Summary table. Prepared by the author

	Año de construcción	Cantidad de edificaciones construidas.	Número de pisos	Cantidad de departamentos por edificio	Cantidad de departamentos totales del proyecto.	Cantidad de departamentos por planta tipo.	Condición de financiamiento	Inversión total proyecto (euros)	Costo de inversión por m2 (euros)	Promedio de repetición de recintos	Promedio de repetición de muros interiores
Caso 1 **Frauengasse**	2002	1	4	22	22	6	Subsidiado	2.400.000	1.300	4,08	4,67
Caso 2 **Holz Passivhaus**	2006	6	5	16	70	4	Subsidiado	11.000.000	1.630	3,33	1,94
Caso 3 **Holz 8**	2011	1	8	16	16	2	Privado	2.500.000	1.533	1,08	1,25
Caso 4 **Strandparken**	2014	2	8	31	62	5	Privado	19.670.000	1.982	1,73	2,00
Caso 5 **Hummelkaserne**	2016	4	6	23	92	4	Subsidiado	4.850.000	851	1,92	1,38

5 Conclusion

This research represents a new contribution to the study of modular standardization as a strategy applied to multi-family CLT buildings, with the aim of making their design and construction processes more efficient.

The analysis and comparison of five buildings constructed in Europe between 2002 and 2016 allowed for the derivation of important preliminary conclusions regarding complementary modularity strategies. However, it should be noted that the methodology implemented needs to be applied to a larger number of cases to achieve more conclusive results.

Furthermore, it should be noted that all the case studies implemented structural modularity through panelization (repeated two-dimensional structural elements) and did not use volumetric modules (prefabricated three-dimensional elements), in which the use of architectural-spatial and structural standardization strategies can pose greater design challenges.

First, the research made it possible to establish an initial distinction between architectural-spatial standardization—as a strategy for achieving efficient levels of coordination between design and manufacturing—and construction standardization—as a strategy for achieving more efficient levels of fabrication and assembly. In this regard, the study reveals the relationships between these two strategies, in terms of optimizing the design process for manufacturing and assembly during the construction of the buildings under study.

In the cases studied, a partial difference was observed between the design of the earliest buildings constructed—which exhibit greater architectural-spatial and construction standardization—and the more recently constructed buildings, which feature more flexible and customized designs with lower levels of construction standardization (Table 3), (Table 4), and (Table 5). This may indicate an evolution in the design and construction processes of these buildings over a short period of time, which can be attributed to advances in virtual design (VD) and BIM, as well as to the evolution of CLT as a construction technology. These factors have enabled more efficient coordination between design and manufacturing platforms.

In the design of the older cases, such as the Frauengasse and Holz Passivehause residences—built with public funding in 2002 and 2004, respectively—a high degree of architectural and spatial repetition is observed (Table 5). This demonstrates the use of simultaneous standardization criteria—both at the architectural-spatial level and at the construction level—aimed at optimizing industrialization processes, but which limit variations in housing design.

On the other hand, in more recently constructed buildings, there is less standardization—both architectural-spatial and structural—at the typical-floor level, which indicates a shift in criteria and strategies toward more flexible architectural

designs and manufacturing processes. In this regard, it is worth noting that in buildings with a greater number of floors, there is a decrease in architectural-spatial and construction standardization per typical floor plan, indicating a preference for repeating construction components by floor rather than by floor plan. This allows for a greater degree of flexibility in the architectural design of the typical floor plan, while maintaining construction standardization as a criterion for optimizing manufacturing and assembly processes. However, it is important to note that the Hummelkaserne residences, built in 2016, despite being low-rise, feature a high degree of flexibility in their floor plan design, likely coupled with reduced construction costs compared to the other cases studied. This demonstrates progress in the efficiency achieved in the construction of these building typologies in Europe in recent years.

Another relevant aspect observed in all the cases studied—regardless of the level of floor plan flexibility or the year of construction—is the high degree of standardization of balconies. This reveals the architectural integration of spaces that connect with the outdoors.

Finally, it is important to note that numerous studies have shown that standardization remains an efficient strategy for reducing project delivery times (including design) and optimizing manufacturing processes (Smith, 2016; Shafiee et al., 2020b). Therefore, even though the latest technological advances aim to achieve a high degree of flexibility in both the design and manufacturing processes of the buildings under study, the application of modular construction standardization criteria can be an effective strategy for reducing both costs and waste. However, this latter aspect was not included within the scope of this research; therefore, it would be important to consider it in future studies.

Based on the above, the use of construction standardization strategies that ensure acceptable levels of design customization could be an alternative for achieving more economical and sustainable solutions with high real estate potential.

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Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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