

Chapter 2

A New Taxonomic Perspective on Wood-Based Technologies for the Transformation of the AEC Sector



Abstract The transformation of the built environment requests specific considerations in the definition of construction strategies. Under the technological perspective, the major requirements are lightness and efficiency, intended as the minimization of the impact over the existing building, along with the maximization of the building performances and overall value. To find suitable solutions, this chapter investigates wood as a construction material. At first, it defines the domain of the timber construction industry, by addressing the state of the art on wood innovations, between processes and products, according to the literature review and the outcomes from the interviews with international stakeholders. Afterward, it describes the taxonomic approach as a method to characterize building systems, proposing a revision of the current classification approach and the introduction of a creative taxonomy of timber-based construction systems. Finally, this taxonomy review is used to structure the final case-history survey upon timber construction strategies for building transformation, whose methodology and results are presented accordingly.

Keywords Wood-based construction materials · Wood-based construction technologies · Timber construction systems taxonomy · Wood innovation

2.1 Wood as a Construction Material: Innovations Within Processes and Products

Wood is one of the oldest materials for constructions [1, 2]. Its availability and the ease of processing in manufacturing have allowed over time the diffusion of a multitude of varied construction techniques on a global scale: from the northern European *Blockbau* and *Fachwerkbau*—respectively the fathers of the Canadian log system and the American Balloon Frame—to the Japanese joinery crafts, which—e.g.—still marvelously define the solid structure of the Horyu-Ji five-stories pagoda, the oldest wooden building of the world [3].

Today, the continuous innovations of the research in material sciences [4, 5], prefabricated products and technological solutions, and automated production

This chapter is authored by Federica Brunone.

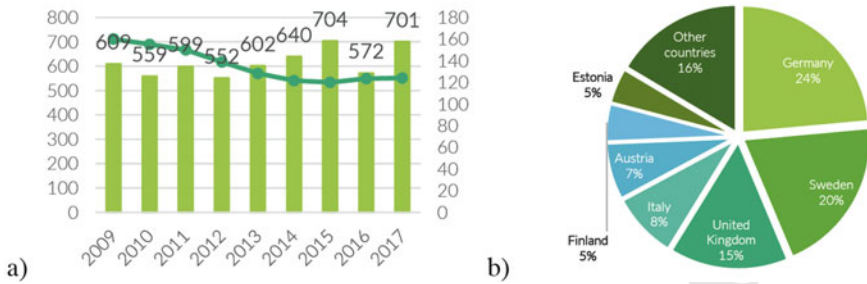


Fig. 2.1 a Historical trend of the Italian building production: comparison between the investments in the construction sector (dark line) and the annual production trends of timber buildings (bar chart); values in millions [€]. b Timber building production by 2017. *Source* Author's elaboration based on statistical data by Prodcum, Ance, Eurostat, and Istat, as retrieved from [7, 8]

processes [6] let the wood construction industry experience a strong growth. It is attested by the values of the market trends: Italian data showed a production stability until 2014 despite the overall contraction of the construction sector [7], and a progressive increasing from 2016 accordingly to the economic recovery of the market [8] (Fig. 1a). On a European level (Fig. 1b), timber buildings registered +5.9% of production [8] by 2017, following the positive trends of the recent past years.

Timber is fascinating the decision-makers of the building process, especially since sustainability has become one of the major drivers crossing multiple aspects of our lives: wood as a construction material has been already attested to have a positive impact on the environment, thanks to the low embodied energy and carbon storage (Table 2.1) [9, 10], and considering the increasing adoption of the certification systems that attest a sustainable forestry management [11–13].

Wood has just become once again a total material for constructions, with applications in structures and envelopes, even in those areas where other materials had prevailed since the end of the XVIII century.

2.1.1 Wood Dimensions

Wood a hard substance that forms the branches and trunks of trees and can be used as a building material [14].

Timber trees that are grown so that the wood from them can be used for building; wood used for building [15]; uncut trees or logs that are suitable for conversion to lumber; wood sawn into balks, battens, boards, etc., suitable for use in carpentry, joinery and general construction [16].

Lumber Timber sawed or split in the forms of beams, boards, joists, planks, etc. [17].

Table 2.1 Embodied energy and carbon storage inventory data of the most common construction materials.

Construction material	Embodied energy (MJ/kg)	Carbon storage (kgC/kg)
Steel	24.40	0.482
Concrete	0.95	0.035
Portland cement	4.60	0.226
Bricks	3.00	0.060
Timber	8.50	0.125
Glue-laminated timber	12.00	–
Hardboard	16.00	0.234
MDF	11.00	0.161
Particleboards	9.50	0.139
Plywood	15.00	0.221
Sawn hardwood	7.80	0.128
Sawn softwood	7.40	0.123
Veneer particleboard	23.00	0.338

Source Data extracted from [9]

“Wood”, “timber”, and “lumber” are the first three keywords to enter the multi-dimensional world of this material, even if just limited to construction applications. Only by their definitions, these terms introduce already a set of other tags, that go beyond a pure semantic matter. Wood, per se or within the expressions “wooden buildings”, “wood-based technologies”, “timber products”, etc., actually implies a complexity that is identifiable already in the material essence.

2.1.1.1 Wood Materials

Despite a similar constitutive structure which outlines the main physical and mechanical features of this material (both already widely analyzed in the technical literature [2, 18–21]), wood is represented by a diversified spectrum of different species, commonly divided into soft (gymnosperm) and hard (angiosperm and monocotyledons) wood, whose specific characteristics and properties define their applications within the building sector, by addressing specific requirements. Different species mean, indeed, different features in terms of natural durability and treatability, such as gluing and manufacturing and implying, therefore, different uses.

Cedar, Cypress, Douglas-fir, Inoki, Larch, Pine, Spruce, Sugi, and Yew; Birch, Cherry, Chestnut, Iroko, Locust, Mahogany Maple, Oak, Teak, Walnut, and Bamboo are only a few of the numerous existing essences used nowadays in the building sector, from the most common practices in constructions and furniture, to the advanced



Fig. 2.2 Wood species for construction uses. *Source* Author's elaboration on illustrations retrieved from [19]

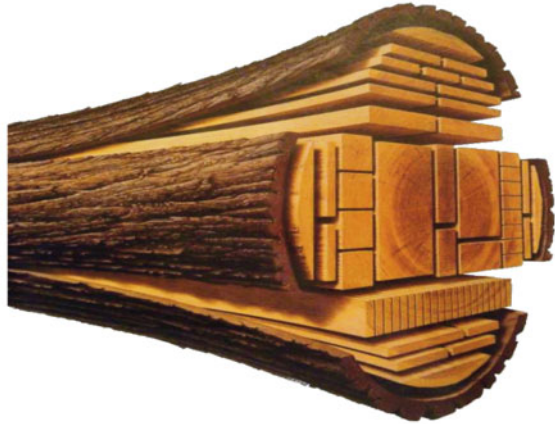
71 experimentations of design, technology, and research. In particular, for structural
72 and construction purposes [19], the main wood species (Fig. 2.2) are:

- 73 • Spruce (density [$u = 15\%$] = 450–470 kg/m³), mainly applied as solid wood in
74 framed structures or within glued-laminated products for big slender constructions
75 or massive planar products;
- 76 • Pine (density [$u = 15\%$] = 520 kg/m³), used for structural elements, carpentry,
77 and derived products (engineered timber);
- 78 • Larch (density [$u = 15\%$] = 600 kg/m³), thanks to its natural durability and varying
79 texture that progressively change color according to the outdoor exposition, is used
80 frequently for finishing layers of structural elements as well as envelopes;
- 81 • Douglas-fir (density [$u = 15\%$] = 510 kg/m³), for indoor and outdoor finishing
82 and fixtures;
- 83 • Beech (density [$u = 15\%$] = 720 kg/m³), mainly used for engineered timber
84 (layered or cross-layered of veneers, strands, or fibers);
- 85 • Oak or Durmast (density [$u = 15\%$] = 690 kg/m³), used for structural elements
86 installed on-site with high levels of exposition class for durability.
- 87 • Ash (density [$u = 15\%$] = 690 kg/m³), Locus (density [$u = 15\%$] = 770 kg/m³),
88 and Chestnut (density [$u = 15\%$] = 630 kg/m³), used for indoor or outdoor
89 finishing layers, thanks to its high natural durability and resistance to fungal
90 attacks.

91 2.1.1.2 Wood Innovation

92 Besides a complexity of multiple essences within the same construction mate-
93 rial, another taxonomic dimension derives from the innovation of the industrial
94 manufacturing processes and the resulting definition of multiple derived materials
95 and products [22–25]—such as the engineered or the recycled wood—defined to
96 overcome most of the limitations of traditional solid wood: bound dimensions,
97 defects, sensitivity to biologic attacks, anisotropic mechanical behavior, and waste
98 management.

Fig. 2.3 The processing of logs into sawn timber, whose elements present different sections to optimize the use of wood and minimize wasting. *Source* Author's elaboration from [26]



99 From the '70s, indeed, the introduction of the finger-joints [22] realized through
 100 CNC—based machines [24] has given the possibility to work with different sizes
 101 of timber sections derived from the parceling of the trunk (Fig. 2.3), by connecting
 102 them to recreate bigger and/or stratified elements.

103 This has allowed the innovation of the industrial production in multiple directions:

- 104 • The log parceling optimizes material use, by processing also those marginal parts
 105 of the trunk previously discharged because of quality lack;
- 106 • The following selection of wood elements allows both avoiding macroscopic
 107 defects by the cut-off of localized faulty parts, and choosing different essence to
 108 optimize mechanical and/or durability properties;
- 109 • The connection of elements lets to overcome the geometrical limitations of solid
 110 wood, due to the restricted dimensions of logs;
- 111 • And, finally, the definition of a wide range of products which populate the
 112 construction market nowadays (Fig. 2.4).

113 Indeed, the finger-joint has been applied, at first, to solid square wood, planned
 114 to size, dried, and recombined with similar pieces, in order to obtain the so-
 115 called KVH (*KonstruktionsVollHolz*) or Finger-jointed solid timber, long beams with
 116 standardized sections [29].

117 Furthermore, the use of finger-joints together with the lamination and gluing
 118 processes has led to the production of glue-laminated timber elements, winning the
 119 challenge of building big-spans structures with wood-based products, still unfea-
 120 sible with traditional solid wood beams. Moreover, by curving the laminates before
 121 the layering and gluing processes, almost all the geometrical boundaries of wood
 122 have been removed and the material has gained the possibility to be applied for
 123 the shapes of contemporary architectures, previously reserved only to concrete (by
 124 forms pouring) or steel (by forms extrusion) [24]. Glue-laminated timber is actually
 125 acknowledged as a specific wood-based construction material, with its own physical
 126 and mechanical properties [30].

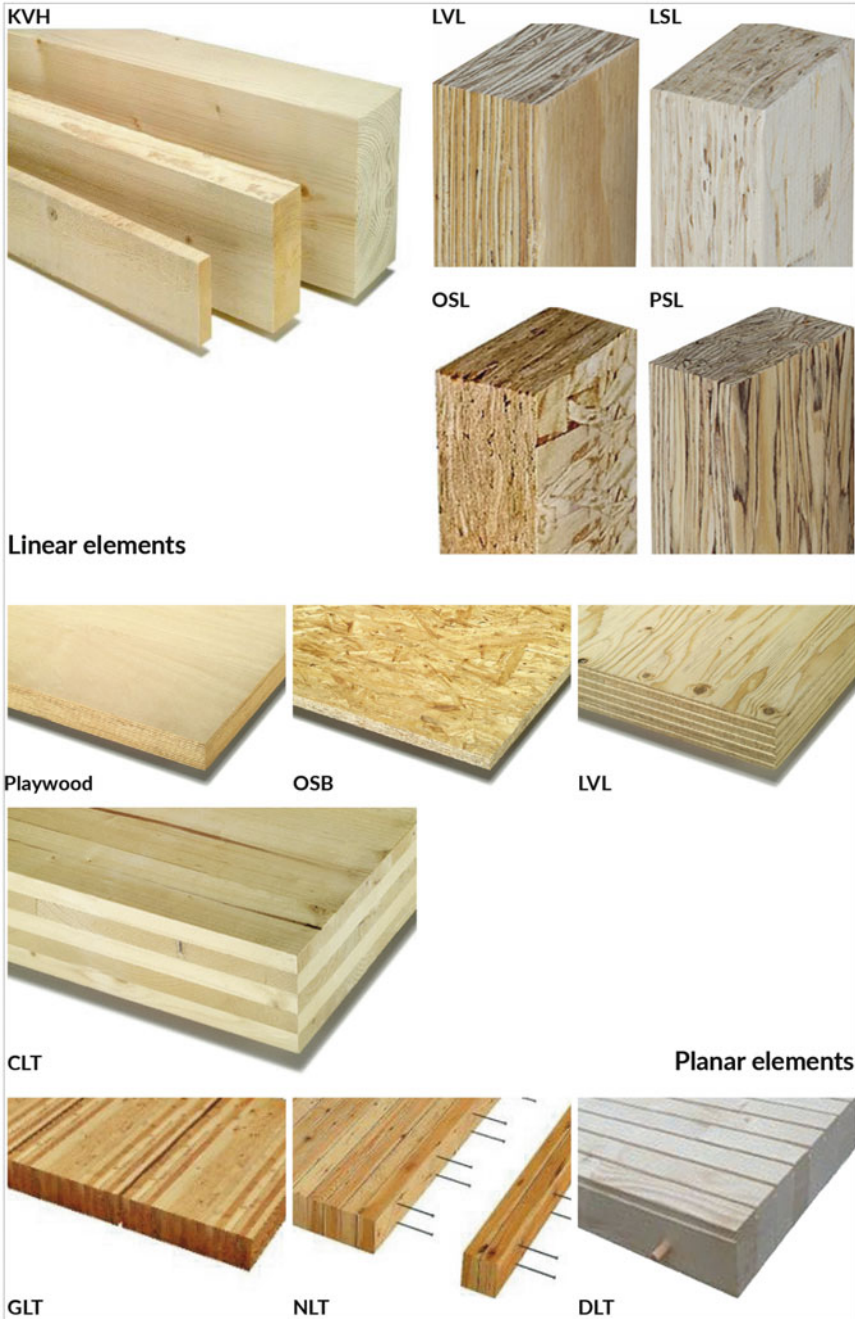


Fig. 2.4 Wood products. Source Author's elaboration on illustrations retrieved from [27, 28]

127 More recently, the sharpening of these laminating and gluing processes has found
128 further improvements and applications within the LVL (Laminated Veneer Lumber)
129 processes [31], whose outcomes are mainly beams and structural panels of layered
130 and glued thin sheets of lumber. Very similar to this new wood-based material, the
131 LSL (Laminated Strand Lumber), OSL (Oriented Strand Lumber), and PSL (Parallel
132 Strand Lumber) are made from flaked wood strands that have a length-to-thickness
133 ratio of approximately 75–150, and—combined with an adhesive—are oriented and
134 formed into a large mat or billet and pressed.

135 By following the history of innovation, it's easy to notice how the same production
136 processes have been adopted to overcome the limitations of plain solid wood and
137 define, as well, the wide panorama of the timber-based panels.

138 As per the veneers-based and wood chips-based beams, the production of OSB
139 (Oriented Strands Board), LVL panels, and plywood panels proposes the use of
140 waste particles from the prime sawing process, then glued and pressed. Besides the
141 optimization of the productive cycle and the recycling aim, the adoption of stratified
142 and glued thinner layer helps, indeed, to overcome the dimensional limitation of solid
143 wood to reach considerable spans of the planar dimension only by prime sawing
144 processes.

145 The main difference between OSB and plywood panels lies in the size of the
146 primary elements that enter the second step of the production chain, and—above
147 all—in the mutual position of single layers. The crosswise joining of plywood allows,
148 indeed, to overcome the issues of the typical anisotropic mechanical behavior of
149 wood, defining a more homogeneous load-bearing material.

150 This last consideration was the spark to take another innovative leap in the thread of
151 the timber industry: the definition of CLT (Cross Laminated Timber) panels (Fig. 2.4).
152 The CLT consists of (at least) three layers of softwood-glued planks, where the
153 direction of the grain in adjacent layers is perpendicular to each other, and the planks
154 may be joined by edge-gluing and finger-jointed in the longitudinal direction. CLT
155 represents, therefore, the gradual transition from multi-layered solid wood panels
156 and/or laminates-bases panels (LVL or plywood), as presenting a larger dimension
157 of individual elements [32]. Moreover, the layering allows to detail the functional
158 performance of each stratum, and thereof chose the best wood essence that could
159 satisfy the specific local requirement.

160 Besides the CLT, other production processes could define massive, load-bearing,
161 timber panels, such as the GLT (Glue-Laminated Timber), based on glue connection
162 similar to glulam and/or LVL, where layers are oriented primarily in the same direc-
163 tion. A mechanical connection system, instead, is used for NLT (Nailed Laminated
164 Timber), with metal-based connectors, and DLT (Dowel Laminated Timber), with
165 inner wood joinery (Fig. 2.4).

166 In particular, these two last solutions aim to cut off the negative environmental
167 impact of the high glue-content of CLT and GLT panels. Nevertheless, the CLT design
168 and production chain could be, sometimes, smother than the NLT or DLT ones. The
169 latter, e.g., have to include the specific design of the connections' placement, as
170 related to the eventual voids defined for the specific project.

In conclusion, processes and products' innovation, in a virtuous mechanism of continuous implementation, has led to a first taxonomy of elements, which renews the collective imagination of *wood*: from a rough material linked to traditional constructions and practices, to a modern high-tech product [25], always suitable for further implementations.

2.1.1.3 From Products to Systems

The assembly of different products allows the definition of components and technological solutions for the envelope, where timber-based materials could be used for both the structural elements, insulations (fiber panels, e.g.), and indoor/outdoor cladding layers.

This part of the design process is linked to the definition of those features, typical of the building components, able to meet the needs required to the envelope: thermal insulation, airtightness, durability, acoustics... [27, 33].

In particular, timber-based constructions belong to dry, layered, and light technological systems, which are able to specifically satisfy each requirement by the layering of the most proper materials, properly analyzed within their features as single elements and part of a more complex solution [28].

Regarding the thermal properties, wood-based insulating materials, such as cork or wood-fiber panels, are capable of good levels of both thermal transmittance, and thermal capacity, thanks to the high density (Table 2.2).

On the wider and more complex perspective of technological solutions, the framed walls (Fig. 5a), i-e., offer the maximum levels of thermal performances with a very reduced overall thickness (if compared to cement-based or brick-based constructions), adding also a proper thermal delay—for summer seasons—when equipped with insulations layers of variable density.

Besides the thermal requirements, the choice of the most proper insulating product is often affected by the evaluation of the ease of installation, since any insulation discontinuity could cause humidity fluxes and mold.

The hygroscopic balance is, indeed, another important aspect for the design of an optimal technical solution, since wood is very sensitive to variations in its humidity content, especially for low-frequencies (seasonal) variations [34]. Indeed, the application of vapor barriers (inside) and wind-barriers (outside) grants the airtightness of

Table 2.2 Comparison among the thermal properties of the most diffused insulation material and vegetable-derived material

Construction material	Density (kg/m ³)	Thermal conductivity (W/mK)	Thermal capacity (J/kgK)
Rock wool	30	0.040	830
Polyurethane	30	0.030	1480
Wood-fiber	150	0.038	2100
Cork	110	0.045	1700

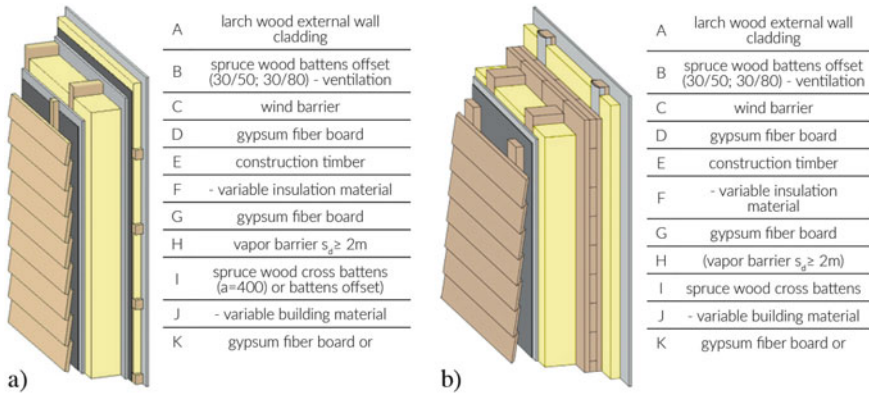


Fig. 2.5 **a** Framed technological solution. **b** Massive timber technological solution. *Source* Author’s elaboration on image and technical details retrieved from the dataholz catalog [32]

203 the envelope and the durability of all the materials, by balancing the fluxes of water
 204 vapor between the building components and the outdoor and indoor environment. In
 205 particular, the technological design needs to focus on the sd (the equivalent thick-
 206 ness to air) [m], which represents the resistance to vapor diffusion. According to the
 207 approach that the designer rather follow:

- 208 • To manage the vapor fluxes, by adopting a permeable technological solution, made
 209 of consecutive layers with a decreasing sd value from inside to outside;
- 210 • To avoid any vapor or air permeability, completely blocking any flux from the
 211 outdoor or indoor environment.

212 A special remark has to be given to massive timber solutions (Fig. 5b), where
 213 the continuity of the structural layer grants a high value for the resistance to vapor
 214 transmittance ($sd = 3.4– 6.8 m$).

215 Great support in the control of the humidity content and the quality of realization
 216 for timber-based building components is given by the great prefabrication potential
 217 that timber-based constructions have, thanks to the enormous advancement of the
 218 4.0 approach within the timber industry (Fig. 2.6). Lightness and ease of manufact-
 219 ure allow, indeed, the introduction of different levels of prefabrication, shifting
 220 the amount of assembling processes that are performed between the factory and the
 221 work-site, according to the most suitable solution for each project (transport issues,
 222 accessibility limitations, need to build in a hygroscopic controlled environment...).
 223 In particular, different levels of prefabricated wood components are:

- 224 • Single Structural Elements—structural elements: i.e. parts of beams, lattice
 225 beams, etc. that are produced from the first sawing process and deliver directly to
 226 the construction site;
- 227 • Two Dimensional Elements—wall and floor elements commonly prefabricated
 228 (usually supplied as already equipped with insulation and waterproof layers, or
 229 even already with mechanical and electrical installations);

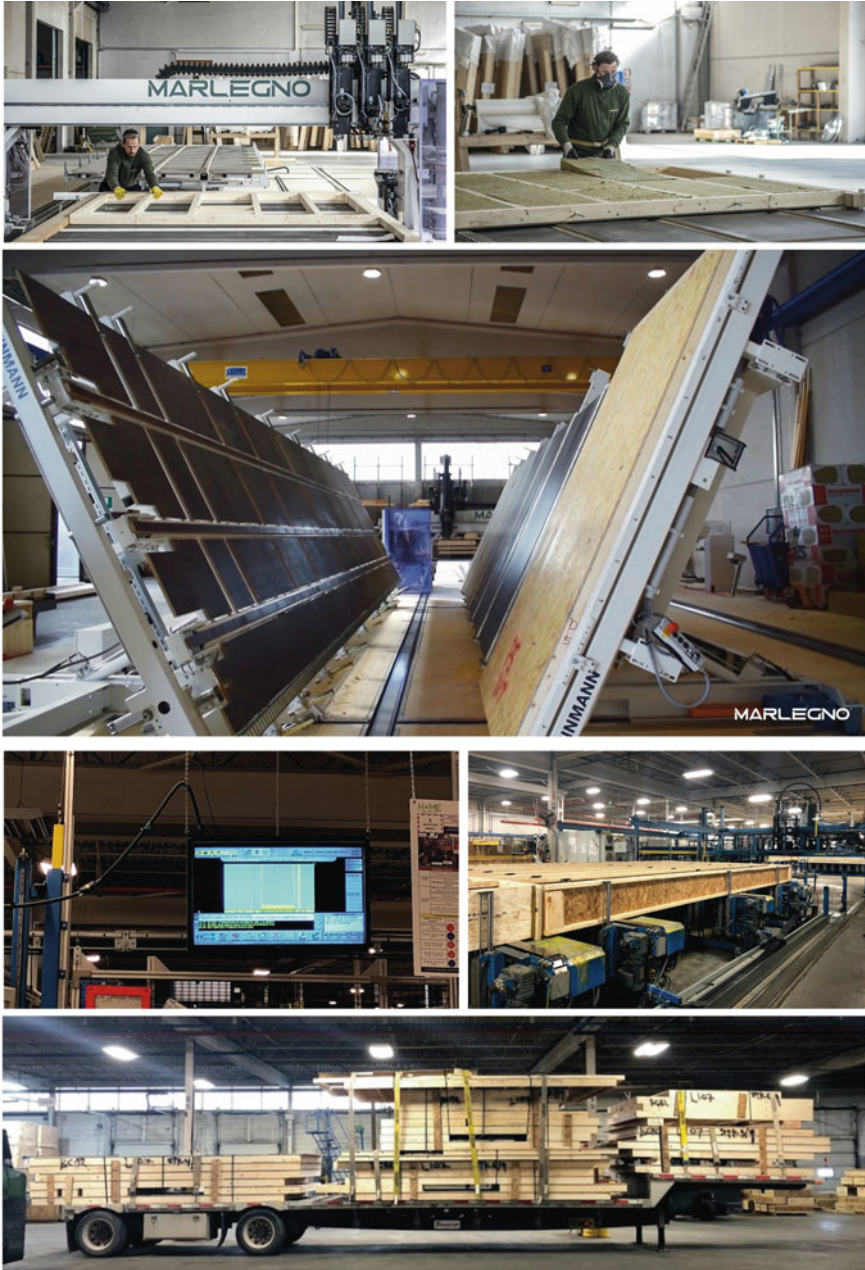


Fig. 2.6 Above, the prefabrication plants of Marlegno near Bergamo, Italy. *Source* Marlegno photo courtesy. Below of Great Gulf in Toronto, Canada. *Source* Author's photo credit

- 230 • Three Dimensional Elements—complete spatial units, also available with
231 mechanical and electrical installations, or even completely finished and including
232 furniture;
- 233 • On-Site Prefabricated Elements—assembly great prefab modules, otherwise not
234 transportable.

235 **2.2 Timber Construction Systems: A Taxonomic** 236 **Perspective**

237 **2.2.1 The Taxonomic Approach to Building Systems**

238 The technical literature and the national and international guidelines and standards
239 have since always tried to explain the complex and articulated panorama of building
240 systems, according to a multitude of different approaches.

241 By analyzing the technological thread, the first criterion is the construction
242 material [35]—concrete, masonry, steel, wood, glass, or textile membranes... [36].

243 Besides, the continuous innovation of these practices has led to other approaches,
244 i.e. based on the contrast between the so-called traditional construction systems and
245 the newer ones of dried construction technologies [37, 38].

246 As specifically related to timber construction, an additional criterion is represented
247 by the concept of *wall-systems* [39], which considers for a taxonomic evaluation
248 only the technological solutions that are currently used for the vertical enclosures.
249 Besides, other studies propose a taxonomic review based on the variety of wood-
250 based products and components available on the market, and thereof categorizes
251 systems as framed or panel-based ones [20].

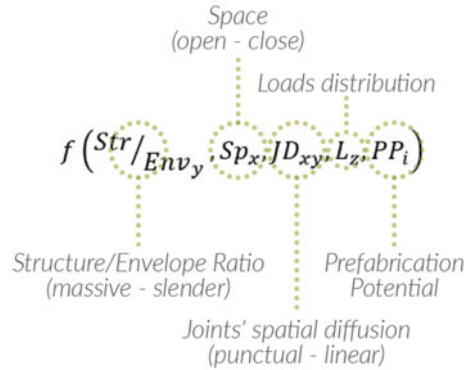
252 Finally, other possible taxonomies concern the application [35], within new
253 constructions or building retrofit, and thereof the impact those systems have
254 on building performances, or the different building typology—i.e. the Canadian
255 taxonomy of timber construction systems of mid-rise and high-rise wooden buildings
256 [40].

257 **2.2.2 Timber Construction Systems**

258 Moving from the literature review, the author proposes a new creative taxonomy of
259 timber-based construction systems, starting with the analysis of the triad:

- 260 • *Products*, as solid, engineered, or recycled wood-based;
- 261 • *Processes*, as the assembly of timber-based devices, within the different levels of
262 industrial productions and prefabrication;

Fig. 2.7 The function to outline the criteria of the proposed taxonomy for timber construction systems.
 Source Author's elaboration



- 263 • *Projects*, embedding the designing processes that result in the best application
 264 practices.

265 And which follows a set of criteria, i.e.:

- 266 • *Construction typology*, which considers the ratio between Structure and Envelope
 267 (S/E) and results in the duality of the massive and slender system;
 268 • *Spatiality*, which accounts for the relation and possible fluxes between the outer
 269 space and the open or close construction volume;
 270 • *Joints' spatial diffusion*, resulting as a tendency from the integration of the
 271 previous two criteria, from punctual to linear connections;
 272 • The mechanical behavior of the system under the *Loads distribution*.

273 The taxonomy has been resumed throughout the function of Fig. 2.7 and resulting
 274 in the diagram of Fig. 2.8.

275 2.2.2.1 The Creative Taxonomy of Timber Construction Systems

276 **Structural Frame System.** It represents a punctual framed system, with customized
 277 linear products (beams and columns), derived from solid wood, KHV, and/or glue-
 278 laminated timber processes. It is considered as a slender construction type, with an
 279 open spatiality, and punctual mechanical connections between vertical and horizontal
 280 elements.

281 The system could be structurally realized through Posts and Beams solutions,
 282 usually realized on-site, or as pre-assembled Portal Frames (Fig. 9a).

283 **Timber Framed System.** It is mainly considered as a lightweight framed wall
 284 system, based on the traditional North-European *Fachwerkbau* and the North-
 285 American *balloon frame* and *platform frame* techniques. It is, indeed, the results
 286 of the assembly of standardized linear products (timber studs), derived from solid
 287 (finger-joint or glued-squared) KVH and glulam processes. The construction type
 288 is slender, with an open spatiality bounded to the standardized span between the

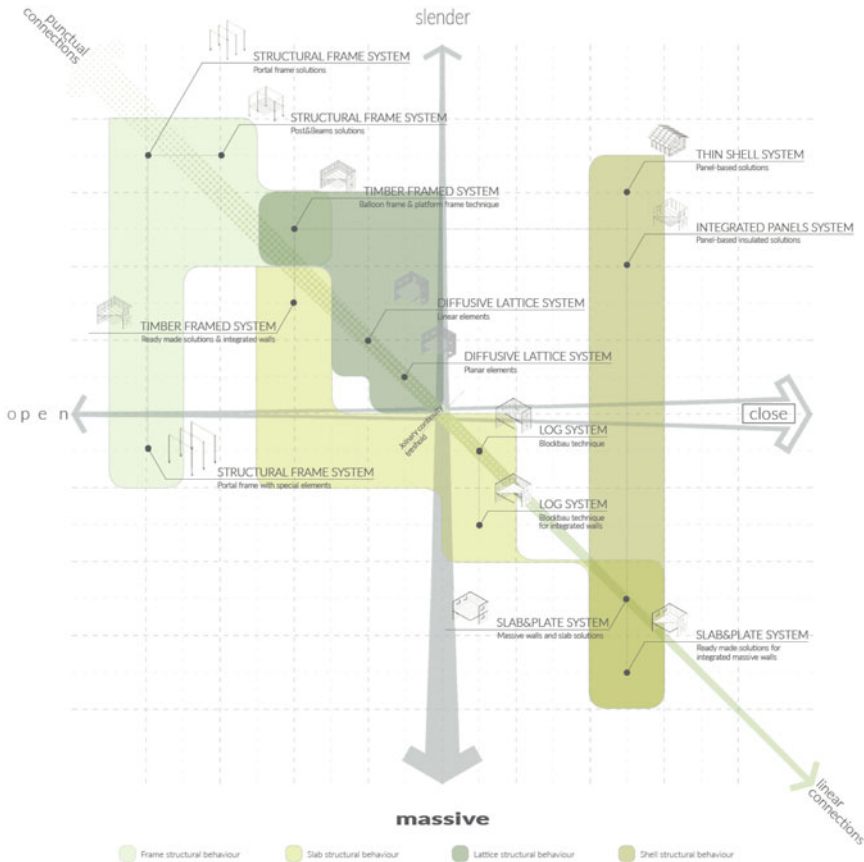


Fig. 2.8 The proposed taxonomy for wood-based construction technologies started from the basic distinction between slender and massive systems, furthermore, classified into open and close structures. The intersection of these four parameters enhanced a trend about the joints’ spatial diffusion. *Source* Author’s elaboration

289 elements—usually 600 –650 mm, as related to the application of timber panels as
 290 wind-bracing elements. The mechanical behavior is, indeed, considered as a framing
 291 response, when claded by solid wood boards, or as a braced frame system if reinforced
 292 by timber-based panels—OSB, plywood, etc.

293 The level of prefabrication of this system is flexible: from the assembly of singular
 294 elements on the construction site to the realization of the reinforced frame, then
 295 equipped by insulation layers, as *ready-made* solutions, till the integrated walls with
 296 mechanical and electrical systems, or even windows, further assembled as three-
 297 dimensional modules and shipped (Fig. 9b–c).

298 **Diffusive Lattice System.** From the Japanese traditional crafts of wooden joinery,
 299 this wall system is represented by scattered structural nodes, along the planar, or
 300 even the third dimension (Fig. 9d–e). A set of customized linear or planar products,



Fig. 2.9 Architectural examples of the application of timber-based construction systems. *Source* Author's elaboration

301 derived from solid wood, glulam, or massive timber processes, are mechanically
302 assembled through wooden connections in structures, whose slenderness could be
303 varied according to the parametric variation of the structural spans.

304 The defined rhythm of the enclosures is, indeed, the place where the contemporary
305 and innovative interpretation of the Asian craft, today realized through CNC-based
306 processes, meets the Eastern philosophy of Void and Emptiness, embedded in the
307 porosity of the system. Its spatiality results, therefore, as semi-closed and ephemeral,
308 where the Joints' spatial diffusion presents an upgrading intensity on bi-dimensional
309 and three-dimensional building components (enclosure solutions).

310 **Mass Timber—Log System.** Based on the North-European *Blockbau* technology,
311 or the Canadian log system, traditionally realized through piled wood trunks, this
312 system uses massive linear elements, horizontally laid and piled up to define wall
313 components. The currently used timber products derive from solid wood (glued and
314 squared), with particular edge profiles to allow the connection between consecu-
315 tive linear elements along the vertical structure, and the joint of different building
316 components (Fig. 9f). Therefore, the system spatiality results in a close volume,
317 where the Joints' spatial diffusion is linked to the linear and continuous contact
318 surfaces between the singular linear elements.

319 The level of prefabrication is relatively low, due to the continuous stratum of
320 massive timber, which implies a considerable total weight (>3000 kg) of the single
321 components to be easily enlivened on site. However, the market presents different
322 technical solutions, already studied as *ready-made*, in terms of assembly and thermal
323 performances.

324 **Mass Timber—Slab/Plate System.** Based on the big-span planar products of
325 CLT, DLT, NLT, GLT, and MHM technologies, it is considered as one of the most
326 innovative construction systems, thanks to the ease of application and installation
327 on-site and the high load-bearing capacity of the single elements, both used as slabs
328 and plates for a shell-based distribution of the loads along the three-dimensional
329 closed volume. This feature has allowed, indeed, to consider timber as a material for
330 constructions of mid-rise to high-rise buildings, otherwise realized through pre-cast
331 concrete (Fig. 9g).

332 The construction type is, therefore, a massive structure, with a close spatiality,
333 where the Joints' spatial diffusion is related to the continuous linear connection
334 between the planar elements.

335 **Thin Shells System.** Reducing the thicknesses of the single panels, by choosing
336 plywood boards, LVL, or OSB items, this system represents a three-dimensional
337 box system, with pre-shaped planar products of multi-layered timber panels, derived
338 from recycled wood processes, and fixed through specific and patented wood joints
339 (Fig. 9h).

340 The construction type results, therefore, slenderer than the mass-timber systems,
341 even though it still presents a close volume and a continuous contact between the
342 planar elements, combined with the specific punctual connection.

343 **Integrated Panels System.** It is represented mainly by wall elements, realized
344 through timber-based sandwich panels. A pair of prefabricated self-supporting and

345 load-bearing boards, derived from plywood or OSB, is filled with insulating mate-
346 rials, such as EPS foam, in order to grant both the structural and thermal properties
347 required. The construction type is light, thanks to the lower weight of the insulation
348 layer, and closed, due to the presence of a continuous planar layer.

349 **Modular Elements System** This last category collects all the experiences derived
350 from the application of timber-based modular elements, which follows the assem-
351 bling approach of brick-based constructions. The prefabricated components are real-
352 ized through recycled wood processes; in particular, CNC-cut OSB panels are used to
353 create light brick-shaped elements, with edges specifically designed to allow a mutual
354 connection along with the vertical enclosure. The inner void could be filled with insu-
355 lating materials, directly on-site by pouring granulates, or within the prefabrication
356 process, likewise the previous Integrated Panels system.

357 **2.3 Timber Construction Strategies for Building** 358 **Transformation: Applied Solutions from Realized Case** 359 **Studies**

360 Structural lightness [41], positive environmental footprint [9, 10], and high prefab-
361 rication potential are the key features that are driving the decision-makers towards
362 timber-based solutions today.

363 The added value of timber-based constructions relies, indeed, on the natural high
364 recyclable content and the capacity to store the CO₂, reducing the GHGs' net emis-
365 sions, and positively affecting the balance of the overall ecological footprint for the
366 renovated building.

367 These features embody the natural potential of wood as a construction material, in
368 particular when applied to building transformation, reducing its impact on existing
369 buildings, which is one of the main issues related to sustainable management of
370 the built environment. Moreover, the structural lightness of timber-based solutions
371 allows to several positive implications, such as the trivial reduction of the over-
372 loads for the existing structure, which means: (i) to ease the structural verifications
373 and (ii) to minimize the eventual reinforcement of the existing structure elements,
374 if compared to other construction materials. It suggests, thereof, an optimization
375 of the process, in terms of time and resources consuming, during both the design
376 and the construction phase. These circular economies grow even more if adding
377 the benefits of prefabrication and ease processing/assembling, which characterizes
378 timber construction systems and points to a lower impact on the worksite, for the
379 sake of function and business continuity within the existing buildings, and the quality
380 of the final result.

381 The different timber-based construction systems represent, therefore, different
382 options, flexibly suitable to satisfy the variety of requirements of building transfor-
383 mation practices, especially for the environmental and structural aspects, which are
384 specifically entailed with the technological choices.

2.3.1 Timber Construction Systems Within the Additive Retrofit Strategies: The Outcomes from the Case History Analysis

The above guesses have been confirmed through the analysis of a wide portfolio of case studies, some of reported in the last chapter of this dissertation. The final discussions over the data-collection enhance, indeed, a considerable application potential for timber-based constructions for building transformation. The identified solutions are suitable both to meet the initial need and aims of the retrofit strategies and to be flexibly applied to the different existing contexts, in terms of varied building typology and urban scenarios.

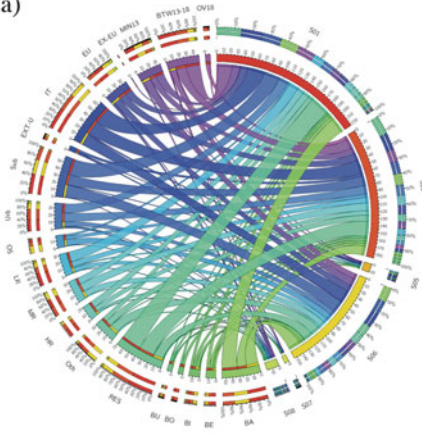
2.3.1.1 Distribution Trends

As outcomes of the survey, the circular distribution graphs illustrate the trending fluxes of the different parameters. In particular, the graphs of Fig. 2.10 resume the mutual distribution between retrofit strategies and timber construction systems. It needs to be noted that the shown trends have to face the limitations of the survey, mainly due to the boundaries of the investigation domain: by drawing on for information from a strictly defined data source, the results cannot avoid being influenced by the actual trends of the Italian network experiences. The national market of timber constructions, indeed, relies on 55% slender systems and 38% massive timber panels (CLT) [8]; a similar distribution is traceable on the graph of Fig. 10b, where Structural Frame Systems (42%), Timber Frame System (26%) and the Mass-Timber—Slab and Plate System (32%) define the 100% of the experiences of a vertically-up expansion (so-defined Building Above strategy).

Besides, the choice of the proper timber system for the spatial re-functioning and re-organization of existing indoors (Building Inside and Building Under strategies) is strictly related to the level of prefabrication and the work-site conditions: the trends show, indeed, that Mass Timber panels are frequently used—35% as Building Inside and 30% as Building Under -, as walls or box-shaped volumes, with a high level of prefabrication content. However, the analyzed cases of the survey present situations where the spatiality of the existing building offered the possibility to access the existing building spaces with ready-made—and quite hulking—elements; otherwise, the most suitable solution is represented by the Timber Frame solutions, where the prefabrication potential is more variable, and the level of assembly from the factory to work-site is always adjustable.

In conclusion, the results of the survey prove the effective reliability of timber-based construction systems—some more than others—as valid solutions for building transformation, flexibly suitable to satisfy its variety of requirements and final aims.

a)



LIST OF SYMBOLS

CONSTRUCTION SYSTEM: **S01:** STRUCTURAL FRAME System - Post and beams; **S01B:** STRUCTURAL FRAME System - Portals; **S02:** TIMBER FRAME System; **S02B:** TIMBER FRAME System - Ready made solutions; **S03:** GRID SHELL System; **S04:** DIFFUSIVE LATTICE System; **S05:** MASS TIMBER - LOG System; **S06:** MASS TIMBER - SLAB/PLATE System; **S07:** INTEGRATED PANELS System; **S08:** THIN SHELL System; **S09:** MODULAR ELEMENTS System; **S10:** MODULAR ELEMENTS System; **S11:** other.

DESIGN STRATEGY: **BA:** Building Above; **BE:** Building Beside; **BI:** Building Inside; **BO:** Building Outside; **BU:** Building Under.

USE: **RES:** Residential; **TUR:** Touristic; **OFF:** Offices; **IND:** Industries; **HOS:** Hospital; **REC:** Recreational activities; **RET:** Retail; **SPO:** Sports; **EDU:** Education; **RUI:** Ruin.

BUILDING TYPE: **HR:** High-rise building; **MR:** Mid-rise building; **LR:** Low-rise building; **OS:** One-storey building.

URBAN CONTEXT: **HIS:** Historical center; **URB:** Urban center; **SUB:** Suburbs; **IND-A:** Industrial area; **RUR-A:** Rural area; **EQUI:** Equipment and Facilities area; **EXT-U:** Extra-urbs.

LOCATION: **IT:** Italy; **EU:** Europe; **EX-EU:** Extra-EU.

YEAR: **MIN13:** before 2013; **BTW13-18:** from 2013 to 2018; **OV18:** after 2018.

b)

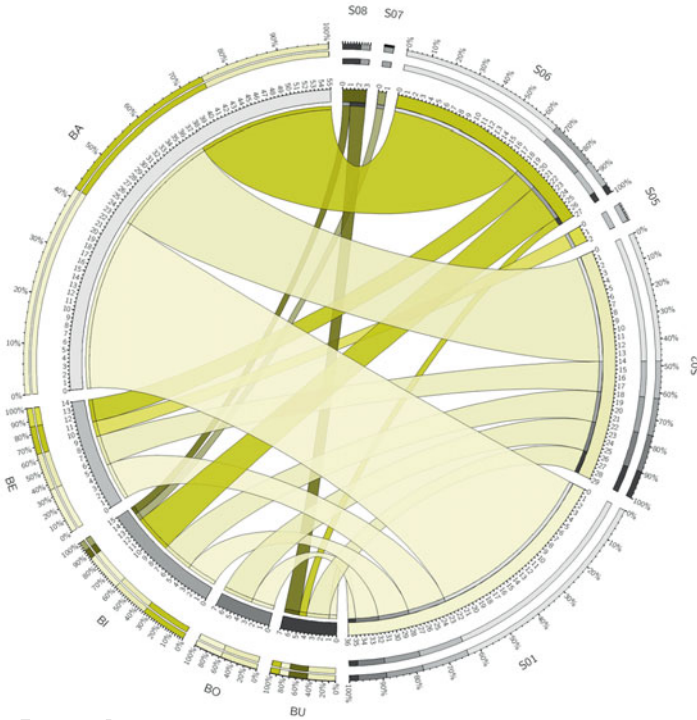
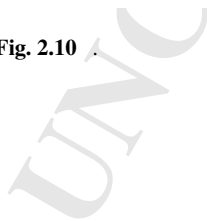


Fig. 2.10



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Chapter 2

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