How advancements in manufacturing processes and design workflows could inform a new circular tectonic language of contemporary timber architecture?

Michał Kasperski

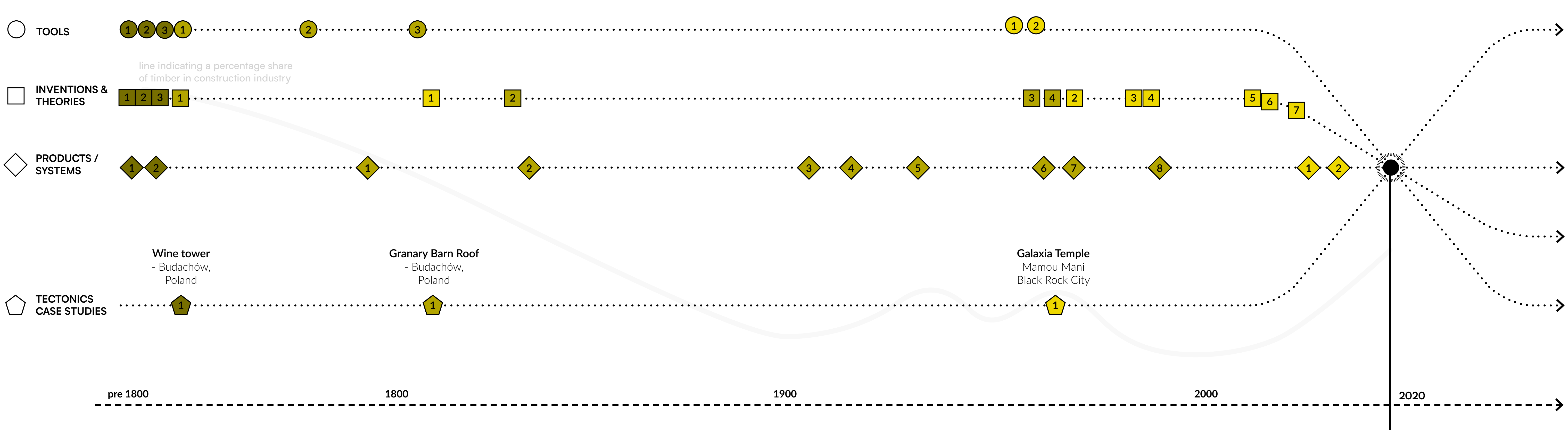
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft

Abstract

The objective of this research is to reflect on the contemporary meaning of tectonic culture in architecture and understand the evolution of timber structures in relation to the tools, methodologies, and technology available to produce them. An attempt is made to assess those tools in the context of challenges defined by the transition towards the circular economy. The goal is to set the grounds for discussion on how contemporary building technologies could be more closely integrated with natural and cultural systems in the light of the industrialisation of the building process. The research framework is built upon Christoph Schindler's periodisation model which describes the evolution of timber construction in three phases: a hand- machine- and information- tool technology. Analysing both tools of manufacturing and tools of design communication each phase is supported by detailed case study analysis. Key conclusions point towards possibilities of innovative timber tectonics to improve the cascading potential of wood in a circular economy and stress the importance of designing not only with local materials but more importantly in consideration of local manufacturing possibilities.

Keywords: *tectonics, timber construction, circular economy, forestry, manufacturing*

Appendix 1
Evolition of timber tectonics timeline



HAND-TOOL TECHNOLOGY

Tools:

1 **Wedge & chiesels** The earliest known wedges were made by people as early as 2.6 million years ago.
2 **Axe** - first true hafted axes are known from Mesolithic perios (ca. 6000 BC)
3 **Hand-saw** - 31st Century BC

Inventions & Theories:

1 **Log Construction** - Bronze Age around 3500 BC
2 **Iron smelting** - Late Bronze Age
3 **Cruck Frame** - evolved in early Anglo-Saxon times around 4th century

Products & Systems:

1 **Half-timbered system** - originated around 5th century BC built by Saxons and peaked in Medieval Europe
2 **Timber Frame Construction** - dates back to 200 BC

Case Study:

1 **Wine tower** - Budachów, Poland XVIII century

MACHINE-TOOL TECHNOLOGY

Tools:

1 **Sawmill -** The Dutchman Cornelis Corneliszoon (1550-1607) invented his type of sawmill by applying a pitman arm onto a wind mill, which converted a turning motion into an up-an-down motion
2 **Circular saw -** inveniton often credited to Gervinius of Germany in 1780
3 **Hand operated veneer machine** - Sir Marc Isambard Brunel is awarded the British patent in 1806

Inventions & Theories:

1 **Steam engine** - The first commercial steam-powered device was a water pump, developed in 1698 by Thomas Savery.
2 **Electric motor** - In February 1837 the first patent for an electric motor was granted to the US-american Thomas Davenport.
3 **Sketchpad CAD** - developed by Ivan Sutherland in 1963, it allowed the designer to interact with their computer graphically;
4 **Autodesk AutoCAD** - 1977 - first Architectural CAD drafting software

Products & Systems:

1 **Plywood** - Samuel Bentham, a British mechanical engineer made a patents application in 1797, what he described as a concept to laminate layers of veneers by gluing them together what is today known as plywood.
2 **Baloon Framing** - first prefabricated building system - George W Snow, invented the balloon frame in 1832 and revolutionized construction practice.
3 **Glue-laminated timber** - 1905 - First patent by Otto Hetzer
4 **Platform Framing** - developed as a progression of ballon framing by the 1910s,
5 **Panel Construction** - Developed in Europe around 1930
6 **Oriented-strand-board (OSB)** was conceptually invented and patented by Armin Elmendorf in 1965 as waferboard.
7 **Laminated-Veneer-Lumber (LVL)** - the invention of LVL was not until the 1980s after the invention of oriented strand board
8 **Cross-laminated timber (CLT)** - Austrian-born researcher Gerhard Schickhofer presented his PhD thesis research on CLT in 1994. Austria published the first national CLT guidelines in 2002

Case study:

1 **Granary Barn Roof** - Budachów Poland XIX century

INFORMATION-TOOL TECHNOLOGY

Tools:

1 **CNC milling machine** developed in 1952, Richard Kegg, in collaboration with MIT called the Cincinnati Milacron Hydrotel. Five years later, in 1958, he filed a patent for a "Motor Controlled Apparatus for Positioning Machine Tool".
2 **First robotic arm** introduced by Unimate in 1962. The arm was invented by George Devol and marketed by Joseph Engelberger.

Inventions & Theories:

1 **Punch-card loom** - invented by Joseph Jaxquard in Lyon France around 1801
2 **Microchip -** the integrated circuit invented by a Texas Instruments engineer Jack Kilby in 1958
3 **World Wide Web** - initiated by Tim Berners-Lee in 1989
4 **BIM concept** - Building Information Modeling The concept of BIM has been in development since the 1970s, but it only became an agreed term in the early 2000s.
5 **Grasshopper** developed in 2007 by David Rutten at Robert McNeel & Associates
6 **Parametricism** term coined by Patrik Schumacher in 2008
7 **Circular Economy** - as defined and widely promotend from 2009 Elen McArthur Foundation - propsting first models and international guidelines

Products & Systems:

1 **Wiki house & open systems lab** - open source project for designing and building houses initiated by Alastair Parvin in 2011
2 **Katerra** - company founded in 2015 offering technology-driven off-site construction systems

1 **Case study:**
Galaxia Temple - Studio Mamou Mani & Format Engineers

1. Introduction

Working and building in a circular economy challenges many of the conventional solutions in the building industry and establishes a new dimension of tectonic practice - linking the materials used and the ways they are processed and put together, with the ecosystems they are part of. This ecological perspective evolves in parallel with the technological perspective asking us, young designers, to understand circularity in the light of industrialisation of the building process.

The point of this study is to reflect on the contemporary meaning of tectonic culture in architecture and understand the evolution of timber structures in relation to the tools, methodologies, and technology available to produce them. The goal is to assess those tools in the context of challenges defined by the transition towards the circular economy and set the grounds for discussion on how contemporary building technologies could be more closely integrated with natural and cultural systems.

The study will revolve around the two concepts, the one of architectural tectonics and circular economy – both compound definitions – therefore it is important to first describe the scope at which they will be looked at in the further analysis.

What's interesting is that linguistically *tectonics* closely relates to the wood as a material (Christiensen, 2014) as originally the Ancient Greek *Tektōn* was used in relation to carpenters, joiners, and shipbuilders. Karl Christiansen analysing the origins of the word tectonics concludes that *"In general, the concept to a much greater extent indicates a method rather than any material aspect, namely the process of producing, manufacturing, processing, bringing about and causing, even breeding."* It is with that understanding in mind, that the following research gives more attention to methods and tools of manufacturing and design instead of material properties which nevertheless play a crucial role in shaping them.

When talking about tectonics in the architectural context it is impossible not to mention Kenneth Frampton – a central figure in contemporary discussion of the topic - who defines architectural tectonics as an act of using construction in a way that it becomes an integral component of the design and actively helps to shape it articulating both the poetic and the cognitive aspects of its substance. (Frampton, 1995)

Most of the discourse in the field of tectonics following Frampton was preoccupied with similar notions of poetic of construction, telling the story of its making. But in recent years, in the context of unprecedented evolution of design and manufacturing tools and increasing climate emergency Anne Beim rightly noted that *"Most of the prior definitions of tectonics and the making of buildings have been responses of profoundly different and much less complex circumstances in architectural construction than we know of today"* (Beim, 2014) With her concept of *'Tectonic ecologies'* (Beim, 2019) she introduces to tectonic discourse *"the correlation between the materials used, the ecosystems they form a part of and the resources we share as common members of the global community"* putting building culture in a broader context of natural and cultural systems. And as the goal of this research is to analyse the timber tectonic culture in the light of circular economy principles, this more complex, ecological, and systemic component stressed by Anne Beim cannot be overlooked.

When it comes to the concept of *circular economy* there are multiple definitions varying in their focus and scope, but for the purpose of this work, it is best to be understood according to *three key principles* proposed by Ellen McArthur Foundation (2013) as it is a definition most closely linked to and driven by design and fabrication – *to eliminate waste and pollution, to keep products and materials in use and to regenerate natural systems.*

2. Method

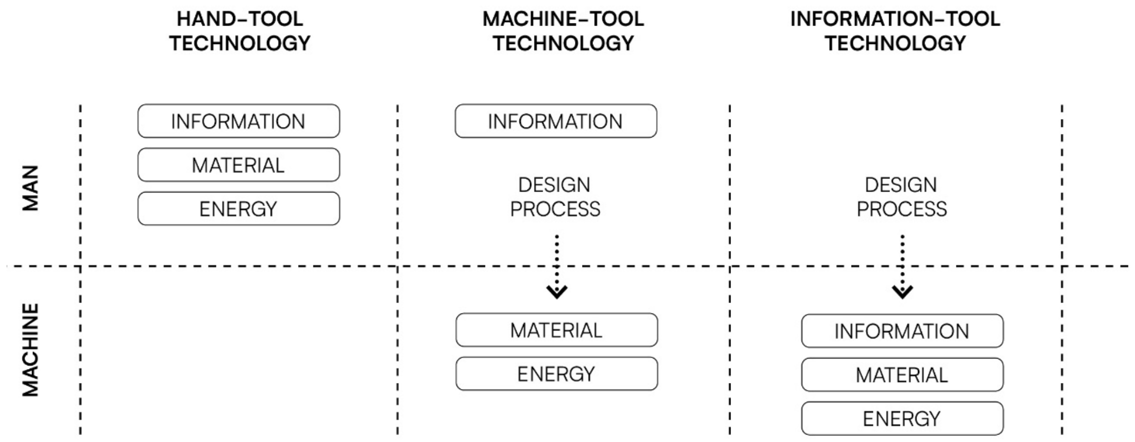


Figure 1. Diagram explaining concept behind Christoph Schindler's periodisation model

The research framework is built upon a periodisation model proposed by Christoph Schindler (Schindler, 2011) which describes the evolution of timber construction in three phases: a 'hand-tool technology', a 'machine-tool technology' and an 'information-tool technology'. In order to better understand tectonics, one has to better understand the tools and processes involved in shaping and creation of building components. Thus, the periodisation model provides a useful lens to investigate a changing timber tectonic as it focuses on the evolution of manufacturing technology and its relation to material, energy and information. Through the correlational research and pattern analysis during the literature study a subjective timeline of timber tectonics evolution was developed, serving as an overview and point of reference throughout the analysis. The results are presented in Appendix 1 trying to distinguish in each period the key tools, inventions and products which defined it.

Each of the consecutive sections of the paper focuses on one period. By means of a literature study and focused case study research – studying existing projects by re-drawing, re-modelling, and simulation through digital models - reflects on the consequences this evolution has on timber tectonic thinking. The following chapters should be read in parallel with the corresponding Appendices 2,3 & 4 presenting the key analytical drawings of described case studies and supporting images.

Each section was divided into two parts - tools of production and tools of design communication. A distinction deemed necessary because as architects and designers we rarely manufacture the things we design and operate with tools focused on describing and communicating the intent for the final design. How those two sets of tools evolved and mutually informed each other plays an important role in defining the tectonics of final structures. Each section concludes with a short reflection on the tectonic consequences each technology introduced to timber construction.

3. Hand-tool technology

3.1. Tools of manufacturing

The production of timber building components in the phase of hand-tool technology was completely reliant on a man in both handling of the material and energy used to process it. The foundational tool of timber processing, used to turn logs to hewn timber was wedge followed by axes and chisels – first used to split and shave the natural material. The components were largely defined by the material not only in scale but also in shape and its finish as it was split along the grain of the piece of wood before the development of the saw.

What is interesting is that many of those seemingly primitive tools have not significantly changed their characteristics and basic principles in comparison to their contemporary equivalents, just refined their quality and precision (Refer to the Appendix 2)

3.2. Tools of design communication

The craftsman was in complete control of the design, material, and its processing – one directly informing the other – but more importantly, he was the direct medium of information transfer. As a result, the information loop was very small, and notes and guidelines were often directly inscribed onto the element during manufacturing – following often a highly personalised code. This system was used to define the location of an element in relation to the rest of the structure often by simply indicating its adjacent element and allowed for simple transfer of information from carpenter to assistants and workers on site. This system was used to define location of an element in relation to the rest of the structure often by simply indicating its adjacent element and allowed for simple transfer of information from carpenter to assistants and workers on site.

3.3. Case study: Budachów Wine Tower

(For detailed drawings please refer to Appendix 2) It's an example of XVIII century timber framing – a so called half-timbered frame. It perfectly exemplifies the hand-tool processing expressed through its non-uniform structural members and spans limited by the tree sizes. The traces of tools used, inaccuracies and ad-hoc workarounds are all visible at closer inspection. The defining feature of this very functionalist structure is the outdoor terrace gallery on the first floor. A structural element that made it possible was the arched bracket transferring load to the main columns – which utilised the bowed timbers from skewed tree trunks - a proof of a direct relation between material source and component characteristic to this period. Interestingly, the structure's simple tectonics enabled its successful complete disassembly and relocation to an open air museum some 30 years ago – an example of XVII century circularity?

3.4. Tectonic consequences

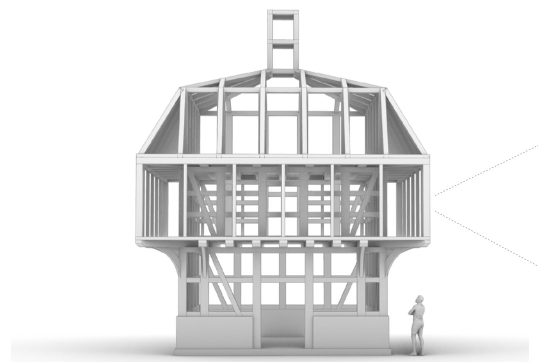
The design in the hand-powered period was often defined directly by the size of the trees themselves – which directly shaped the tectonic and scale of resulting structures. It was characterised by a very close and direct understanding of the material and resulting structures were inherently characterised by clear tectonics working with not against the material. The scale of the components was deliberately kept suitable for manual handling and their precision was limited by the material source and skill of the human hand.

Despite their limitations the knowledge embedded in traditional building practices and especially their close understanding of material properties and their sources formed the basis for new innovative solutions.

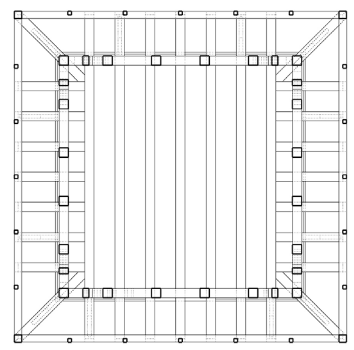
Appendix 2
hand-tool technology

Case Study:
Wine Tower - Budachów, Poland

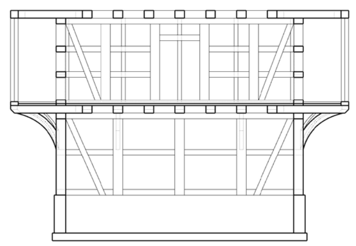
An example of XVIII century timber framing a so called half-timbered - a method of building where walls are constructed of timber frames and the spaces between the structural members are filled with various materials such as brick or wattle and daub.



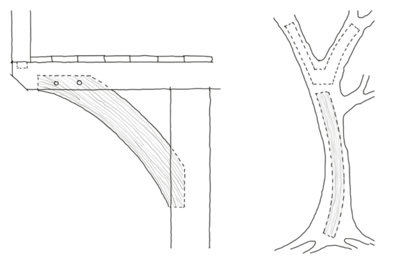
This two-storey structure with a square plan was a part of a complex of manor buildings and located on a top of a south-facing slope with wineyards. A gallery on the first floor provided an overlook of the entire plantation. Generous canopy protected equipment used in wine juce extraction and processing.



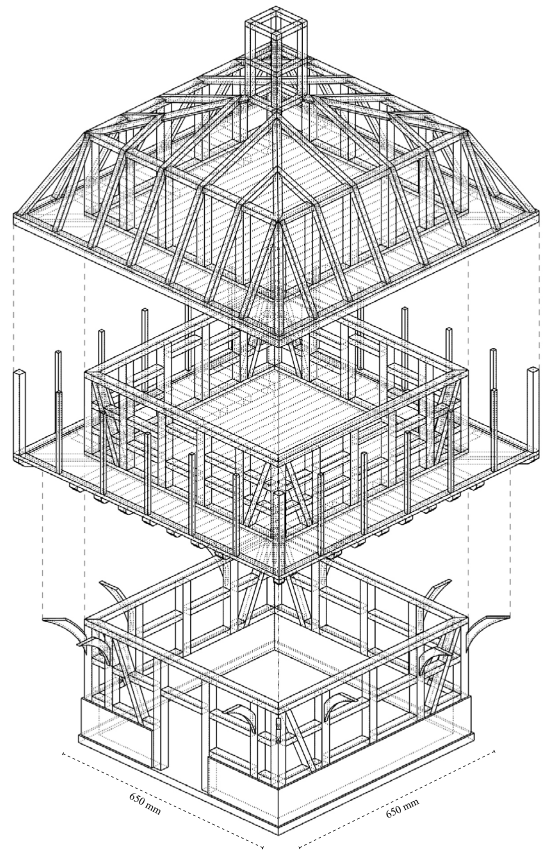
Plan - based on a 6.5 x 6.5 m square with overhanging balcony around entire perimeter (drawn by an author)



Section cut throuhg ground and first floor showing half-timbered structure

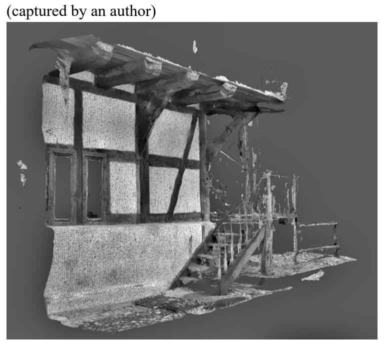


Detail of a curved timber element supporting the overhanging balcony on the first floor and its origin (drawn by an author)



Exploded axonometric 3D model of the entire structure (modelled and drawn by an author)

A 3d pointcloud scan of a fragment of an original structure captured on site - the only method of capturing which does not simplify irregularities of the hand-tool system (captured by an author)



Selected photos of structure and details in context (taken by an author)

Tools of manufacturing:

Roman Jack Plane, Pompei 79 AD. and a Roman Axe head ca. 500-200 BC. (source: Goodman, 1964)

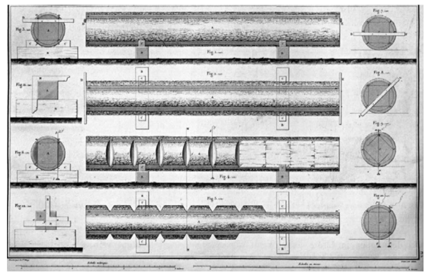


Diagram showcasing how trunk is turned into a beam (source: Emy 1841)

A carpenter using an axe in a proces pictured on the infographic above (source: Goodman, 1964)

Tools of design communication:

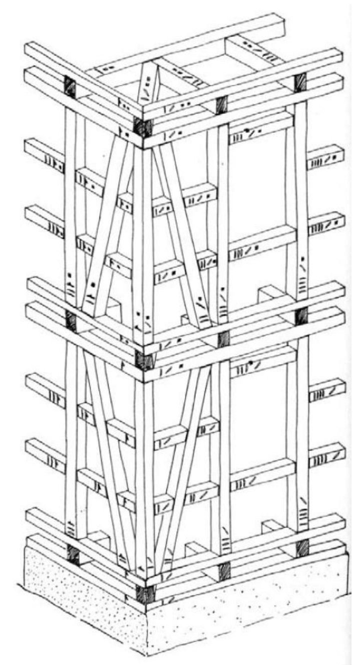
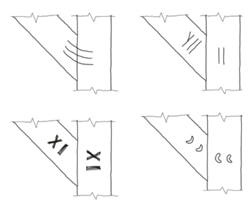


Diagram showing assembled timber frame highlighting reference joinery marks (source: Weiss 1991, s.84)



Examples of joinery marks and corresponding structural elements (drawn by an author)

4. Machine-tool technology

4.1. Tools of manufacturing

Industrialisation was characterised predominantly by standardisation – and a lot of effort was directed towards the production of large quantities of components mostly linear and equally dimensioned.

This has led to the appearance of standard dimensional lumber based on which entire systems like balloon frame or platform frame were developed and their tectonic quality was determined mostly by the constructional grid and regular spacing of structural elements. Soon, not only single structural members but entire building components were assembled in factories paving the way for increased off-site prefabrication, elevating the quality of detailing. A wide range of innovation was also driven by the invention of rotary cutting machines and a process of lamination popularized in Europe by Otto Hetzer. (Müller, 2000)

As a result of those changes the material and energy required to process it, was transferred to the machine – but the guidelines and information of what to process and how was still in complete control of the operator with precision ensured by the mechanical tools. (Schindler, 2007)

4.2. Tools of design communication

Ways of design communication evolved significantly during industrialisation as further specialisation led to the separation of building trades. The carpenter was now usually responsible for the manufacturing of components previously specified by architects and engineers so the language of 2d technical drawings and standards developed significantly and used precise units of measurements and standardised elements.

4.3. Case study: Budachów granary barn

(Please refer to Appendix 3) A great example of a structure defined by machine-tool technology is a roof of an early industrial granary barn – constructed a century later in the same area as previously discussed wine tower. Its tectonics is dictated by a regular spacing of a single structural truss module – a prefabricated component made out of standardised timber lengths.

Traditional wood joining was mostly replaced by screws and connectors although as an early industrial structure some traces of traditional joinery are still visible in the trusses which enabled an uninterrupted span of 15m with the highest point at almost 9.5m. It's an example of how mechanisation led to increased number of elements in assembly and complexity of the overall structural system while at the same time ensuring its precision.

4.4. Tectonic consequences

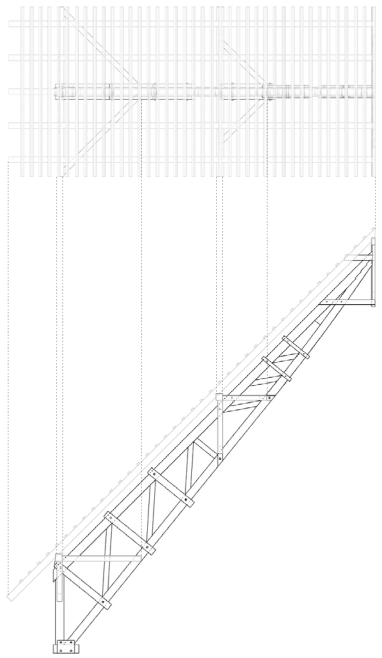
As a consequence of standardisation, single components had to become reliable and interchangeable which in the case of such a heterogeneous material such as timber required its homogenisation. This led to the most significant tectonic consequence for the material - the process of lamination and turning the linear log into planar sheets of plywood and boards which presented architects and engineers with a set of completely new possibilities – introducing spans and shapes previously unattainable in timber construction limited by the tree dimensions.

Another factor that significantly affected the tectonic expression was a replacement of traditional timber joints with more readily available screws, ties, and more elaborate connectors highly altering what timber elements on their own were capable of.

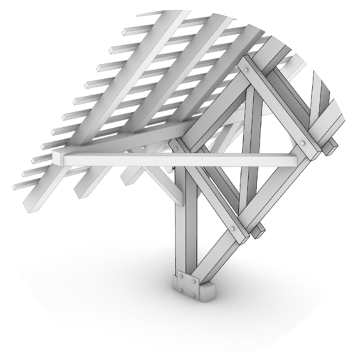
Appendix 3
machine-tool technology

Case Study: Granary Barn Roof Budachów

An early industrial granary barn - a masonary structure topped with an impressive pitched roof providing an unobstructed 15 m long span and covering an area of 850m² thanks to prefabricated timber trusses made out of standardised timber sections.

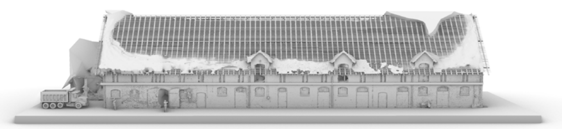


Single truss - a key standardised and repetitive structural element in plan and elevation (drawn by an author)

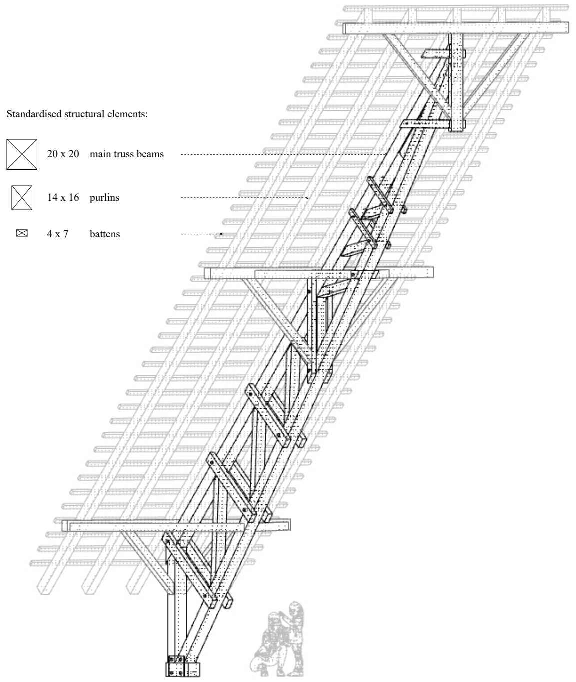


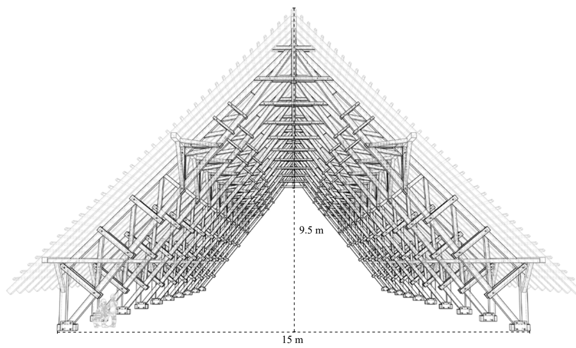
Zoomed in detail of the bottom of the timber truss transfering load to masonry walls below (modelled by author)

A 3d pointcloud scan of a fragment of a lower part of the truss captured on site for 3d model reference



A 3d model of an entire structure merging a photogrammetric 3d scan with detailed timber roof structure overlay giving a sense of scale (modelled by an author)



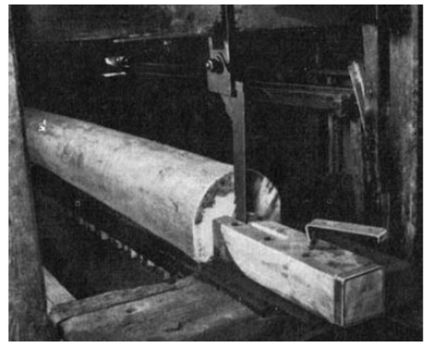


Above: an axonometric view of a single Truss member with the supported roof plane - an assembly of standardised dimensioned timbers.
Below: a perspective view of entire roof showing how system of identical repetitive elements creates a spatial enclosure (modelled by an author)

Photo of the truss structure form interior showcasing the scale of the elements (taken by an author)

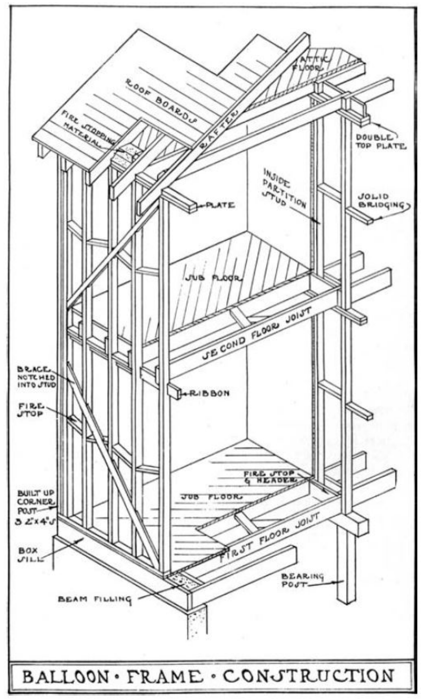
Tools of manufacturing:

Industrialised timber workshop factory line, New Albany, Indiana USA (source: Kelly 1951)

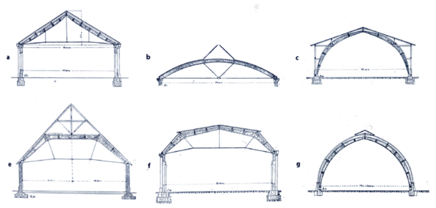


An example of an early frame saw cutting log into dimensioned timber (source: Finsterbush 1987)

Tools of design communication:



An infographic presenting standardised Ballon Frame construction stystem (source: Holman 1929)



Extract from the catalogue of glulam roof solutions byt company of Otto Hetzer (source: Muller, 2000)

5. Information-tool technology

5.1. Tools of manufacturing

The information-tool technology period fundamentally challenged the relationship between tools of production and tools of design. There is no longer a sharp boundary between the two and therefore the close engagement with materials and manufacturing tools and processes is intrinsic to the design process. With the appearance of electronically controlled machines and parametric design tools variable components could be manufactured without any losses in efficiency and accuracy of production.

The ease of processing of wood and already advanced mechanisation of the timber industry made it a perfect material to quickly adjust to those inventions and fit in a digitally controlled workflow.

5.2. Tools of design communication

Parametric models introduced a completely new way of development and communication of design geometry. In a model defined by the parameters the form is no longer drawn but there is a defined process that generates the form based on current inputs which could be constantly adjusted. Such a design process creates a new common ground for design information exchange between architects, engineers, and manufacturers even early in the design process while allowing for its real-time adjustment.

More significantly, in the light of this research, it created an opportunity to incorporate material properties and manufacturing constraints as parameters in a design process – tectonically bringing the design intent, tool and manufacturing process closer together again.

5.3. Case study: Galaxia temple – Mamou Mani

The tools and process of communication described above are perfectly exemplified by a Galaxia Temple structure designed by Mamou Mani and Format Engineers

By recreating the parametric model of this structure I was able to understand the origins and key parameters behind the final geometry and showcase how using the same definition it is possible to generate multiple alternative solutions. (please refer to Appendix 4). A model like this was successfully used by architects to communicate with structural engineers who then used the same inputs to structurally test and optimise the geometry in Karamba 3D (Format Engineers, 2018). They adjusted design parameters so that all structural members could be assembled from simple 2x4 and 4x4 inch timber sections. What's interesting is that from the beginning the structure was meant to be assembled largely by unskilled volunteers (Mamou-Mani, 2018). Despite its geometric complexity, parametric workflow enabled automatic generation and manufacturing of precisely labelled kit of parts and connectors which then could be assembled by anyone with a clear guideline sheet and a hand-drill. (Appendix 4 – tools of design communication)

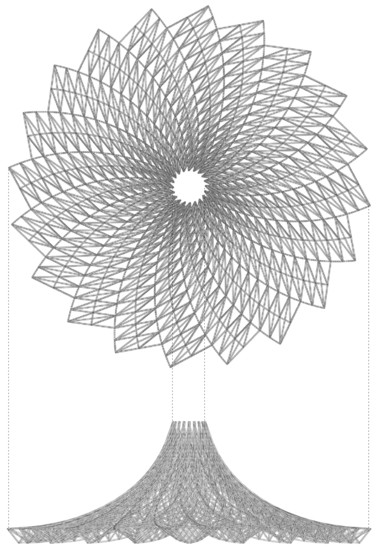
5.4. Tectonic consequences

As was shown by case study this evolution allowed not only for manufacturing of more complex elements but also made feasible complex assemblies of simple and widely available components. Information-controlled tools made manufacturing of individualised components economically feasible therefore allowing for a greater diversity of structural components in the system. Despite driving further specialisation it tightened co-dependence and collaboration of building construction trades limited by early industrialisation. A fully-digitalised processes at large became less forgiving for material inaccuracies and favored more homogenised timber components – glulam, CLT, LVL's and composite boards.

Appendix 4
information-tool technology

Case Study:
Galaxia Temple - Mamou Mani

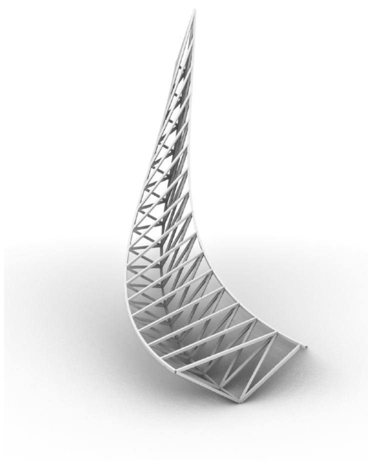
An early industril granary barn - a masonary structure topped with an impressive pitched roof providing an unobstructed 15 m long span and covering an area of 850m² thanks to prefabricated timber trusses made out of standardised timber sections.



Plan and elevation of a recreated Galaxia Temple, matchin original proportions - drawn by an author.
The whole structure is mostly made out of 4x4 and 2x4 inch timber sections and prefabricated steel connectors.

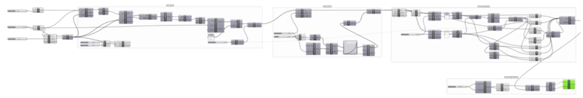
4 x 4 inch timber section

2 x 4 inch timber section

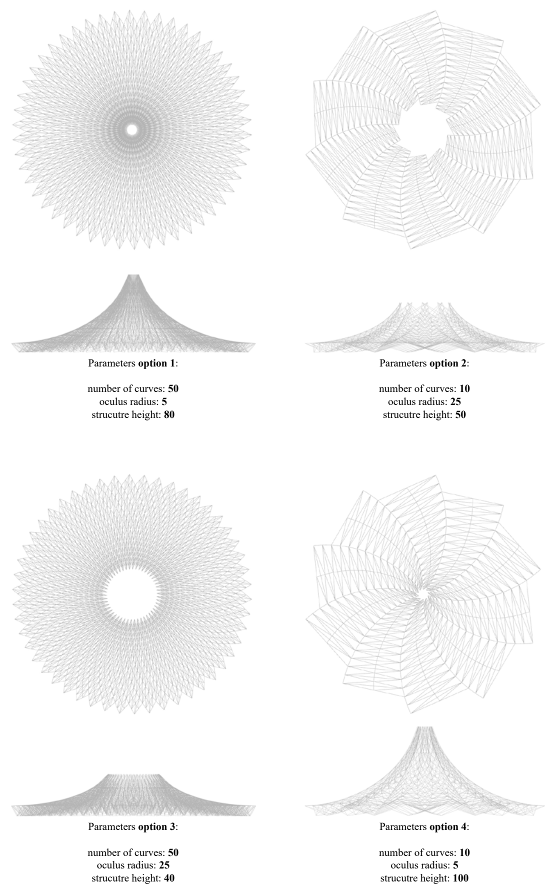


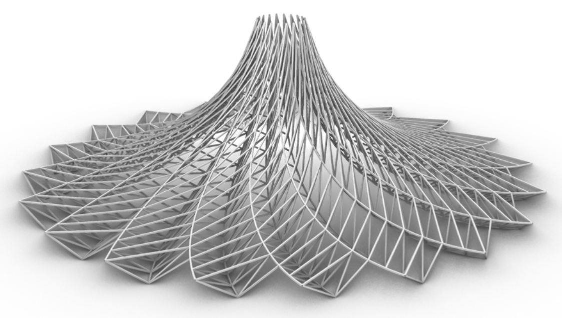
An isolated single piece of spiral timber spaceframe - the entire structure consists of 20 of such assemblies.

Aerial photograph of a completed structure on site (formatengineers.com, access: 05.01.2022)



An entire Grasshopper definition used to describe the adjustable parametric model defining key structural principles of the final form (recreated by an author)



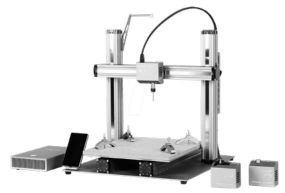


Above - four variations of the structure generated using the same definition by changing key parameters and a perspective view of a 3d model optimised to resemble the original structure (modelled by an author)

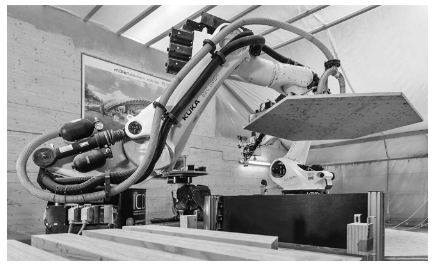
Series of photos from construction site showing - simplicity of the structural elements and different stages of assembly (formatengineers.com, access: 05.01.2022)

Tools of manufacturing:

5-axis industrial CNC machine by Maka (www.maka.com, access: 05.01.2022)

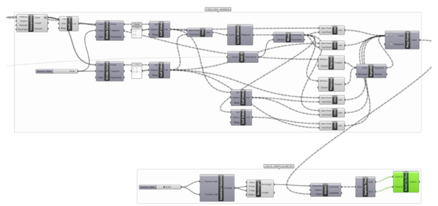


Affordable table-size Snapmaker 2.0 with 3-axis CNC module (snapmaker.com, access: 05.01.2022)

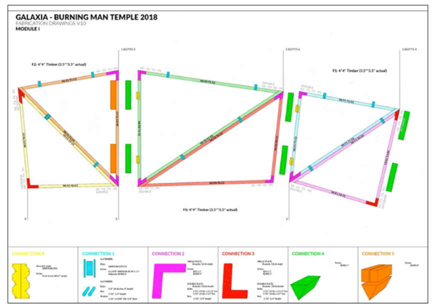


KUKA industrial robotic arm handling pieces of plywood for numerically-controlled fabrication (kuka.com, access: 05.01.2022)

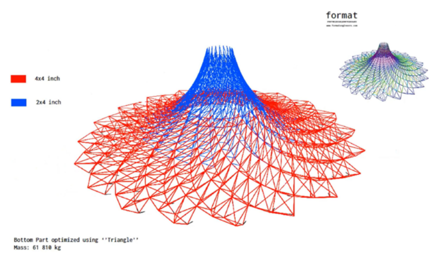
Tools of design communication:



A fragment of grasshopper definition used to manipulate input geometry parameters (recreated by an author)



An assembly guide sheet of a single element of a space frame with exact join instruction (formatengineers.com, access: 05.01.2022)



Parametric model adapted by engineers specifying distributin of 4x4's and 2x4's to optimise the structure (formatengineers.com,

6. Conclusions

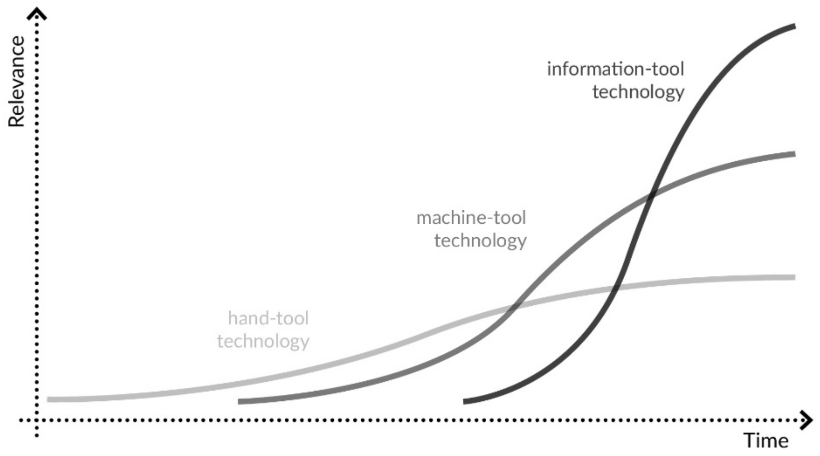


Figure 2. Schindler's periodisation model – relevance over time (Schindler, 2009)

After critically reflecting on the research methods I used, they might be considered selective and simplistic given the potential breadth of the study but focusing on particular case studies and connecting isolated events enabled me to translate global phenomena into more concrete and tangible examples to analyse.

The periodisation model proposed by Schindler while seemingly chronological stresses the fact that the development of new methodologies always builds upon the previous discoveries which although quickly surpassed by innovative solutions still remain relevant and develop over time. Reflecting on the study it is interesting to note how some ideas reverberate over time in a slightly altered form. From carpenter's scratches system on corresponding beams to laser engraved codes on digitally manufactured components. From solid log constructions to lightweight and modular frame systems now competing again with solid timber walls in form of CLT panels.

A broad overview of timber tectonics evolution enabled me to somehow begin to position myself within this evolutionary timeframe and gave me a better understanding of both origins and direction of those changes. Even when we look at such seemingly novel concepts as circular economy based on a premise of component reuse - the Wine Tower with its demountable solid oak half-timbered structure, relocated some 100 km away from its original site - is a perfect example of XVII century circularity. Perhaps unintentionally but buildings of the hand-tool technology have been well suited for disassembly so there are important lessons to be drawn regarding the approach to joinery and conservation and there is no reason why this way of thinking could not be reintroduced at wider scale with modern ways of construction.

There seem to be a significant link between timber tectonic strategies and the cascading potential of wood in circular economy which has been a subject of an increasing amount of research in recent years (Höglmeier 2013). While studying the Sankey diagram of wood flows in Europe (Appendix 5) we can see that only about 30% of harvested forestry biomass in Europe is turned into wood products, nearly 40% is burned for energy and the remaining turned into pulp products. In the light of long-term forestry management and carbon capture, we should encourage increasing share of long-lasting products in timber sector (Bellasen, 2014) As architects we could contribute to that by adapting tectonic strategies for disassembly and creating a long-term value by elevating the design standards and durability – both structural and cultural – of our design proposals.

In context of circular economy timber is a unique natural resource which in case of Europe has a potential to significantly reduce the dependency on non-renewable materials in construction. The information-driven tectonics creates opportunity to directly link data from forest sector with demands of the industry and in a way relate material to the natural world in deepest sense before it becomes objectified construction component.

What can be also concluded from the study overview is that undoubtedly the industrial transformation is followed by an increasing specialisation. Contemporary timber construction is a more collaborative practice than ever and requires from us designers an engagement with the recent 'tools of design communication' to ensure smooth collaboration with other specialists.

An important premise of circularity is to decrease the reliance on global supply chains and support whenever possible a multi-scalar fabrication ecosystem. What should travel far and wide is information and knowledge, not materials. This was exemplified by Galaxia Temple structure, designed using latest parametric workflows in UK while being conscious that the structure will be assembled by mostly unskilled volunteers in USA desert from most basic local timber sections.

An important takeaway for me is that circular timber tectonic must take into consideration not only local materials available for construction but, even more importantly, the state of local manufacturing possibilities. Is the local industry operating predominantly in information-driven technology, is it mechanised, is it remote and completely reliant on craftsmen? I believe that architects and designers in the age of transition towards circular economy should be conscious of that, adapt accordingly and, in some cases, attempt to challenge and drive the advancement of local manufacturing potential in given area through architectural proposals.

References

1. Christensen, K. (2014) 'An Etymology of Tectonics', in Beim, A., Madsen, U. (eds.) *Towards an Ecology of Tectonics: the need for rethinking construction in architecture.* Stuttgart: Edition Axel Menges, pp. 26-27.
2. Frampton, K. (1995) *Studies in Tectonic Culture: The Poetics of Construction in the Nineteenth and Twentieth Century Architecture*. Cambridge, Massachusetts: MIT Press.
3. Beim, A. (2014) 'An Ecology of Tectonics', in Beim, A., Madsen, U. (eds.) *Towards an Ecology of Tectonics: the need for rethinking construction in architecture.* Stuttgart: Edition Axel Menges, pp. 20-23.
4. Beim, A. (2019) 'Tectonic ecologies in architecture – a critical perspective in a time of transition' in Cruz P. (ed.) *Structures and Architecture: Bridging the gap and crossing borders.* Lisbon, Portugal: CRC Press, pp. 11-27.
5. Ellen MacArthur Foundation (2013) *Towards the Circular Economy: Economic and business rationale for an accelerated transition.* Available at: https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an (Accessed: 5 January 2022)
6. Schindler, C. (2009) Ein architektonisches Periodisierungsmodell anhand fertigungstechnischer Kriterien dargestellt am Beispiel des Holzbaus. PhD thesis. ETH Zurich
7. Goodman, William Louis. *The history of woodworking tools.* London : Bell, 1964
8. Emy, Amand-Rose. *Traité de l'art de la charpenterie.* Paris : Carilian-Goeury [etc.], 1841
9. Weiss, Walter. *Fachwerk in der Schweiz.* Basel : Birkhäuser, 1991
10. Müller, C. (2000) *Holzleimbau – Laminated Timber Construction*. Basel: Birkhauser.
11. Format Engineers (2018) *Temple Galaxia.* Available at: https://formatengineers.com/projects/2018-09-02-galaxia.html (Accessed: 05 January 2022)
12. Mamou Mani (2018) Project Galaxia. Available at: https://mamou-mani.com/project/galaxia/ (Accessed: 05 January 2022)

13. Burnham, K. (1951) *The prefabrication of houses : a study by the Albert Farwell Bemis Foundation of the prefabrication industry in the United States.* Cambridge: MIT Press.
14. Finsterbusch, E. (1987) *Vom Steinbeil zum Sägegatter : ein Streifzug durch die Geschichte der Holzbearbeitung.* Leipzig: VEB Fachbuchverlag.
15. Höglmeier, K., Weber-Blaschke, G., and Richter, K. (2016) 'Evaluation of Wood Cascading', in Dewulf, J., Meester, S., Alvarenga, A., (eds.) *Sustainability Assessment of Renewables-Based Products: Methods and Case Studies*, New Jersey: John Wiley & Sons.
16. Bellassen, V., and S. Luyssaert. (2014) 'Carbon Sequestration: Managing Forests in Uncertain Times', in *Nature* 506, pp. 153-155.
17. Mantau, U. (2012) *'Wood flows in Europe'*, EU 27 Project report.