Classification of Wooden Housing Building Systems

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Wooden housing is one of the most sustainable building alternatives. In many European and North American countries, wooden houses provide the most common, economical, and practical solution for construction. The timber buildings present adequate levels of durability, acoustics, and thermal comforts. Despite their popularity, wood houses do not have a standardized classification to define and organize their main aspects. In literature dealing with timber construction, most authors emphasize structural systems for large spans (bridges, hangars, roofs, *etc*.). The presence of some classifications of timber construction results in unclear issues, and few studies have covered and regarded wooden buildings as residential construction typologies. Accordingly, this paper proposes a classification that connects the aspects and details of wooden housing materials in relation to the industrialization level and chronological origin. We expect this classification to assist in a better understanding of distinct wooden housing techniques commercially produced worldwide, diffusing their concepts and possibilities as forestry-timber products.

Keywords: Classification; Wooden typologies; Timber; Residential building; Construction; Forest product

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INTRODUCTION

Wood is one of the most abundant construction raw materials because of its wide availability in nature and relative ease of handling (Pfeil and Pfeil 2003; Radkau 2011). It is a modern material (Fengel and Wegener 1983) owing to its environmental friendliness (Asif 2009), as well as an extensive range of end-uses (Eaton and Hale 1993).

Additionally, wood has a solidified position in various stages of the construction process (Oliveira and Hellmeister 1998). Timber is biodegradable, renewable, and recyclable, and the expansion of responsibly managed forests is ideal both socially and environmentally (IKEA 2014). Wooden products tend to have a timely environmental profile compared with other equivalent products based on different materials (Werner and Richter 2007), *e.g.*, wood-frame buildings have substantially lower life cycle carbon emissions than concrete-frame buildings (Dodoo *et al*. 2009). These versatilities are the result of the material's wide product range, as it can be used either directly in the building structure or as components of other subsystems, such as flooring, roofing, facings, and façades. Commercially, wood for construction can be found as solid and reconstituted.

Solid woods are prepared in various shapes, with options including round log, hewn, sawn, and machined products (Pfeil and Pfeil 2003), necessitating a large range of processing levels – low to high – depending on the specific product dimensions (Zenid 2009).

Reconstituted wood includes composites manufactured and classified by their respective uses, typically categorized into two groups, listed below:

a) Structural: plywoods (marine and aircraft ply), glued laminated timber (Glulam), cross-laminated timber (CLT), particleboards (OSB and waferboard), structural composite lumber of wooden veneers (LVL) or strands (LSL, OSL and PSL), *etc*.;

b) Non-structural: fiberboards (MDF and HDF), particleboards (MDP and HDP), mineral fiberboards (wood-cement panels), *etc*.

For most countries in the Northern Hemisphere, wooden houses are the most common, economical, and practical housing solution. According to Marcin (1987), wood-based products dominate housing construction in the United States. Approximately 80 million single-family houses in the U.S. are predominantly built using wood-frame (Kirkham *et al*. 2013). Residential construction consumes about 26% of the total wood harvest in the U.S., revealing its great role in the forestry products value chain (Wherry and Buehlmann 2014). More than 40% of social housing in the United Kingdom is built using timber framing, which is also gaining popularity in Ireland and France (Lavoie 2008).

Construction Systems Made with Wood and its Composites

A construction system can be regarded as a process that has high levels of industrialization and organization, and is composed of a set of elements and components which interrelate and integrate the process (Sabbatini 1989). San Martin (1999) remarks that the construction system is a set of elements and actors that interact in the production function, integrating each element when constructing a building. Wood housing systems incorporate techniques that materially use structural timber parts (Table 1 and Fig. 1).

Table 1. Wooden Housing Techniques and their Relative Terms in Portuguese

English Terms			Portuguese Terms
	Hut or *Mocambo*	*Mucambo*, *Tejupar*, or *Palhoça*	
	Rammed Earth	*Taipa de Pilão*	
	Wattle and Daub	*Taipa de Sopapo* or *Pau a Pique*	
	Half-timbered Frame	*Enxaimel* or *Columbagem*	
	Laft hus (Scandinavian former log house)	*Casa Primitiva de Toras Escandinava*	
	Log-cabin (American former log house)	*Casa Primitiva de Toras Norte-Americana*	
	Log-homes	*Casa de Toras*	
	Clapboard and Wainscot	*Tábua e Mata-junta* or *Tábua e Ripa*	
	Double Wall of Nailed Clapboards	*Parede Dupla de Tábuas Pregadas*	
	Horizontal Clapboards Between Studs	*Tábuas Horizontais entre Montantes*	
	Timberframe or Post-and-beam	*Entramado Pesado* or *Pilar-viga*	
	Woodframe (Balloon or Platform)	*Entramado Leve (Balão* or *Plataforma)*	
	Mobile and Modular Homes	*Casas Móveis* and *Casas Modulares*	
	Nautical Houses	*Casas Náuticas*	
	Houses on Wheels	*Casas sobre Rodas*	

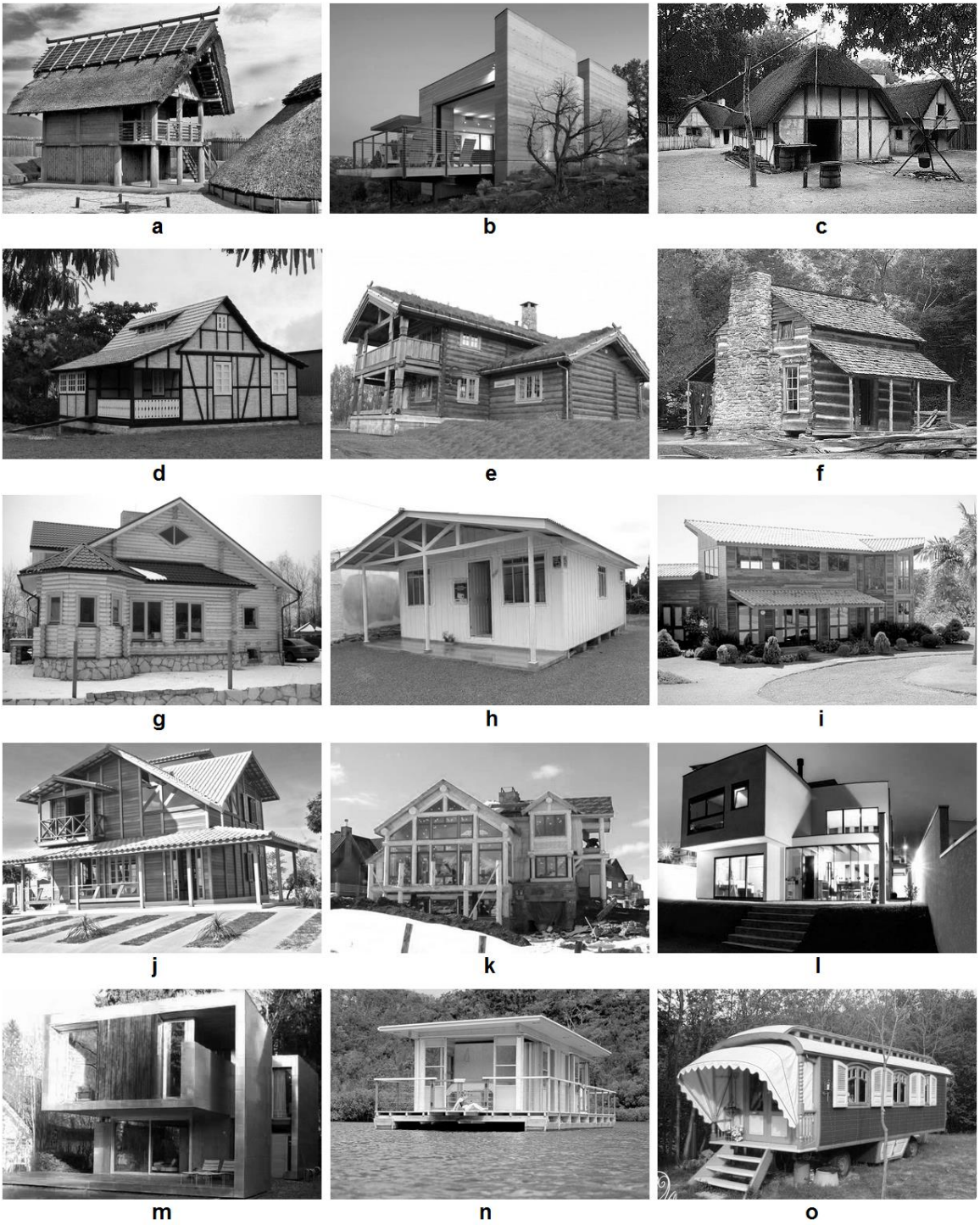

Fig. 1. Wooden housing techniques: (a) hut in *mocambo* hut (Adams 2005), (b) house in rammed earth (Construction Zone 2008), (c) wattle and daub home (Rowan 2012), (d) half-timbered frame (Volles 2011), (e) *laft hus* (Tinnoset Bygg og Laft 2004), (f) log cabin (Farkas 2011), (g) log home (Gratia Grupa 2005), (h) clapboard and wainscot home (Itacasas 2014), (i) double walls of nailed clapboards (Casas Condor 2010), (j) house in horizontal clapboards between studs (Brasil Casas 2012), (k) post-and-beam house (Canada's Log People Inc. 1999), (l) woodframe in platform type (Tecverde 2016), (m) modular home prefabricated with cross laminated timber (Cagnon and Pirvu 2011), (n) houseboat (Boardman 2011), and (o) house on wheels (Burke 2013).

Therefore, a housing system that utilizes lignocellulosic material coincides with any building process that integrates, with consistency and balance, one or more sets of structural elements and/or subsystems made with wood, bamboo, natural fibers, and/or industrialized composites. Thus, the paper describes the state of the art of wooden houses.

The term hut or *mocambo* corresponds to a rudimentary shelter formed by a frame of bamboo culms or wood logs filled by bamboo, bushes, straw, or by any combination of the aforementioned materials. A hut has a roof made of straw, bushes, thatch, *etc*. From Indigenous and African influences (Freyre 2006), ancient huts have been found in Africa, Asia, and America, with wood structures up to or exceeding 10-meter spans (Kahn 1973).

Rammed earth is formed by tamping clay mortar into molds, with the structural reinforcements and roof frame built with wood. Encyclopedia Britannica (2014) clarifies rammed earth is based on the compacting of certain soils, which is rammed into a box-shaped mold, where two wooden planks are separated by a spacer bolt. The soil is then rammed into these individual layers, respectively. Humid soil is distributed into the molds, not exceeding 7 cm per layer, tamping the soil to 30 cm tall (Viñuales 2007).

Wattle and daub is a term used to denote a house with structural frames made of wood and bamboo, which are manually filled with a mixture of mud, manure, straw, and sand. Graham (2004) states that their stems originate from primitive buildings, where earth walling could be used as a base for the roof (relatively easily), or higher walls could be formed to raise the roof away from the ground. These structures include bamboo or wood frames, usually arranged in two directions (horizontal and vertical, or cross-braced) between the floors, creating an independent structure (Viñuales 2007). They still are found in the Amazon (Figueiredo *et al*. 1999) and Kenya (Fleischer and Laviolette 1999).

A half-timbered frame or *colombage* denotes a house formed with a massive wooden frame, which is filled with masonry, bricks, adobe, or rocks. Its origin can be traced to the border region between France and Germany. Tosolini (2008) highlights that *colombage* is widely used in the vernacular rural building. Furthermore, the vertical and horizontal wooden elements are limited to the upper part of the facade. A half-timbered frame is made with vertically squared timbers, normally braced, and the spaces between the parts are filled with various materials (Kniffen and Glassie 1966).

Laft is a Scandinavian housing technique made with wooden logs, using joints for the wall corners (Mello 2007). Their logs are cut so that they can be laid horizontally on top of each other and notched into walls (Clementz and Flatland 2008). *Laft hus* (or *laft* house) is simple and quick to build; however, there is a risk of draughts and leakage, which can be reduced by sealing the wooden logs with hemp and tar (Bonde *et al.* 2014).

Log-cabins are typically North American homes made with wood logs – similar to the Northern European *laft* – which utilize round- or rough-hewn wood. Neufert and Neff (2013) stated the former method of housing is produced by craft practices with solid timber. These timbers are notched at the ends, making each member immovable when locked to the timbers above and below (Kniffen and Glassie 1966). Rowell *et al*. (1977) adds that such structures can be built with green logs, but there are some limitations when using small logs. Wooden log walling gaps are filled with chips and mud (Pollio 1914).

Log-home is most often manufactured using industrialized wooden logs, with the prefabrication of elements and log machining/turning. Kretschmann (2010) states the logs are formed in a variety of shapes for log-homes, *e.g.*, vertical surfaces may be varied for aesthetic purposes, while horizontal surfaces generally reflect structural and thermal considerations. Machined logs or planks overlap are structurally interconnected by joints or grooves (Neufert and Neff 2013). Log-home is very popular in Northern Hemisphere.

Clapboard and wainscot are terms used to describe a house composed of vertical walls of spaced wood clapboards. Additionally, the spaces between each board are sealed with wooden thin slats. According to Berriel (2009), the structures of clapboard and wainscot are freestanding, and the structure is formed by the top and bottom frames, which are interconnected through studs joined to the roof structure and the additional structures, such as the horizontal fencing (floors and ceilings) and vertical (boards and wainscot) to seal the joints. The structure is characterized by the vertical outdoor texture of the walls, frequently manufactured using Pine (Imaguire Junior and Imaguire 2011). This Slavic timber typology is popular in the Southern and Southeastern Brazilian states.

Double walls of nailed clapboards are formed by a very simple sandwich wall, with two coverings of clapboards nailed in a compact frame of sawn wood. Frequent in Brazil, external clapboards are usually horizontally oriented, and the internal coverage is vertically disposed, ensuring a different finish for these surfaces. An inverse orientation is also possible, despite an ineffective use of the raw material, *i.e.*, wooden clapboards.

Horizontal clapboards between studs typology refers to wooden housing produced with horizontal clapboards joined together with tongue and groove joints, and stabilized laterally by notched studs. Popular in Brazil, this technique has been widely used in wood houses for higher income people, especially as a second option for beachside homes, cabins, cottages, and chalets (Cesar 2002). Usually produced in kits, this typology has self-dockable parts made with green wood, whose freestanding walls suffer adjustments along the assembly and dwelling, *i.e.*, in its initial period of occupation (Casema 1998).

Timberframe results in houses with robust frames made with blocks of wood and no-freestanding sealing, *e.g.*, post-and-beam or –lintel, and stick-frames. Benson (1997) defines timberframe as a self-supporting timber structure fixed with connections between wooden elements, with the structural framework set at its basis. Worldwide, a traditional timberframe is made of large sawn timbers connected to one another by hand-fabricated joints (*e.g.*, mortise-and-tenon), typically involving sophisticated joinery (Wacker 2010).

Woodframe houses can be divided into two construction types based on their wall framing: platform and balloon-frame (Anderson 1975). These two woodframe styles are distinguished from timberframe building by their use of lightweight, thin, factory-milled lumber, and simply cut with nailed connections. Proper lumber manufacturing requires compact crews, a minimally-skilled workforce, and rudimentary tools (Lanier and Herman 1997). Balloon-frame is a type of wooden light-frame, formed by skeletons made of long pieces of timber, and sealed with robust freestanding wooden panels. According to Anderson (1975), balloon-frames have studs that extend from the sill of the first floor to the top plate or the second-floor rafter, whereas the platform-framed wall is complete for each floor. The platform-frame is the modern and rationalized evolution of balloon. American Wood Council (2001) adds that its first floor wood beams are entirely covered, forming a platform upon which the exterior and interior walls are erected. Thallon (2008) state the platform is the most popular housing system in use today in North America.

Mobile-home or modular-home units are transportable houses manufactured in wooden structural modules, based on timber techniques of "sandwiched" or panelized (CLT boards) framing. Gutierrez (2008) indicates these systems are derived from trailers, specifically those with larger dimensions for the purpose of permanent housing, and this term refers to housing units manufactured in industrial plants, transported, and installed anywhere. The panels are produced off-site, using the platform frame system, and then assembled on site. Such panels are sized on the basis of the standard board size and are employed to build various space combinations (Marchesi and Ferrarato 2015).

Nautical houses consist of floating houses in wood and panels, such as yachts and houseboats. According to Parry (2000), some houseboats are not motorized because they are usually moored, kept stationary at a fixed point, and often tethered to land to provide utilities. In contrast, many nautical houses are capable of operation under their own power. Houseboats are popular in Netherlands, Germany, and France (Loois *et al*. 1994).

Houses on wheels are vehicular homes very popular in North America, used for housing and/or recreation. They are typically made with wood and panels, such as trucks, trailers, and motorhomes. Eure (2005) states most motorhomes are designed for a body inserted in a bus platform (bus chassis), whose bodies are structurally made of wood, aluminum, or a combination of both, featuring wood trim, and upgraded carpet and tile.

Classifications of Housing Systems Incorporating Lignocellulosic Materials

The topic of wood building systems is a relevant subject for construction literature because of the presence of different classifications, each with its own particular approach. Due to several disconnected classifications and/or the lack of a standard order for wooden housing, a nebulous situation has been observed in the countries where, culturally, the utilization of timber in building elements is more accepted and/or popular. In this atypical scenario, a single standard still does not necessarily apply to all wooden houses, nor does classify these typologies. For that reason, different classifications vary according to the origins over time or particular aspects, a fact that creates some confusion among readers. Moreover, many authors treat wooden houses as only a subject of the theme "timber structures," generating some imprecision with incomplete and generalist approaches.

Meyer-Bohe (1969) adopted criteria based on four wood prefabrication methods:

a) Building with frames or skeletons: formed by a freestanding frame, braced by diagonals, and sealed in massive or double layers;

b) Building with composites: bearing wall formed by sandwich or composite boards;

c) Building with massive boards: freestanding massive walls, prefabricated in two-dimensional walls, and assembled with cranes or hydraulic jacks;

d) Building with three-dimensional parts: complete volumetric parts, with low mounting (*e.g.*, mobile-homes), assembled with derricks or large cranes.

Many directions can be followed in this subject. Teixeira-Trigo (1978) proposed, in a synthetic manner, four criteria which classify the building solutions (Table 2).

Table 2. Criteria to Classify Building Solutions According their Possibilities

Criteria		Examples
I	Industrialization level, in ascending order	Primitive building; Handmade traditional building; Rationalized traditional building; Performed with industrialized forms
II	Wall materials, in view of the representative volume inside the construction	Wood; Stone; Brick; Concrete block; Others
III	Typology of freestanding structure, with emphasis in the structural system	Reticulated structure; Wall structure
IV	Weight of structural material, both materials used in structure and in sealing	Heavy construction; Semi-lightweight construction; Lightweight construction

Adapted from Teixeira Trigo (1978)

From a production standpoint, the wood used for a building in criterion "I" can be classified into any of the mentioned cases. Thus, Teixeira Trigo (1978) complemented such a scheme with another general classification based on criteria "III" and "IV", directed to heavy construction from:

a) Heavy systems with reticulated structures: structures manufactured on site, lifting systems, and prefabricated structures;

b) Heavy systems with a wall structure: resistant masonry, structures manufactured on site, heavy prefabricated panels, prefabricated boxes;

c) Solutions mixed of heavy construction;

d) Lightweight systems.

This classification is restricted to heavy structures, a fact that demonstrates the low application and importance of wood to the construction industry in the 1970s.

Morgado *et al.* (2012) defined wooden structural systems *via* element geometries such as linear components, flat components, three-dimensional components, and mixed.

In a parallel view, Mello (2007) redefined construction system classification, with regard to time, arranging the wooden techniques into two categories:

a) Traditional techniques, consisting of old techniques;

b) Contemporary techniques, consisting of recent techniques.

For this chronological classification, the traditional techniques are defined as the methods of construction which have existed since the dawn of humanity, up to the period prior to industrialization of wooden elements (parts) and components for buildings. In turn, contemporary techniques are those that emerged during the industrial period up to the present. Then, the use of wood composites and prefabricated parts is its dividing line.

In another argument line, Pozo (1984) proposed a classification of wooden houses focusing on two aspects of manufacturing: on-site and industrial production. In this case, the manufacture of wooden constructions is defined using the following systems:

a) Vernacular: industrialization entirely absent, with the manufacturing of all wood-based elements and components on the construction site;

b) Semi-precut: reduced industrial level, without the use of wooden panels and with a strong amount of onsite work;

c) Pre-cut: industrial activity based on the prefabrication of wooden elements for the assembly of finished parts on site;

d) Prefabrication of panels and components: high industrial level, with the use of wooden panels and beams and pre-assembled components (arches, trellises, *etc*.);

e) Volumetric prefabrication: full industrial level, where the construction site receives the finished modules to their final merger.

Wooden housing classification reflects a tortuous theme of literature, considering many criteria, and analyzing different aspects from many authors. Each author identifies and proposes his own classification, based on specific theories; however, they are somewhat inclusive. For these classifications, a building system can be classified by more than one genre or attribute.

Accordingly, this study is formed by two parts: the state of the art about the wooden housing techniques commercially produced worldwide, and the proposal of the standardized classification to cover and enclose the main aspects analyzed in this particular topic, *i.e.*, manufacturing level and chronological origin.

A PROPOSED CLASSIFICATION OF WOODEN HOUSING SYSTEMS

Wooden housing can be mixed with other materials or integrally produced with timber parts and elements. This second style is composed by a house with all parts and rooms, excluding finishing and details, in wood and its composites. In turn, a mixed one is structurally made with wood, but it can present other materials in wall finishing (metal, plastic, and bricks) and some rooms (toilet, laundry, and kitchen) in masonry, adobe, *etc*. Whilst a log-home is fully made in timber, woodframe styles use plaster in internal walls.

Then, in an effort to overcome the incomplete aspects of the previously published classifications, this research considers a combined approach based on a synthesis of two principles used in other studies. The synthesis is based on a comprehensive survey of the wooden housing systems. After scouring the world literature (*e.g.*, books, journal articles, scientific papers, technical reports, government documents, and producers' websites), the wooden housing systems and their main characteristics have been defined in this paper, to assist in their distinction and classification. From the collected data, we observed there is a lack of standardization for the classifications of wooden residential techniques. Thus, there is a need to create a standard classification of the residential systems in wood, which is used to cover all existing typologies, emphasizing its more evident identities.

The design of the proposed classification addresses interconnected parameters, reflecting a precise definition for future evaluations of wooden housing techniques. Through the principles set forth by Mello (2007), wooden systems are defined based on their chronological origins, *i.e.*, traditional or contemporary. Simultaneously, the building classification considers its industrialization level, *i.e.*, the intensities of on-site or industry work, based on the concepts of Pozo (1984). Here, it is proposed to combine aspects of these two approaches. Figure 2 shows the chart of the full classification of timber houses.

In Fig. 2, the dashed line indicates the system is semi-industrialized, meaning the system has some industrialization phases in milling plants; however, the classification also depends on the demand of work made on site, featured in a mixed system.

The solid line (continuous line) reflects only one type of production system, solely referenced by the levels of on-site production (handicraft) or total industrialization, according to its origin. Despite the complexity of the presented diagram, its intention is to obtain a broader coverage of many existent construction systems, structurally produced with timber and/or its structural composites (wood-based boards and beams). Apart from the modular-home typology, woodframe platform and the nautical houses are modern ways to obtain an industrialized home. Nevertheless, the latter two techniques can also offer a possibility of craft on site production.

The most important point about the creation of this classification is related to the standardization of the technical terms for the wooden housing typologies. The goal is to avoid misconceptions concerning the identification of these wood-based construction systems, as well as to circumvent misunderstandings about the characteristics of each timber housing technique (Fig. 1).

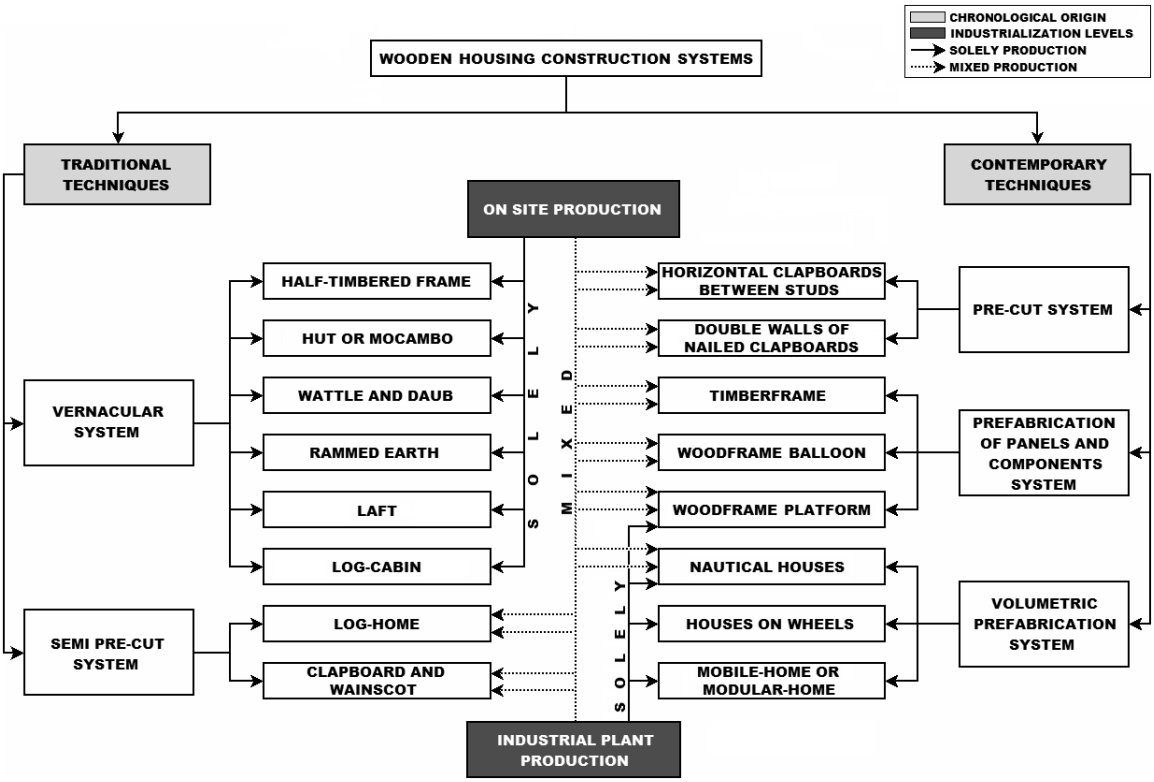

Fig. 2. Classification of housing construction systems made with wood and/or its composites

This tool provides clarity to easily identify and compare all the wooden housing systems for professionals from forestry-timber and construction chains, *e.g.*, engineers, technicians, suppliers, manufacturers, and entrepreneurs, as well as readers, academics, researchers, professors, students, and customers. The proposed classification (Fig. 2) and the standardization of the terms in the English and Portuguese languages for each wooden typology (Table 1) is intended to mitigate any miscomprehension about the topic.

In the scientific circles, the technical descriptions aim to bring order to this topic, enabling everyone to study, compare, and quote similar examples with a common term, *i.e.*, standardized, contributing to a better understanding by the authors and readers.

For the corporate ambit, when wooden housing advertising is created by their manufacturers, it is central that all the professionals use the same language, because an accepted and usual standard is still nonexistent.

In the market scope, a unified list is important because the consumers would be able to know and compare the existent techniques according to the following aspects:

a) Industrialization levels: clients could check the production levels, ranging from artisanal (handicraft) to industrial practices, ordering them according to assembly speed and type, raw material rationalization and utilization, costs, *etc.*;

f) Chronology: clients could verify the typological housing system according to its characteristic in time, *i.e.*, from the antique to modern styles.

Finally, there are spaces for more wooden housing ordinations, for example, by other different viewpoints or parameters such as structural aspects, architectural styles, sustainability grades, ranges of cost, categories of weight, timber volume and species, *etc*.

Furthermore, other wooden construction systems could also be inserted in the future, whereas newer wood-based typologies are created, modified, or refined, and/or recent prototype techniques achieve good levels of popularity worldwide.

CONCLUSIONS

1. The proposed classification, which groups the most popular wooden housing building systems, aims to assist in the distinction and reordering among existent techniques. Thus, this study standardizes (in a single diagram) the commercially available wood-based housing techniques in regards to vernacular, traditional, and contemporary characters. Moreover, we expect this arrangement can facilitate in the understanding and the distinguishing all the building techniques made with wood for dwelling.
2. Before this study, there was a lack of standardization in the industry and literature, resulting in an imprecise interpretation of building techniques, because many systems were not mentioned or were treated in a general way, thus reports did not address building details which differentiate them from each other. Hence, this proposed classification focuses on the creation of a selection standard, which is more comprehensive and thorough in grouping of houses commercially made with wood and/or its composites.
3. This diagram could serve as a global reference, using established parameters and guidelines, allowing the forestry-timber and construction industries to advance with industrialization and technological innovation of forestry products, through the range of available models in all the countries.

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