Assessing the Complexity of Timber Gridshells in Architecture through Shape, Structure, and Material Classification

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New possibilities offered by recent modelling software allow the design of organic shapes that are appealing to architects and engineers but may encompass serious issues such as an overconsumption of materials. In this context, there is a renewed interest in systems allowing the materialization of curved surfaces such as timber gridshells, which can be defined as shells with their structures concentrated in strips. However, gridshell design becomes highly challenging if complex grid configurations and new material possibilities are combinedly explored with form generations. These upheavals highlight the need for a classification system to seize the potential and the limitations of timber gridshells to address complex geometries. The classification of 60 timber gridshells enables a critical examination in the course of the ceaseless quest for complexity in architecture by evaluating current building possibilities and predict future building opportunities in terms of form, structure, and materiality.

Keywords: Timber gridshells; Architectural complexity; Classification method; Free-form geometries; Non-standard grids; Natural composite materials

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INTRODUCTION

The recent democratization of powerful modelling software allows architects to explore a broad range of complex shapes, structures, and materials (Teyssot and Bernier-Lavigne 2011). In this context, digital architects suggest an alternative to the perception of form by advocating curvilinearity (Picon 2010). Because CAD software continues to change how architecture and structures are designed, planned, and built (Block *et al*. 2017), it is fair to expect an increasing number of projects with free-form geometries (Kim *et al*. 2015). However, the use of traditional constructive techniques in the realization of curved shapes may result in inflated budgets, extended schedules (Lee 2008; Kim *et al*. 2015), and increased material consumption (Ney and Adriaenssens 2014). Thereby, there has been a quest for complexity that is characterized by a holistic architecture of depth and pluralism (Jencks 2016).

Recently, diverse strategies have been developed to build free-form shapes efficiently, including innovative timber structures. For instance, there is a renewed interest in gridshell structures, which can be defined as "a shell with large openings in it in a manner that allows the remaining strips or grids to behave, structurally, as a shell" (Harris *et al*. 2003). Unlike shell structures constructed with panels, gridshells redirect the compression and shear forces along the longitudinal axis of their members (Adriaenssens *et al*. 2014) and therefore minimize the amount of material to cover large-span spaces (D'Amico 2015; Cuvilliers *et al*. 2017). However, there are few built precedents in the world (Ghiyasinasab *et al*. 2017). The main reason for their underutilization, once attributed to a lack of knowledge and data (Harris *et al*. 2003), has now shifted toward manufacture and constructive issues (Liuti and Pugnale 2015), which are different depending on the category of gridshells.

Elastic gridshells are characterized by a flat grid made of unbent continuous laths, which is subsequently deformed into the desired shape (Lienhard *et al*. 2013; Naicu *et al*. 2014). The advantage of this system lies in the materialization of curved shapes using straight members with standard wood sections and unique connectors. (D'Amico 2015). The Weald and Downland gridshell (Fig. 1) is a well-known contemporary example, but its erection has implied, among other limitations, the need for a large construction site for on-site manufacturing and a slow phase of construction due to the difficulty to manipulate the flat mat using straps and scaffoldings (Chilton and Tang 2017).

Fig. 1. The Weald and Downland gridshell, Singleton, UK

Rigid gridshells are made with relatively short elements fabricated off-site and assembled to each other on-site into a discrete grid (Naicu *et al*. 2014). This technique might appear accessible since it replicates a traditional way of erecting a structure, especially for apparent simple forms and grids such as the roof of Crossrail Place, Canary Wharf in London (Fig. 2). Nonetheless, in this project, the axis of each successive element twists slightly around the roof; the angles at the nodes become more acute and asymmetric creating a broad range of diversified steel node connections (Chilton and Tang 2017). Thus, even if irregular grids can offer more structural redundancy (Malek and Williams 2013), they generally increase the challenge of components manufacturing (D'Amico 2015; Mesnil *et al*. 2017).

Fig. 2. Crossrail Place, Canary Wharf, London, UK

The constructive difficulties associated with the exploration of complex geometries and non-standard grids also conducted to a transition from a tectonic to a composite logic, overshadowing natural materials in favour of synthetic ones (Bernier-Lavigne 2014). Since the deployment of the first elastic gridshells, timber has proven to be the most suitable material for creating malleable lattices due to its lightness and flexion properties (Paoli 2007; Harris and Roynon 2008). Wood is also an abundant, sustainable, low-cost and easy to manufacture material (Taggart 2011). However, composite materials, which are stiffer while having a comparable forming ability to that of wood (Kotelnikova-Weiler *et al.* 2013), generate new opportunities for gridshells. For instance, Glass Fibre Reinforced Polymer (GFRP) allows more pronounced deformations and stiffer structures that are less subject to buckling (Tayeb *et al*. 2015). They are also produced industrially, which guarantees the constancy of their mechanical properties, unlike wood, which is anisotropic and has variable composition. In this context, timber gridshells must prove their architectural relevance as well as their ecological advantages to compete against synthetic materials.

The shifts from angled to curved shapes, from traditional to innovative structures, and from natural to synthetic materials are important evolutions in contemporary architecture. Even if gridshells are scarcely used, this paper provides the classification of a corpus of 60 projects to evaluate if they have followed these morphological, structural and material progressions and have the potential to become a relevant constructive system that materializes complexity.

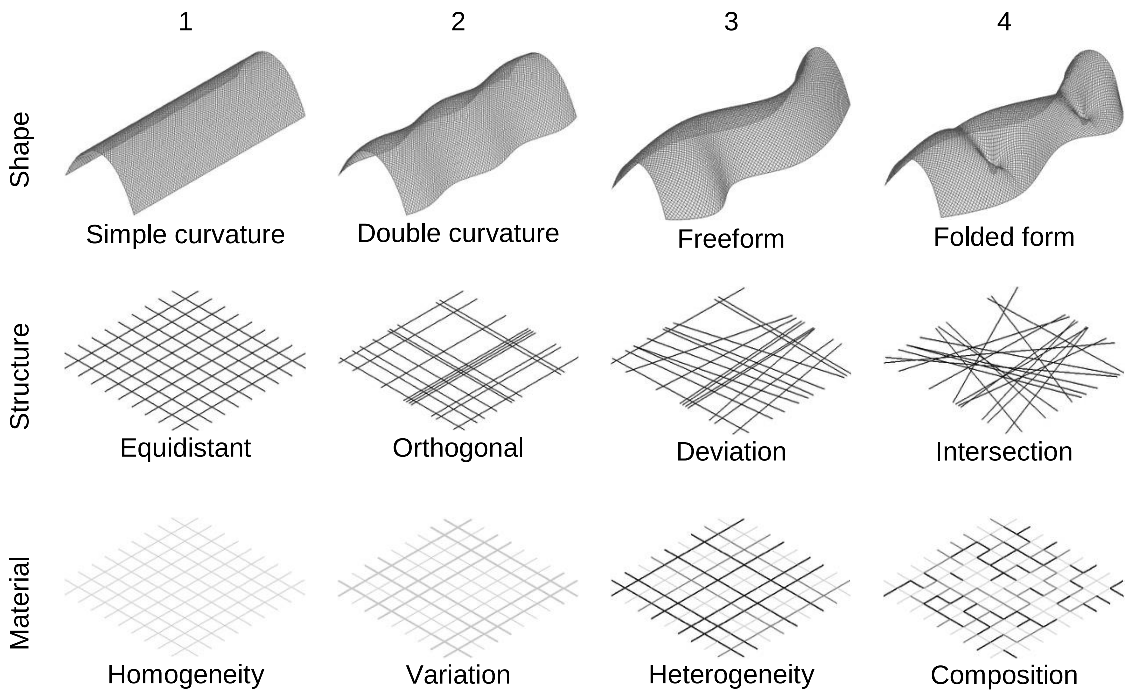
EXPERIMENTAL

This research develops an analytical exercise that identifies achievable levels of timber gridshell complexity aiming to generate recommendations to design more accessible constructive systems. The research focuses on early design phases in order to provide insights on the achievability of complexity. Consequently, a classification implement was developed to analyze gridshell precedents. It features three axes (shape, structure and materiality) divided into 4 levels organized from the simplest constructive solution to the most complex one (Table 1). The 64 (4^3) families are the result of subtle variations, but which can substantially affect the overall geometry, structural response and material behaviour.

The first axis shows a shape evolution regarding two parameters: the curvature of the geometry and boundary conditions. For instance, Level 1 has straight edges as boundary conditions, and a unidirectional curved surface. Level 2 has symmetric boundary conditions and a double-curved surface. Level 3 refers to a free form and level 4 to a free form that folds back onto itself to create a supporting element. This structural strategy could for instance architecturally define a central courtyard. It can also refer to a discontinued grid resulting in openings such as a skylight.

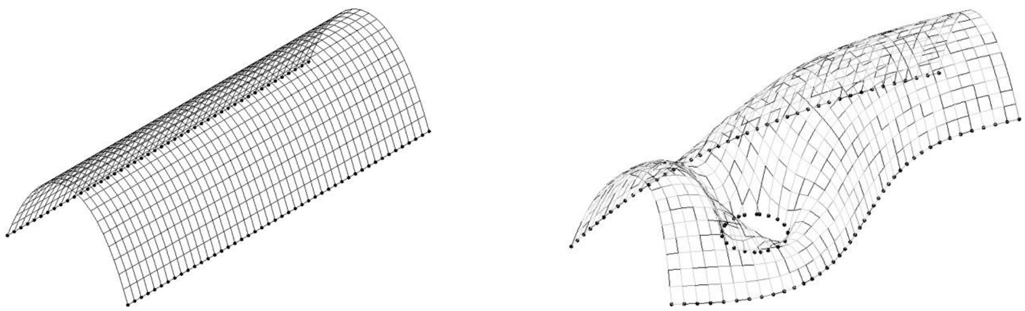
The second axis corresponds to the structural complexity, which increases with the regularity and/or the irregularity of the mesh. Level 1 has a regular grid with equidistant laths and orthogonal nodes. Level 2 has orthogonal laths as well, but the distance between them may vary to achieve optimized configurations. Level 3 allows members to deviate, resulting in components that are not necessarily parallel. In the case of elastic gridshells, this definition concerns the lattice before its deformation since the permissiveness of the connectors allows a rotation of the members that modifies the cells' geometry during the erection. Finally, Level 4 has the least restrictive arrangement in which the members can intersect and regroup to adopt unpredictable configurations. Those configurations can greatly influence the erection process of elastic gridshells and consequently the final geometry. They can also lead to more efficient structural configuration through complex nodal connections. Architecturally, this versatility creates unique spatial environments by filtering light through variable openings. Discontinuous grids of members belong to the last complexity level of the axis.

Table 1. The Level of Complexity in the Shape, Structure, and Material Axes



The third axis details the material complexity. To consolidate the structural relevance of wood, some researchers suggest that its composite nature might constitute an inspiration (Menges *et al*. 2017). Available in several species with diverse physical and mechanical properties, wood has the potential to replicate heterogenous lattice optimizing the structural behaviour of gridshells. Hence, level 1 has a homogeneous lattice composed of a single wood species. Level 2 suggests mixing compositions of unique wood species in which members are sorted mechanically and positioned according to their specific properties. Level 3 has a mixed arrangement matching different wood species or wood products according to stress intensity. Finally, level 4 corresponds to material variations within the same member, in the image of composite materials. For instance, a segment can start with a piece of spruce joined to a piece of oak that ends with a piece of fir. It should be noticed that the structural complexity does not include the bracing members that are usually added after the erection process.

The three axes of shape, structure, and material become the vocabulary basis of a classification tool in which each family can be represented by an "identification code". For instance, Fig. 3(a) represents the simplest case with a unidirectional curved shape, composed of an orthogonal and equidistant lattice made with a single wood species. Architecturally, this configuration can be used for generic buildings that need to be efficient and affordable, such as warehouses. The code for this family is [F1: S1: M1]. In contrast, Fig. 3(b) shows the most complex case with a free form that folds into its center, composed of erratic grid members having multiple wood species. Architecturally, this configuration is more likely to refer to exceptional buildings in which form, structure, and materiality contribute to the spatial experience of users such as museums. In this case, the code is [F4: S4: M4].



(a) (b)

Fig. 3. Examples of the simplest [F1:S1:M1] (a) and the most complex case [F4:S4:M4] (b)

The tool was used to sequence the "identification code" of 60 gridshells built between 1962 and 2016 (Table 3). These precedents were mainly selected from Chilton and Tang (2017) because they were included in a recent and exhaustive account of timber gridshells made over the years. The analysis is represented as a histogram and three scatter plots (one for each axis). The histogram shows the distribution of a selection of projects over the years and graphically illustrates the proportion of elastic versus rigid gridshells. The scatter plots use Cartesian coordinates to display the average level of complexity over time. They include a correlation coefficient (R), which give the direction and the strength of the relationship between the variables (Glass and Hopkins 1996). Every correlation was analyzed with a linear trend line, which shows that the levels of complexity increase or decrease at a steady rate. Table 2 illustrates the qualification of the correlation coefficient according to its values.

Table 2. Qualification of the Correlation Coefficient

Correlation	Negative	Positive
Inexistent	0.00	0.00
Weak	-0.30	0.30
Moderate	-0.50	0.50
Strong	-0.70	0.70
Perfect	-1.00	1.00

RESULTS AND DISCUSSION

This section presents all the projects, their classification using the "identification code" (Table 3), their distribution over time (Fig. 4), and the analysis of their complexity on each of the three axes previously defined (Fig. 5, Fig. 6, and Fig. 7). It also details a digital simulation showing the potential of material complexity (Table 4).

The exercise showed that families are not mutually exclusive but act as benchmarks on a complexity spectrum. In some cases, the geometry, the grid, or the material might not be clearly defined in the literature, and a different interpretation could tip a project from one category to another. A project may also present a combination of rigid elements and elastic lattices. In such a case, a particular look on the fabrication and erection processes is required to determine whether it should fall in the rigid or elastic category. In this research, a gridshell was considered as elastic when its members are deformed on the construction site. Conversely, it was considered as rigid when members are mainly prefabricated at a factory. Nevertheless, this classification remains relevant and sufficiently reliable to reveal the main trends in a census covering more than 50 years.

Table 3. Corpus of Timber Gridshell Projects and their Classification

#	Project	Year	Type		Shape				Structure				Material			
			E	R	1	2	3	4	1	2	3	4	1	2	3	4
1	German pavilion, Essen, Germany	1962	■			■			■				■			
2	German pavilion vestibule roof, Montreal, Canada	1967	■				■		■				■			
3	The S.T.I. experimental model at IL, Stuttgart, Germany	1973	■			■			■				■			
4	Multihalle and restaurant, Mannheim, Germany	1975	■				■		■				■			
5	Solemar Therme, Bad Dürrheim Brine Baths, Germany	1987		■				■	■				■			
6	Silk road exposition, Nara, Japan	1988		■			■		■				■			
7	Mermaid bowl, Hiroshima, Japan	1989		■		■			■				■			
8	EPFL Polydôme, Lausanne, Switzerland	1991	■			■				■			■			
9	Uchino community centre, Fukuoka	1995	■				■		■				■			
10	Boat house, Morges, Switzerland	1995	■		■						■		■			
11	Piscine Saint-Quentin en Yvelines, Saint-Quentin, France	1997		■		■					■		■			
12	Exhibition hall for handicrafts, Ober-Ramstadt, Germany	1997	■			■				■			■			
13	Dome roof, Triesen, Principality of Liechtenstein	1998	■			■				■			■			
14	Earth Centre, near Doncaster, UK	1998	■			■			■				■			
15	Flimwell woodland centre, Kent and Sussex borders, UK	1999	■		■				■				■			
16	Toskana Thermal Springs, Bad Sulza, Germany	1999		■			■		■				■			
17	Canopy roof, World Exhibition, Hanover, Germany	2000		■		■				■					■	
18	Bamboo roof, Rice Pavilion, Houston, USA	2002	■				■					■	■			
19	Weald and Downland Museum, Singleton, UK	2002	■			■				■			■			
20	The Kupla gridshell, Helsinki, Finland	2002		■				■			■		■			
21	Alishan Bridge, Taiwan	2003		■			■				■		■			
22	Dome for an equine therapy centre, Uzwil, Switzerland	2004	■			■					■		■			
23	Law court building, Antwerp, Belgium	2005		■		■					■		■			
24	The Savill Garden, Bershire, UK	2005	■			■			■					■		

25	Beatuse!, New York, USA	2006
26	The Chiddingstone castle orangery, Kent, UK	2007
27	Terrace pergola of a rural house, Ostuni, Italy	2008
28	Woodome 1.0, Lecce, Italy	2009
29	Toskana Thermal Springs, Bad Orb, Germany	2009
30	Caves Visitor centre, Otorohanga, Waikato, New Zealand	2010
31	Hermès store, Rive Gauche, Paris, France	2010
32	Trio Entrance Roof, Lecce, Italy	2010
33	Metropol Parasol, Seville, Spain	2010
34	Haesley Nine Bridges Golf Resort, Yeoju, South Korea	2010
35	Centre Pompidou-Metz, Metz, France	2010
36	UNAM campus gridshell, Mexico City, Mexico	2011
37	The Swells gridshell, Sheffield, UK	2011
38	Kreod pavilions, London, UK	2012
39	Toledo gridshell, Naples, Italy	2012
40	Woodome 2.0, Selinunte, Sicily, Italy	2012
41	University of Exeter Forum, Exeter, Devon, UK	2012
42	Jukbuin Pavilion, Barcelona, Spain	2012
43	Woodome RFI, Milano, Italy	2013
44	The almond, Catalunya, Spain	2013
45	University of Technology and Design gridshell, Singapore	2013
46	Heydar Aliyev Airport Terminal, Baku, Azerbaijan	2014
47	Accoya timber gridshell, Melbourne, Australia	2014
48	F^2 gridshell pavilion, San Antonio, USA	2014
49	Alida Woodome, Fratterosa, Italy	2014
50	Farmers' Market Gridshell, Cheticamp, Canada	2015
51	Crossrail Place, Canary Wharf, London, UK	2015
52	The Malaysia Pavilion, Expo'2015, Milan, Italy	2015
53	The France Pavilion, Expo'2015, Milan, Italy	2015
54	The Tree Of Life, Expo'2015, Milan, Italy	2015
55	Lafayette Strong Pavilion, Lafayette, USA	2016
56	Ahuriri Valley Lodge roof, New Zealand	2016
57	Moriko experimental pavilion, Mexico	2016
58	UWE Digital Design Research Unit Pavilion, Bristol, UK	2016
59	Île Seguin 'Cité Musicale', Paris, France	2016
60	Headquarters for Swatch/Omega, Biel, Switzerland	2016

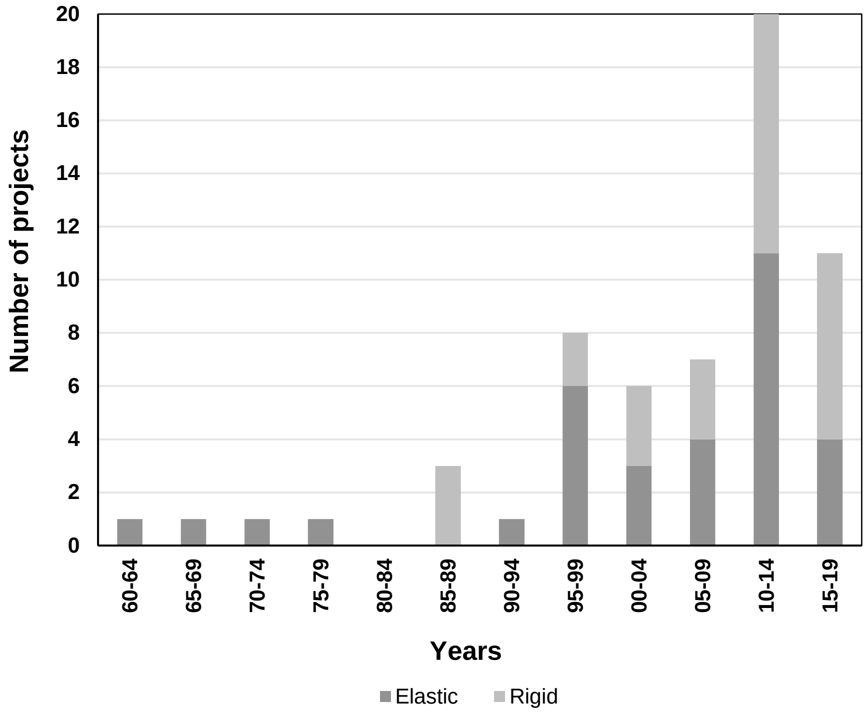


Fig. 4. Distribution of timber gridshell projects over time

Figure 4 illustrates the few number of projects built from 1960 to 1995 followed by a major progression in gridshells. This tipping point corresponds to the moment when computers were used as form generators and suggests that timber gridshells might present a relevant solution to materialize complex geometries. This progression in the number of produced gridshells might also be explained by the growing interest in timber for sustainable design. At the ecological level, timber sequestrates approximately one ton of carbon per cubic metre and can contribute decreasing the embodied energy of buildings by the substitution of high-embodied energy material such as steel (Herzog *et al*. 2005).

Figure 4 also shows an increasing proportion of rigid gridshells over elastic ones, which highlights the fact that manufacturing assistance greatly expanded with the democratization of digital fabrication tools such as milling machines. Their capability of manufacturing a large number of unique components makes it possible to overcome the obstacles of standard construction (Scheurer 2014), which has a great impact on rigid gridshells. Some researchers even suggest that buildability becomes a programming function (Gramazio and Kohler 2008). However, even if the manufacture of complex components is facilitated by digital fabrication, other constraints, such as budgetary ones, limit this freedom to exclusive and high-end buildings (Picon 2010).

Considering these limitations, the future of gridshells might lie in hybrid structures made of rigid elements filled with elastic lattices. The possibility of constructing curved surfaces with rectilinear elements and standard connectors remains relevant today. Over the last 10 years, a great proportion of the projects in the corpus consisted of small-scale pavilions made for research experimentations. However, the constructive issues associated with on-site deformation of a large grid of members appeared difficult to overcome. Hence, the segmentation of a surface using a primary structure of prefabricated components and a secondary structure of bendable grids seems to offer a promising research avenue. This system could combine the advantages of elastic gridshells while promoting complexity exploration *via* rigid gridshells.

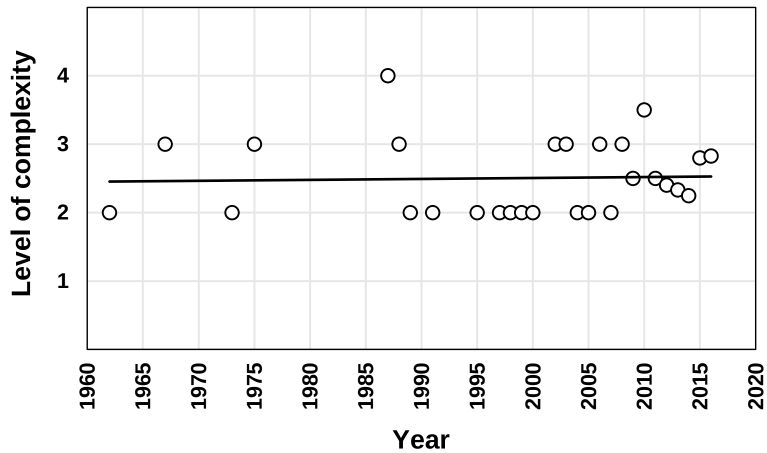


Fig. 5. The average level of shape complexity over time

The complexity of the architectural form did not progress over time, and the trend line stood between levels 2 and 3 with a slight increase in recent years. The correlation coefficient was 0.04, which indicates a lack of meaningful correlation. In other words, it is not possible to extrapolate the values to predict the shape of a gridshell over time. It is noteworthy, however, that the average complexity level has always been 2 or over, which means that the vast majority of gridshells adopt doubly curved geometries. This observation might be explained by the fact that a single vault does not offer the same structural capacity as a double curved shape (Mesnil 2013). Nonetheless, the industry seems reluctant to build folded surfaces, since few projects exceed the level 3 complexity. Hence, architects may well consider gridshells to design large columns-free spaces with continuous doubly curved surface, but they are still uncomfortable in designing discontinuous or folded grid.

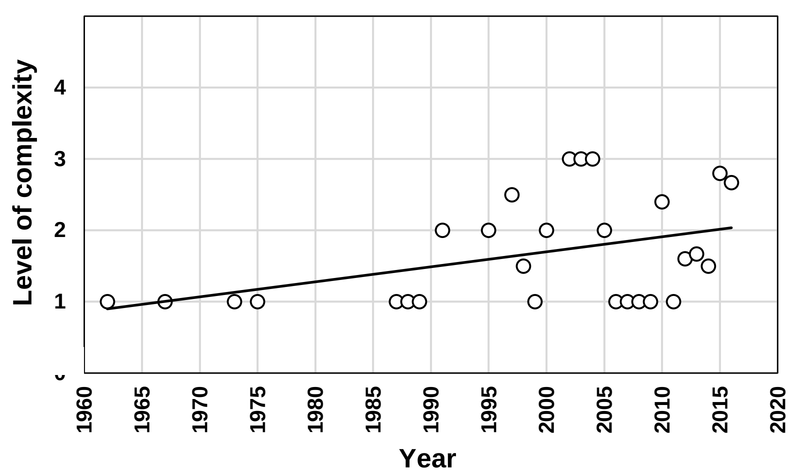


Fig. 6. The average level of structural complexity over time

Unlike form, structural complexity increased over time. The trend line is positive, and the correlation coefficient between weak to moderate with a value of 0.41. This observation means that it might be difficult to extrapolate the results and predict the level of complexity over time. However, Fig. 6 illustrates a general trend for complexification, which is consistent with the shift from elastic to rigid gridshells, as the erection of elastic gridshells with highly complex grid is challenging. A lattice composed of members spreading in every direction becomes stiffer and therefore difficult to deform. Overall, the structural axis suggests that architects and engineers are beginning to incorporate the capabilities of digital manufacturing tools into their workflow and are interested in their potential to design irregular and randomized lattice patterns with optimized structural behaviours.

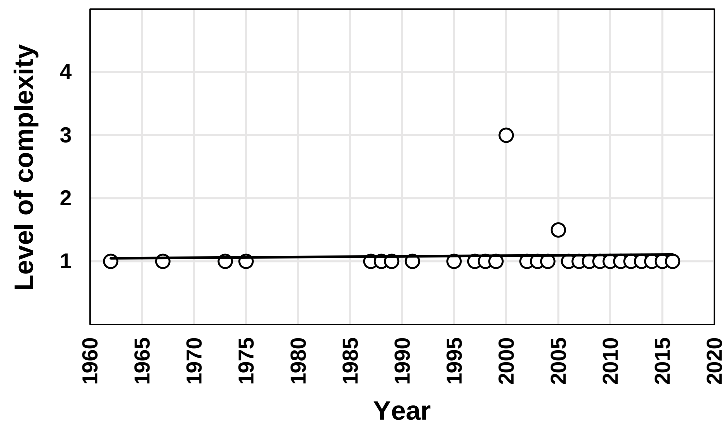


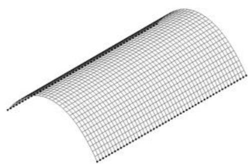
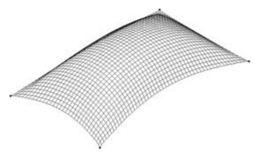
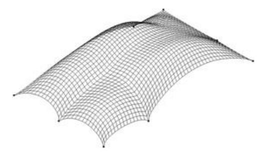
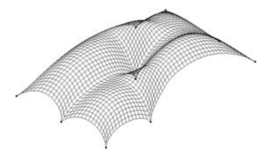
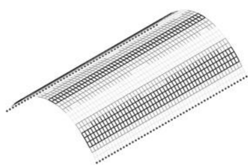
Fig. 7. The average level of material complexity over time

The results indicate little variability within the same project despite the use of different wood species from one project to another. The material axis revealed no correlation, with a coefficient of 0.04. Thus, the selection of a species is a matter of using local, available, and abundant resources rather than a conscious strategy to optimize the structural behaviour of the grid. For instance, the most complex case is the 'Expodach' canopy roof at the World Exhibition in Hanover in 2000 in which the use of plywood in the most solicited areas has tipped the project in the level 3. Because the corpus presents very few projects exploring the concept of material complexity, an experiment was conducted to validate the potential of wood in the construction of heterogeneous lattices.

CASE STUDY

Digital simulation was achieved using a parametric modelling software and a structural plugin performing finite element analysis (Preisinger and Heimrath 2014). It compared the amount of wood used for levels of complexity M1 and M4 relating to four different geometries when the displacement remains constant. The grid, the anchor points, and the load scenario being identical in each simulation, the size of the sections of the members, which are square, was the only variable. At level M1, the wood species is *Pinus strobus*, which had a Young's modulus of 9380 MPa. At level M4, the members were divided into three categories according to their displacements. The first third corresponds to *Pinus strobus* (9380 MPa), the second third to *Picea sitchensis* (11200 MPa), and the last third with the most solicited members to *Larix occidentalis* (14300 MPa) (Jessome 1977). Those species were selected because of the varied values of their Young's moduli to obtain more convincing results, which are detailed in the Table 4.

Table 4. Volume of Wood According to the Shape and the Material Complexity

	F1	F2	F3	F4
M1				
	265.06 m^3	684.78 m^3	163.39 m^3	166.76 m^3
M4				
	203.77 m^3	418.03 m^3	129.52 m^3	132.20 m^3

The results showed an approximate average material reduction of 26%, which represents a major diminution of the environmental impact of a building. The experimentation also suggested savings to be made from material complexity, even if the price of timber may greatly vary from one species to another. The improvement of the structural behaviour can lead to smaller member sections or larger cells of the grid. Moreover, the structure becomes a didactic object that reveals the most stressed areas and expresses the redirection of the loads to the supports. From an architectural point of view, the use of several species may generate particular atmospheres since each species has a unique colour and finish that greatly influences the user's perception (Watchman *et al*. 2016, 2017; Poirier *et al*. 2017). More than any other material, wood humanizes structures (Taggart 2011), creates warm ambiences (Fell 2010), and fosters rich and authentic architectural spaces (Browning *et al*. 2014). Overall, the structural and spatial benefits of wood justify the exploration of complexity in architecture, especially with timber gridshells.

CONCLUSIONS

1. This research has aimed to evaluate the complexity of timber gridshells in architecture and engineering. Sixty timber gridshells have been classified using a methodology characterizing projects according to their shape, structure and materiality. The goals were to identify constructive opportunities available to architects to design timber gridshells, to unveil the industry's past and current know-hows, and to predict trends and future possibilities.

2. A surge in the number of built timber gridshells has been observed in recent years. The surge of building reveals interest in this structural typology in the materialization of contemporary architecture, which is also characterized by digital explorations and complexity.
3. There is a transition from elastic to rigid gridshells. This observation can be explained by the increasing integration of new digital fabrication tools and their potential for mass customization, which provides more control on the final geometry by using a traditional way of erecting a structure.
4. A hybrid structural system could emerge from the latter finding by combining the potential of elastic lattices to create curved surfaces with rectilinear members and the potential of rigid lattices to recreate a more traditional way of building by stacking prefabricated elements one on top of another.
5. Double curve shapes are most relevant for exploring atypical geometries in addition to promoting superior structural behaviours. However, forms that fold back on themselves were categorized at the highest level of complexity. They also appeared to be more challenging to achieve.
6. Grid configurations become increasingly complex over time, an observation consistent with the increasing use of rigid gridshells. While orthogonal and equidistant grids are more suitable for the deployment of elastic lattices, a multiplication of non-standard grids is conceivable in the coming years. These non-standard versions offer the possibility to optimize the structural behaviour and create particular architectural ambiences.
7. The exploration of material complexity using timber is a concept that was practically non-existent in the corpus under study. However, preliminary simulations, which do not deal with the constructive feasibility of connecting two different wood species, show that the selection of several wood species of the same lattice can reduce the amount of wood used for an equivalent structural behaviour by approximately 26%. In addition, the use of natural materials such as wood reflects local ecology and enhances the sense of place unlike synthetic materials.

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