A CRAFTED KIT-OF-PARTS

HEALING THE HUGO R. KRUYTGEBOUW WITH TIMBER FRAMING AND BIOPHILIC DESIGN STRATEGIES

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ABSTRACT

This paper conducts a material assessment of timber and concrete, analyzes historic and modern wood-to-concrete joinery techniques and proposes a healthy and circular building approach using timber framing and biophilic design strategies to revitalize existing 1960s and 70s Dutch concrete structures. It argues for the re-nurturing of natural and local ways of making in existing structures in order to challenge the contemporary building practices in the Netherlands, enhance the sensory relationship humans have with the built environment, and advance people's health, fitness, and well-being. This is specifically applied through a research-by-design approach to the Hugo R. Kruytgebouw located in Utrecht University Campus.

KEYWORDS: *TIMBER, WOOD-TO-CONCRETE, BIOPHILIC DESIGN, HUMAN WELL-BEING, HEALTHY BUILDINGS*

I. INTRODUCTION

Close to a hundred-thousand dwellings built during the 1960s and 70s have reached a building life-cycle of fifty years, making more than 50% of the total Dutch building stock in need of a revision to prepare them for a second-life (de Rouw, 2018; Manifesto, n.d.). Many urgently need a new facade, yet one must remember that within the facades of these buildings often lie toxic materials, such as asbestos (Pijpers, 2021). Having to face challenges of refurbishment (such as toxic materials), questions of material awareness and future construction methods arise. With the building sector accounting for 25-30% of the total waste world-wide, showing how the circular economy can be applied in architecture could help spread awareness about the benefits of material reuse, and material embodied energy in order to avoid the pollution and depletion of natural resources (Beim et al., 2019; Uddin, 2020).

To meet the 2050 climate neutral goal set by the Dutch government and European Union, the existing building stock of the Central Dutch Government Real Estate Agency is facing major renovation challenges that have a big effect on the building industry, building technology, and building material choices (Snijders, 2020). The building industry currently accounts for 36% of the world's final energy use and 39% of energy and process related emissions (IEA, 2019). Concrete remains as the most used material for construction in the Netherlands since directly after the Second World War (Dzhibov, n.d.; White, n.d.). Concrete continues to be a universal environmental problem due to the production of cement. It is estimated that 600 kg $C0_2$ is emitted into the atmosphere per 1 ton of cement (Leschs Kosmos, 2022). Fifteen million cubic meters of concrete is used every year in the Netherlands, resulting in 3.7 Mt of $C0_2$ per year (MVO Nederland, 2021).

Before industrialization, timber construction was all over Europe and Asia. Timber was considered to be the most important material for building (Hudert & Pfeiffer, 2019, p. 101). Due to the vast local availability, ease of use, and good structural properties of timber, skilled craftsman relied on press-fit timber joints for centuries without the use of metal (p. 101). This changed when metal fasteners became cheaper, extinguishing a local tradition from many European and Asian countries (p. 101). Even today, the 'new' construction materials such as cast iron, steel, and concrete remain sold at lower prices because their demand in the global building and construction industry remain high (p. 101). Although the environmental cost also remains high, these costs are left out of the pricing equation due to little action and initiative shown by lawmakers and the building and construction industry (p. 101)(See Appendix A).

The existing concrete buildings in The Netherlands from the 1960s and 70s rely heavily on concrete and non-natural materials. By replacing the existing materials and opting to use non-toxic, natural construction matter in the renovation process, these buildings can be transformed to improve overall human well-being and have a smaller footprint impact on the environment. Designing a kit-of-parts to 'heal' 1960s and 70s Dutch concrete buildings could serve as a resource for the Dutch government to reduce emissions by providing these buildings with a second-life that is carbon neutral, nature inclusive, energy-efficient, and potentially beneficial to the Dutch housing shortage. 'Healing' these concrete buildings is done with local and circular principles by using timber framing and biophilic design strategies since there are clear physiological benefits when humans are surrounded by products from the natural environment (Delagran, n.d.).

1.1. Problem Statement

Existing 1960s and 70s concrete buildings in the Netherlands do not meet state-of-the-art standards. They are poorly insulated, lack the integration of natural materials, and are built without the circular economy in mind (Larsen & Marstein, 2000; Beim et al., 2019). The human consumption of natural resources is out of balance. In fact, human-made mass has now surpassed all living biomass. If current trends of annual building materials continue, manufactured materials will weigh more than twice as much as all natural life on Earth by 2040, approximately 2.2 trillion tons (Stone, 2021).

1.2. Research Question

By conducting historic and modern analyses on wood-to-concrete connections (historic analyzes refer to wood-to-stone connections since this technique is more applicable to the local context) and analyzing the existing concrete structure of the Hugo R. Kruytgebouw, a design approach can be proposed for the renovation of the Kruytgebouw in Utrecht University. This allows for the building to be brought up to state-of-the-art standards and perform better for its users' well-being. This paper searches for historic, circular, and resilient building practices as well as the re-nurturing of nature in our built environment. Hence, the main research question for this paper is the following:

RQ: How does examining historic and modern wood-to-concrete connections lead to a local and circular building approach which 'heals' existing 1960s and 70s concrete buildings?

Additionally, several sub-research questions have been created to help support the analysis.

SRQ1 : How can press-fit timber connections contribute to reducing material waste and $C0_2$ emissions during the construction process?

SRQ2 : What are the advantages and disadvantages of historic and modern wood-to-concrete joinery methods?

SRQ3 : How can biophilic design and timer 'heal' the existing Hugo R. Kruytgebouw?

To address these questions, this paper incorporates both relevant literature studies and a research-by-design method.

This paper argues for the integration of biophilic design strategies (i.e., natural materials, natural light, and plants) and timber framing components in existing 1960s and 70s concrete buildings (see Table 1, Appendix B). This could serve as a circular building model for the Dutch government to adopt today to help lower $C0_2$ emissions, reduce waste, foster resilient growth, and development in tune with the natural environment. Using a biophilic design model could also help harness these circular aspects and reveal the importance of re-nurturing nature in the built environment (Kellert, 2018).

Sub-section 2.1 examines the importance of using timber in construction and provides a material assessment of both timber and concrete; sub-section 2.2 provides a historic overview of wood-to-stone joinery systems; sub-section 2.3 provides a modern overview of wood-to-concrete joinery system; sub-section 2.4 examines how biophilic design and timber can 'heal' the Hugo R. Kruytgebouw; and sub-section 2.5 outlines the design strategy for the renovation process of the building. This paper concludes by identifying how historic and modern ways of joining timber to concrete can lead to an alternative circular building approach which views human well-being and nurturing the natural environment of utmost importance.

II. RESULTS

2.1 Overall Impact of Using Timber in Construction

How can press-fit timber connections contribute to reducing material waste and $C0_2$ emissions during the construction process?

Traditional timber framing is a historic technique which remains visible in few well-kept buildings scattered throughout the world, including buildings such as farmhouses in the Netherlands (Nederlands Openluchtmuseum, n.d.). Although this building technique may seem outdated, more builders today (especially in Germany) are adopting this tradition of building once more (Deutsche Welle, 2020). Timber framing relies on using mainly mortise and tenon joints which are press-fitted together and held by wooden pegs (see Appendix C)(Country Craziness, 2021). Unlike stud framing, timber framing is built to last and is much stronger (Sabon, 1995, p. 15). Due to the modern building materials of the 20th century such as concrete and steel however, traditional timber framing techniques are continuously being overlooked and replaced. Why was such a vernacular, circular and sustainable building tradition discarded by so many cultures? In what way made building with concrete more attractive than timber?

Wood can be fully returned to the natural life cycle after use, while concrete cannot (Zwerger, 2015, p. XVII). According to Zwerger (2015), it has been common practice throughout the history of building to repurpose timber elements for new uses, a practice now revered as a desired modern ‘circular approach’ (p. XVII). Factors that played a role in helping concrete replace traditional crafted timber construction methods are: fear of fire, industry ‘green’ campaigns promoting concrete as a natural material, simplicity, and above all, production cost (Zwerger, 2015, p. XV; Hudert, 2019, p. 101). Zwerger (2015) also states that the introduction of concrete and steel in the building and construction industry seemed to promise a certain change (p. XIII). More durable than wood, strong enough to withstand natural disasters, and above all, resistant to fire, concrete and steel quickly gained a strong foothold in the building industry (p. XIII).

Although there are certain woods and wood-composites deemed stronger and more fire-resistant than steel and reinforced concrete, the high demand of concrete and steel still dominates the markets, resulting in an even wider accustoming of these building materials (Blass & Sandhaas, 2017, p. 310; Song et al., 2018). In order to see the advantages of reverting back to using traditional timber frame construction techniques, a material assessment of wood and concrete is first conducted, followed by an analysis of historic wood-to-stone and modern wood-to-concrete connections (sub-section 2.2 & 2.3).

The following tables reveal a material assessment of timber as shown in Table 2 & 3 and concrete as shown in Table 4 & 5. The tables explicitly examine statements pertaining to material waste and $C0_2$ emissions to answer the sub-research question of this sub-section: How can press-fit timber connections contribute to reducing material waste and $C0_2$ emissions during the construction process?

Table 2. Timber — Regarding Material Waste.

Statements	**Wood**
Material can be totally returned to the natural life cycle after use.	Yes. Wood (not necessarily wood-composites) are 100% recyclable. It is a biotic material that rots at the end of its life and returns to the growth cycle as nutrients (Hillebrandt, A., Riegler-Floors, P., Rosen, A., & Seggewies, J.K., 2019, p. 58).

Material components can be disassembled.	Yes. That is the advantage of using (traditional) timber joints, you can modify as needed over the years (Zwerger, 2015, p. XVII). Modern timber components joined with metal fasteners or adhesives however, can no longer be reused, only downscaled by recycling (Hillebrandt et al., 2019, p. 49).
Material has a high potential of recyclability	Yes. Studies show that around 75% of all wood currently used in construction could be incorporated into cascade utilization due to having low pollution levels (Hillebrandt et al., 2019, p. 65-66).

Table 3. Timber — Regarding $C0_2$ Emissions.

Statements	**Wood**
Material emits carbon dioxide.	No. In fact, trees capture $C0_2$ from the atmosphere, making them a 'carbon-sink'. $C0_2$ (along with other gases) are only emitted during the decomposition phase (Norman & Kreye, 2020).
Material requires energy to produce.	Yes. Natural energy from the sun (Franklin, n.d.).
Material stores carbon.	Yes. 1 m^3 of wood stores 1 ton of carbon (Metsä Wood, n.d.).

Table 4. Concrete — Regarding Material Waste.

Statements	**Concrete**
Material can be totally returned to the natural life cycle after use.	No. It is not a biotic material (Hillebrandt et al., 2019, p. 58).
Material components can be disassembled.	Sometimes. Some pre-fabricated parts can be taken apart, unless components are held together by wet joints (glued together)(Hillebrandt et al., 2019, p. 71).
Material has a high potential of recyclability	No. The recyclability is limited (Hillebrandt et al., 2019, p. 62).

Table 5. Concrete — Regarding $C0_2$ Emissions.

Statements	**Concrete**
Material emits carbon dioxide.	Yes. It is said to be responsible for 4-8% of the world's $C0_2$ (The Guardian, 2019).
Material requires energy to produce.	Production requires approximately 7,000 MJ/t (Hillebrandt et al., 2019, p. 62).
Material stores carbon.	No. Although surfaces naturally absorb atmospheric carbon through a process called mineral carbonation, a process that requires very specific conditions, concrete is a net source of $C0_2$ (Fairs, 2021).

With the accumulated information presented in Tables 2 – 5, it is evident that wood is a building material better suited to reducing material waste and $C0_2$ emissions than concrete. It will take some time and accustoming for traditional timber frame construction to reign the building and construction industry market once more. Until then, more woodlands, especially in Europe, will need to produce more wood locally in order to meet the future demands (Fairs, 2020). It is evident today however, that several participants in the building and construction industries are more aware of the growing need to use wood and other recyclable building materials as an obligation for taking a more honest approach to calculating the cost of the building (Zwerger, 2015, p. XVII).

2.2 Historic Wood-to-Stone Connections

What are the advantages and disadvantages of historic wood-to-stone joinery methods?

In order to apply this research to the re-design of the Hugo R. Kruytgebouw, it is meaningful to undertake an historic analysis of wood-to-stone connections. A summary of wood-to-stone structures during conflicts of war in Western Europe and South Asia is first conducted, followed by a historic analysis of wood-to-stone construction techniques from the Mediterranean and European context. Topics of seismic forces and joinery techniques are provided in this section.

Structures of War

According to Zwerger (2015), there have been countless contributions from carpenters throughout history due to events of war and conflict (Zwerger, 2015, p. 133). Whatever the root cause of the conflicts, structures for military purposes have greatly nurtured the art of carpentry—an example of which were brackets in stone fortifications in Western Europe (p. 134). Due to certain gaps left in a loadbearing stone wall, wooden brackets enabled cantilevers at any height of a wall, making brackets crucial to the building of fortifications (see Appendix D)(p. 134). Most fortress brackets solely relied on simple press-fit wooden joints to connect components in order to be dismantled by the simple soldier and reused (p. 134).

Another wood-to-stone connection which arose from carpenters during conflicts of war can be found in Northern Pakistan. Cantor and Cribbage construction is known to be one of the most elaborate timber earthquake techniques (see Appendices E and F) (Hughes, 2000, p. 2; Carabbio, Pieraccini, Silvestri & Schildkamp, 2018). Although the insertion of wooden horizontal elements in stone masonry walls is a well observed vernacular building technique, Cantor and Cribbage is a timber lacing technique that is more effective in hindering seismic and warfare damage (Ortega, Vasconcelos & Correia, 2014, p. 6) (Hughes, 2000, p. 3). The first description of timber lacing can be traced back to Roman Emperor Julius Caesar, as a technique used by the Celts to build their wall fortifications (p. 3). The Romans would go on to copy this timber lacing technique and incorporate it into their own fortifications of war (see Appendix G)(Beltramini, 2009, p. 202).

Due to the dry-connected timber added to the stone masonry walls, Cantor and Cribbage construction has great tensile and elastic properties. Therefore, structures that use timber lacing techniques are of a military character (p. 3). A variant of timber lacing construction which is still practiced today in parts of Pakistan and India is called *Bhatar* (Carabbio et al., 2018, p. 1). This technique is handed down through generations and is a tradition derived from central Anatolia some 9,000 years ago (p. 2). While this construction method remains practiced in the Himalayan regions of developing countries due to both the economical and constructive techniques, it is lesser known in other regions because of a loss in vernacular building tradition and the greater acceptance of new conventional building techniques (Carabbio et al., 2018, p. 3; Hillebrandt et al., 2019, p. 49). Carabbio (2018) states that according to Professor Emeritus in Architecture Randolph Langenbach, the fundamental principle of the dry-stacked stone masonry *Bhatar* technique is the dissipation of energy through friction (shear) between the elements in the wall—stone to stone and stone to wood (p. 3). The dissipation of energy is very high in the wall due to the thickness and weight of the walls, therefore, the use of mortars, especially cement is not recommended since this would make the walls too stiff and reduce their ability to absorb seismic forces (p. 3). Other variants of timber lacing construction can be found in seismic regions around the world such as Turkey, Macedonia and Italy (Ortega et al., 2014, p. 6). Countries that similarly insert horizontal timber elements into rammed earth walls for seismic reinforcement are Peru and Portugal (p. 6).

Common Connection Types

This section contains an analysis of common historic wood-to-stone connections found in the Mediterranean and Europe context. Several historic stone masonry buildings in these contexts are built with wooden floors to absorb any potential seismic shocks. Wooden floors absorb the shocks by enabling the movement of the surrounding walls; yet, this is only achieved when proper connections between the walls and floors are made so that the vertical structures do not behave independently and risk collapse (p. 7). For some time, reinforced concrete floors replaced the use of wooden floors, however, results were disastrous and this change resulted in many collapses in earthquakes (p. 7). Instead of lowering vibrations and dissipating the seismic energy, the heavy concrete floors increased the horizontal forces and resulted in the collapse of the stone masonry walls (p. 7). Unlike reinforced concrete floors however, applying a thin concrete slab to an existing timber floor in what is known as a timber-concrete composite floor ensures further loadbearing and deformation behaviors (see Appendix H)(Blass et al., 2017, p. 310).

The connections between the structural elements are vital to resist the seismic forces commonly felt around the region (see Appendix I). The internal connection of the wooden floors to the external stone walls are needed in strengthening the structural behavior of buildings. Improving these connections is known as a basic seismic strengthening technique (Ortega et al., 2014, p. 7). The main improvement of wall to floor and wall to roof connections lies in the piercing of the stone masonry wall with wooden floor beams and roof rafters (p. 8). Other similar connections to the main structural elements are done with wooden pegs or beams resting parallel to the stone walls or with metal brackets and ties (see Appendix J)(p. 8). It is common to see flexible joints and wedges in historic stone masonry construction since they allow some movement within the joints, the controlled movement allows for good seismic force absorption (p. 8). These joinery techniques are common in other seismic prone regions, such as India, Nepal, China, Japan, Italy and Turkey (p. 8).

Table 6 provides an overview of the disadvantage and advantages of historic wood-to-stone connections can be (see Appendix K).

2.3 Modern Wood-to-Concrete Connections

What are the advantages and disadvantages of modern wood-to-concrete joinery methods?

In order to apply this research to the re-design of the Hugo R. Kruytgebouw, it is also meaningful to undertake a modern analysis of wood-to-stone connections. An analysis of metal fasteners is first conducted followed by a brief overview of certain modern joinery techniques.

Metal Fastener Analysis

Traditional metal fasteners can be divided into two groups based on the forces they transmit (Blass et al., 2017, p. 325). According to Blass (2017), the first group consists of dowel-type fasteners which includes nails, staples, bolts, screws, dowels, and threaded rods. These fasteners generate bending and tensile stresses in the fasteners as well as shear stresses in the wood. The second group are considered ‘surface-type’ fasteners such as split ring, tooth-plate connectors, and metal plate fasteners, which transmit forces along the surface of a member (p. 325).

Using metal fasteners to join wood-to-concrete is now common practice in the building and construction industry due to being more economically friendly than traditional timber joints (Hillebrandt et al., 2019, p. 49). Although there may be a wider acceptance today to using metal fasteners to join structural components, there are still some disadvantages associated with them. For example, around 85% of all metal structural components used by the building and construction industries are made of steel (p. 68). According to Hillebrandt (2019), steel is a raw material that is costly, difficult to produce and energy intensive during its production phase (p. 68). Yet, since the value and environmental impact of steel and other metals are high, recycling is fortunately a standard part of the metal production process (p. 61).

Furthermore, metal fasteners tend to be hidden or kept out of sight; therefore, it may be assumed that they are not as aesthetically pleasing as traditionally crafted wooden joints. A larger concern however, is their fire resistance. Although it may be more cost-effective to join a wooden beam to a concrete wall with a metal fastener, the loadbearing capacity of metal fasteners is quickly lost when heat is applied (Blass et al., 2017, p. 549). In addition, since metal has a higher thermal conductivity than wood, it transmits heat to the surrounding wooden elements, weaking the overall performance of the structural elements (p. 556). Therefore, metal fasteners are always protected with fire-protective coatings or additional fire-resistant materials (i.e., wood cladding or wood-based materials of a certain minimum thickness) when joining wood-to-concrete (Hillebrandt et al., 2019, p. 69; Blass et al., 2017, p. 558).

Common Connection Types

The most frequently used modern connections to join wood-to-concrete, specifically concrete slabs and timber beams are seen in Appendix L (Blass et al., 2017, p. 311). Most of these connections however, could be adapted to join walls and roof elements as well. Blass (2017), states that the joints are classified by stiffness and reveals that nailed, screwed and doweled connections using fasteners perpendicular to the joint line (see Appendix L, (a) 1 - 3) have the lowest levels of stiffness. Screws that are angled to the joint line (see Appendix L, (a) 4) or surface connectors which are not inserted deeply, are stiffer than connections with dowel-type fasteners loaded perpendicular to the fastener axis (see Appendix L, (b)). Greater stiffness is possible with 'shear keys' otherwise known as pre-made notches in wood which are filled with concrete and function as dowels after the curing process (Appendix L, (c)). The most rigid connections however, are formed with glued joints (see Appendix L (d)(p. 311).

Finally, when joining wood-to-concrete with modern methods, it is standard procedure to seek out a structural engineer's perspective, since concrete and timber behave differently in climatic changes. Concrete is sensitive to changes in temperature while timber is affected by changes in moisture content (p. 315). This is only problematic however if the wood-to-concrete connection is too rigid and if elements are excessively long (p. 315)(see Appendix M for an overview of modern wood-to-concrete connections).

2.4 Biophilia & Timber

How can biophilic design and timber 'heal' the existing Hugo R. Kruytgebouw?

Biophilia can be described as, "the passionate love of life and of all that is alive" (Rogers, 2010). Despite the common tendency to dismiss the importance of nature, there is evidence that the innate affiliation humans have with nature is highly important for people's physical and mental health, productivity, and well-being (Kellert, 2018, p. 4). The senses play a large role in how all attributes of nature are experienced (p. 26). According to Kellert (2018), the more senses which are aroused by biophilic design, the more likely nature has been effectively incorporated into the built environment (p. 26).

By addressing biophilic design elements like natural materials, natural light, plants, etcetera, the renovated Hugo R. Kruytgebouw can become a university campus icon which fosters, connects, and nurtures it's surrounding natural environment (see Appendix B for a detailed list of biophilic design strategies) (p. 27). Introducing new timber additions to the Kruytgebouw will not only 'heal' the building but offer clear physiological benefits for its users, since research has shown that materials have a direct impact on human health (Delagran, n.d.). This is especially important since humans now spend on average 90% of their time indoors (p. vii).

2.5 Design Strategy

The Hugo R. Kruytgebouw contains approximately 33,795 tons of concrete, accounting for roughly 31,430 tons of CO_2. In order to offset these existing emissions 6,337 tons of construction timber is needed, accounting for - 11,406 tons of CO2 (see Appendix N). The revitalization of the Hugo R. Kruytgebouw will take place by incorporating timber framing and biophilic design strategies to its existing unique pre-fabricated structure which receives poor amounts of natural light (see Appendix O, P, and Q). Focus is placed on the facade and interior of the building along the plinth, façade, and roof (see Appendix R). For each of these locations, different applications of timber and biophilic design are conducted.

Along with adding new timber additions to the building, other natural materials such as hempcrete (hemp and lime mix), lime and clay plasters are widely incorporated (see Appendix S)

The design goal of the redevelopment of the Kruytgebouw is to reduce $C0_2$ emissions during the renovation phase by incorporating as much reclaimed timber as deemed possible. To also reduce excess building materials and material waste, a personal design challenge is to rely on using press-fit timber framing joinery which connect the new timber elements with the old existing concrete structure, thus limiting the amount of steel connectors used (see Appendix T and U).

The three main locations in the Kruytgebouw in which new timber additions are to join with the existing concrete structure are seen in Appendices V, W, and X. Each appendix reveals three close-up images highlighting different stages of the reconstruction process, this includes, the current existing structure, the deconstructed state, and a potential re-design of the space.

III. CONCLUSION

This paper outlines various aspects of traditional timber framing techniques which can serve as sources of inspiration to design alternatives for the contemporary building process. With the goal of reducing $C0_2$ emissions and building material waste across the globe, new ways of working with existing concrete structures are needed. In this paper, a material assessment of timber and concrete was conducted and found that when considering $C0_2$ emissions, building with timber greatly reduces the environmental impact compared to concrete. It was also found that timber stores carbon while concrete is responsible for 4-8% of the world's $C0_2$ emissions. When considering building waste, traditional timber construction, such as timber framing, allows for the reuse of elements and is 100% recyclable, while the recyclability and reuse of concrete remains limited.

Following the material assessment, this paper conducted analyses of historic wood-to-stone connections and modern wood-to-concrete connections. It was found that there are advantages to structures built with wood-to-stone connections, since flexible timber joints and wedges absorb any potential seismic forces. Stone buildings built with timber floors are also more structurally sound than buildings constructed with reinforced concrete floors, due to the wooden beams lowering vibrations and dissipating seismic forces. A shortcoming found was that the tradition of building with vernacular wood-to-stone joints is dwindling globally due to a greater acceptance in using international and conventional building materials such as metal fasteners. When considering modern wood-to-concrete connections, advantages included the cost-effectiveness of metal fasteners due to their high demand and the ability to add fire-protective coatings or additional fire-resistant materials to them. Shortcomings included that steel in as raw material which is costly, difficult to produce and energy intensive during its production phase; the loadbearing capacity of metal fasteners is weakened when heat is applied, causing the overall performance of the structural elements to weaken; and metal fasteners tend to be hidden or kept out of sight which could be used to assume that they are not as aesthetically pleasing as traditionally crafted wooden joints.

Finally, this paper aims to serve as a resource for further applications of timber and biophilic design to other 1960s and 70s concrete buildings, which may have similar refurbishment needs like the Hugo R. Kruytgebouw.

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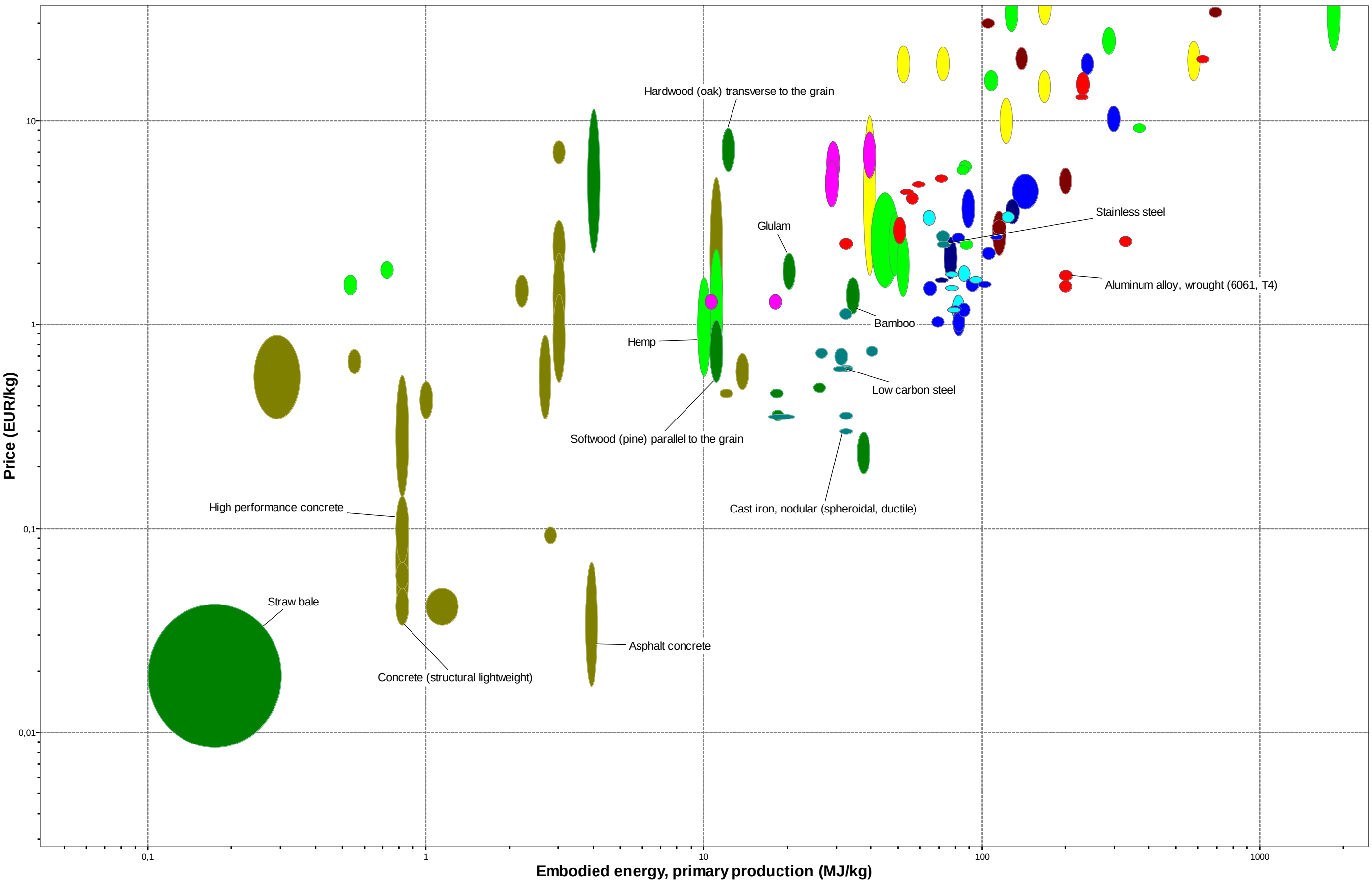
APPENDICES

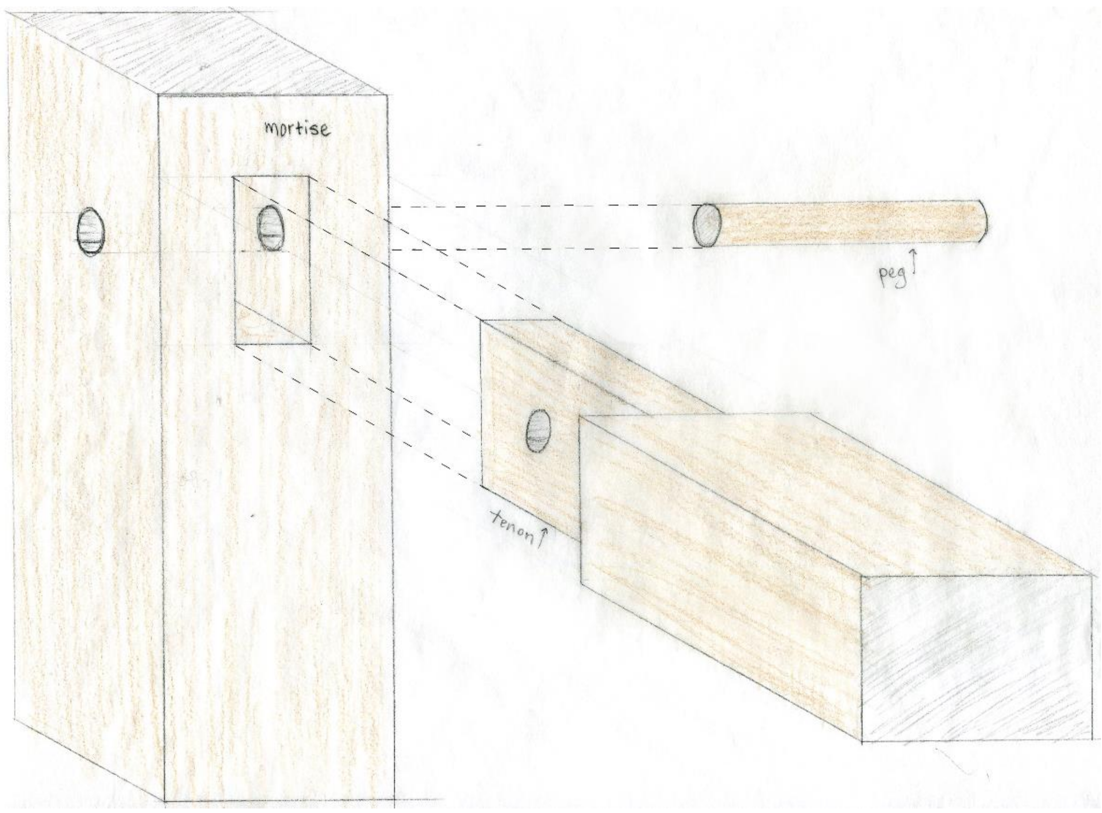


Appendix A : This chart shows that concrete is priced lower than all other available materials, except straw bale. It also reveals that when calculating the embodied energy of these materials, the environmental impact is not considered (Granta EduPack, 2021 R2).

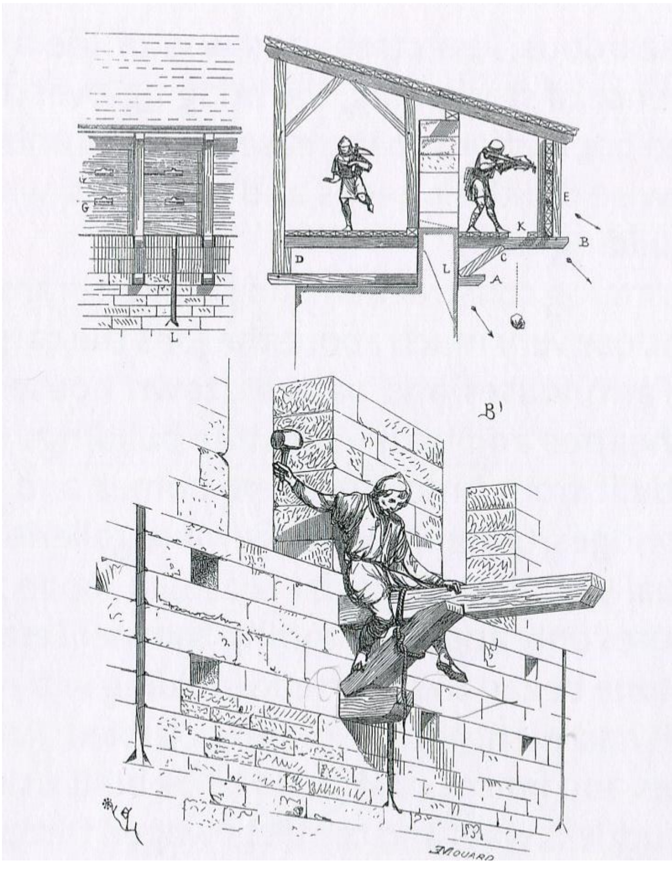
Table 1. Biophilic Design Strategies

Strategies	**Examples**
Direct experiences of nature	light, air, water, plants, views
Indirect experiences of nature	materials, textures, colors
Experiences of space and place	mobility, transitional spaces, place, integrating parts to create wholes

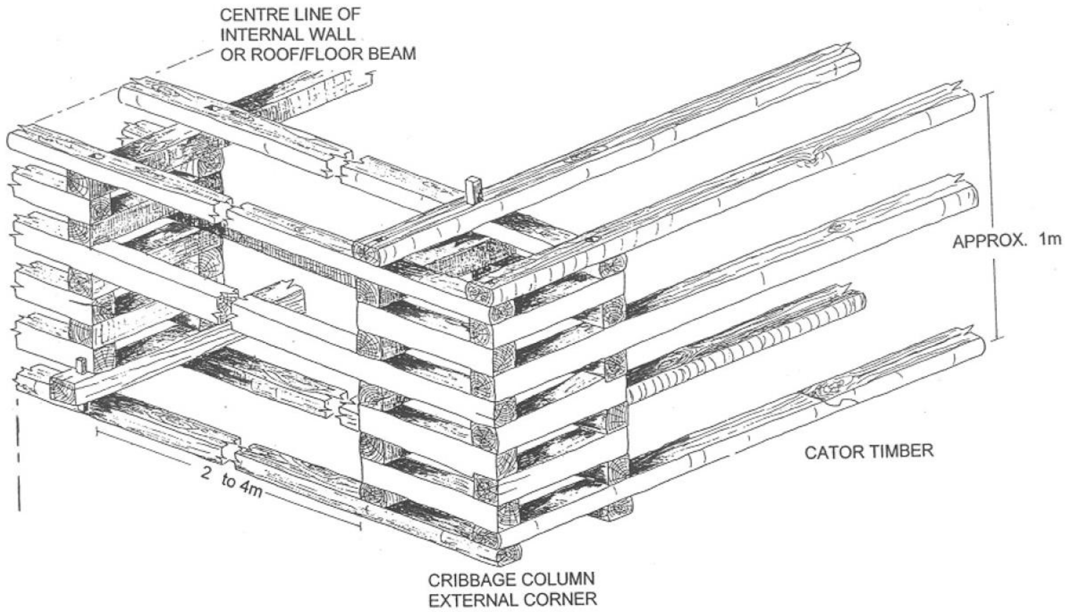
Appendix B : Biophilic design strategies proposed by Stephen Kellert (Kellert, 2018, p. 27).



Appendix C : Drawing of a traditional timber framing joint using a mortise and tenon.

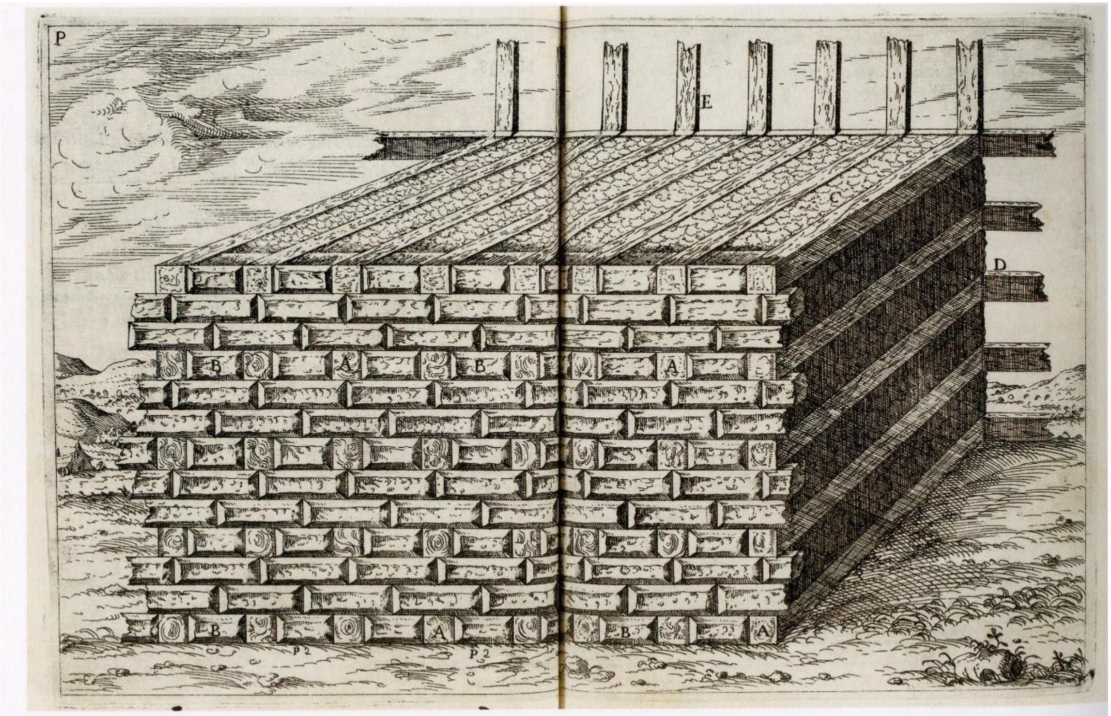


Appendix D : Brackets enabled cantilevers at various heights in fortification walls (Zwerger, 2015, p. 134).

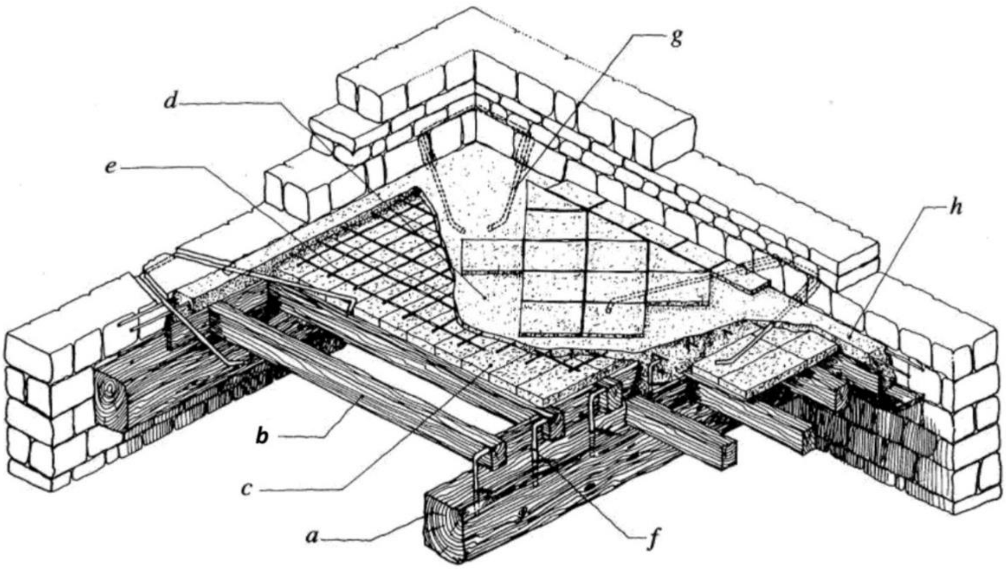


Appendix E : An assemblage of Cantor and Cribbage construction (Hughes, 2000, p. 2).

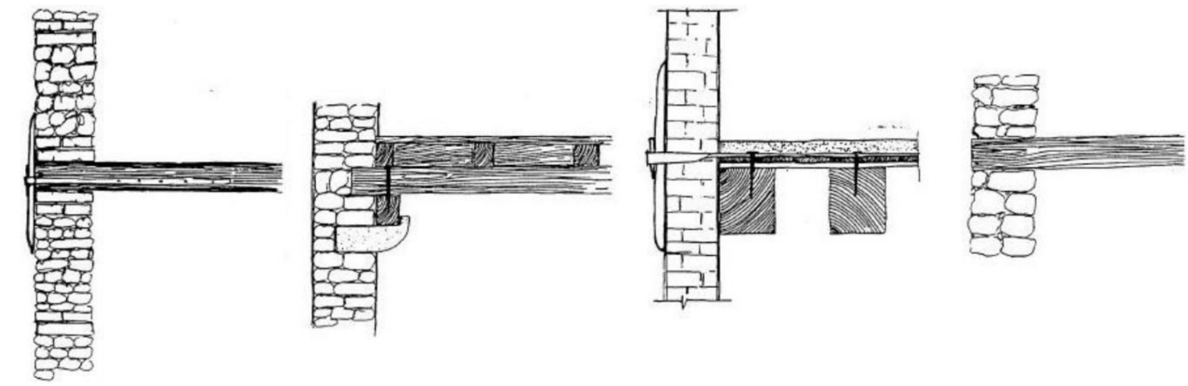
Appendix F : Wooden beams and dry stone masonry (Carabbio et al., 2018).



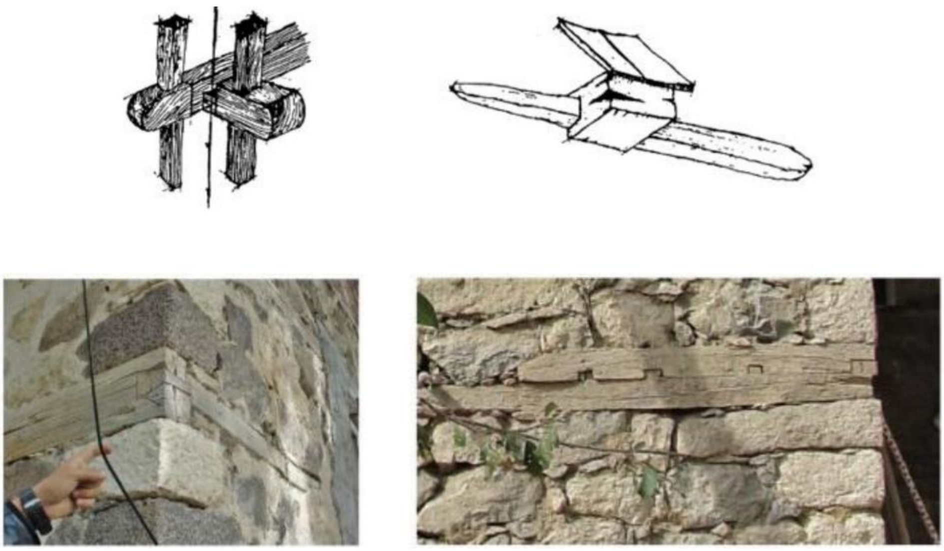
Appendix G : Roman timber lacing technique for fortifications of war (Beltramini, 2009, p. 202).



Appendix H : Timber-concrete composite floor renovation on old timber beams (Blass et al., 2017, p. 310).



Appendix I : Common historic wood-to-stone connections in the Veneto region of Italy (Ortega et al., 2014, p. 7).

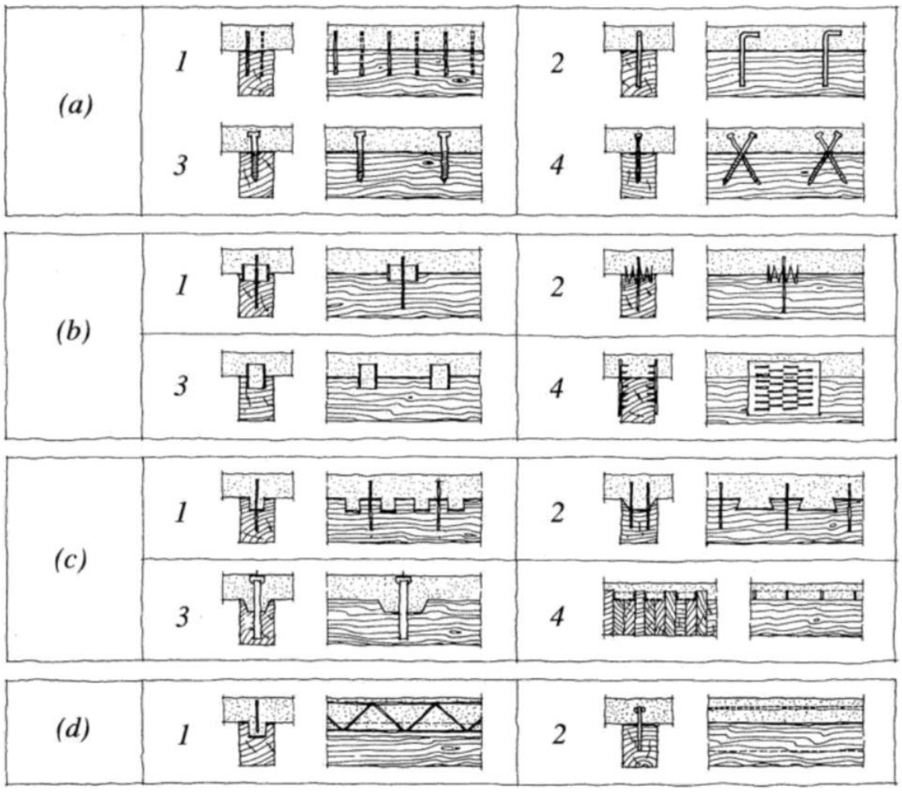


Appendix J : Vernacular joints found in Italy and Turkey using wooden pegs and flexible joints (Ortega et al., 2014 p. 7).

Table 6. Historic wood-to-stone connections

Advantages	**Disadvantages or Shortcomings**
Flexible joints, wooden pegs, metal brackets and ties encourage slight movement in the joints of stone buildings which allows for good seismic force absorption (Ortega et al., 2014, p. 8).	The tradition of building with vernacular joints are dwindling globally due to a greater acceptance in using international and conventional building materials (i.e., metal fasteners)(Hillebrandt et al., 2019, p. 49)
Historic stone buildings connected with wooden floor beams and rafters are more resistant to potential seismic shock (Ortega et al., 2014, p. 7). In fact, historic timber flooring reinforced with a thin layer of concrete known as a timber-concrete composite floor ensures further loadbearing and deformation behaviors (see Appendix E for reference)(Blass et al., 2017, p. 310).	-
When designed properly, a wood-to-stone connection may result in a structurally successful and pleasing aesthetic detail (personal remark).	-

Appendix K : Advantages and disadvantages of historic wood-to-stone connections



Appendix L : The most frequently used modern connections to join wood-to-concrete, specifically concrete slabs and timber beams (Blass et al., 2017, p. 311).

Table 7. Modern wood-to-concrete connections

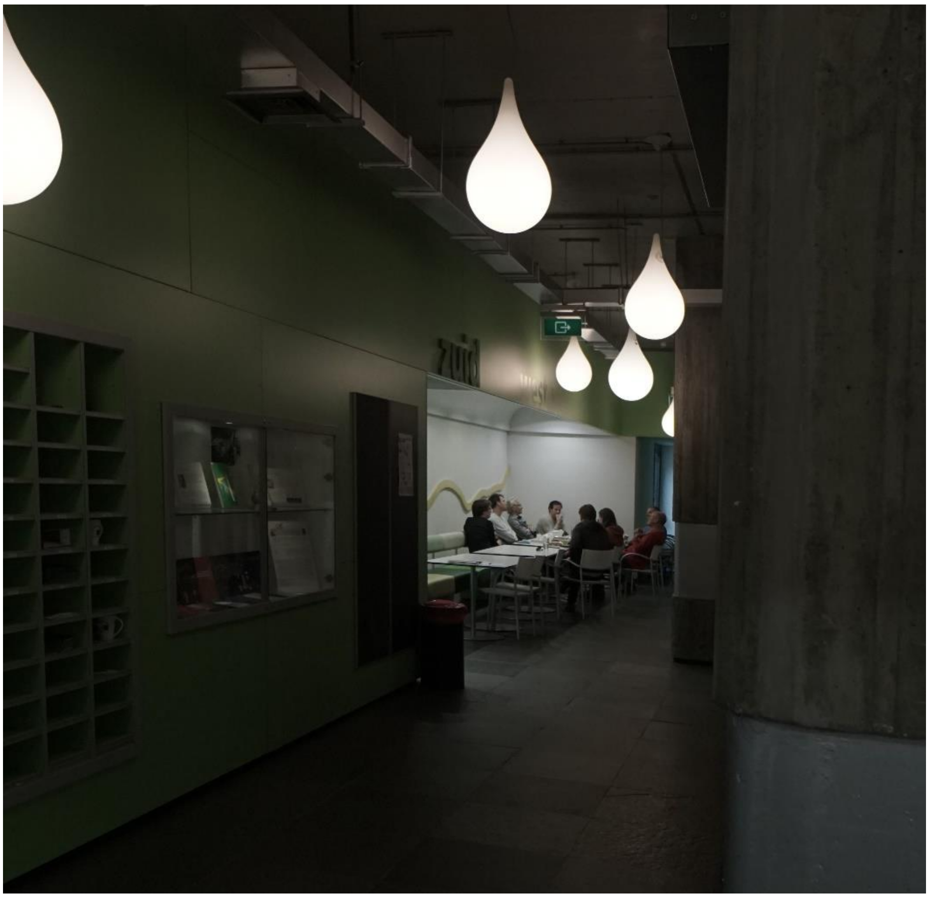
Advantages	**Disadvantages or Shortcomings**
It is more cost-effective to join a wooden beam to a concrete wall with a metal fastener (Blass et al., 2017, p. 549) This however, is only due to the current demand in the building and construction industry (Hudert & Pfeiffer, 2019, p. 101).	Steel is a raw material that is costly, difficult to produce and energy intensive during its production phase (Hillebrandt et al., 2019, p. 68)
Metal fasteners are protected with fire-protective coatings or additional fire-resistant materials (i.e., wood cladding or wood-based materials of a certain minimum thickness) when joining wood-to-concrete (Hillebrandt et al., 2019, p. 69; Blass et al., 2017, p. 558).	The loadbearing capacity of metal fasteners is quickly lost when heat is applied (p. 549) For example, since metal has a higher thermal conductivity than wood, it transmits heat to the surrounding wooden elements, weaking the overall performance of the structural elements (Blass et al., 2017, p. 556).
-	Metal fasteners tend to be hidden or kept out of sight, therefore, it may be assumed that they are not as aesthetically pleasing as traditionally crafted wooden joints (personal remark).
When designed properly, a wood-to-concrete connection may result in a structurally successful and pleasing aesthetic detail (personal remark).	Concrete is sensitive to changes in temperature while timber is affected by changes in moisture content (p. 315). This is only problematic however, if the wood-to-concrete connection is too rigid and if elements are excessively long (Blass et al., 2017, p. 315).

Appendix M : Advantages and disadvantages of modern wood-to-concrete connections

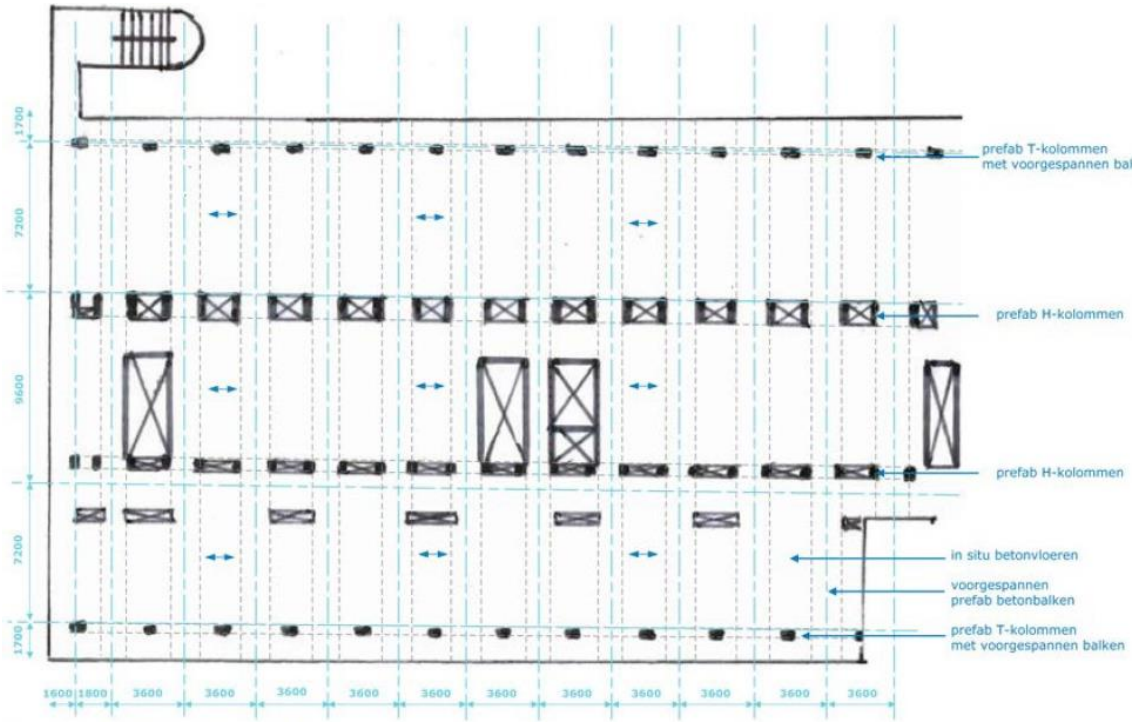
Hugo R. Kruytgebouw

Volume of Concrete					14081,3808	m^3	33795,31392	mass [t]
Total CO2 production (Concrete)							31429,64195	mass CO2]t]
Volume of Timber Needed to Offset Existing Emissions					14.081	m^3	6336,62136	mass [t]
Total CO2 production (Timber)							(-) 11405,91845	mass CO2 [t]
Existing Concrete Elements								
	l [m]	w[m]	h[m]	Size (l x w x h)	Volume	Units	Number of Elements	Total Volume
Foundation Piles	1,11	0,35	0,35	1105 cm x 35 cm x 35 cm	0,14	m^3	50,00	6,77
	1,20	0,35	0,35	1200 cm x 35 cm x 35 cm	0,15	m^3	76,00	11,17
	1,21	0,35	0,35	1205 cm x 35 cm x 35 cm	0,15	m^3	35,00	5,17
	1,31	0,35	0,35	1305 cm x 35 cm x 35 cm	0,16	m^3	37,00	5,91
	1,01	0,35	0,35	1005 cm x 35 cm x 35 cm	0,12	m^3	121,00	14,90
	1,10	0,35	0,35	1100 cm x 35 cm x 35 cm	0,13	m^3	40,00	5,39
	1,11	0,35	0,35	1105 cm x 35 cm x 35 cm	0,14	m^3	48,00	6,50
	1,20	0,35	0,35	1200 cm x 35 cm x 35 cm	0,15	m^3	341,00	50,13
	1,21	0,35	0,35	1205 cm x 35 cm x 35 cm	0,15	m^3	24,00	3,54
	1,31	0,35	0,35	1305 cm x 35 cm x 35 cm	0,16	m^3	77,00	12,31
						m^3	849 Total	121,78
In situ Concrete (includes core)	8,00	3,00	50,00		1200,00	m^3	1,00	1200,00
Prefabricated Elements							3,688	
floor beams (mark CA)				970 cm x	2,95	m^3	308	908,6
floor beams (mark CB)				738 cm x	2,20	m^3	44	96,8
floor beams (mark CC)				910 cm x	2,74	m^3	336	920,64
floor beams (mark CD)				760 cm x	2,20	m^3	308	677,6
floor beams (mark CE)				1500 cm x	4,46	m^3	96	428,16
floor beams (mark CF)				1105 cm x	3,31	m^3	28	92,68
galley floor component (mark EA)	3,58	0,7	0,15	358 cm x 70 cm x 15 cm	0,3759	m^3	736	276,6624
galley floor component (mark EB)					0,3759	m^3	10	3,759
galley floor component (mark EC)				458 cm x 70 cm x 15 cm	0,3759	m^3	32	12,0288
galley floor component (mark ED)					0,3759	m^3	10	3,759
galley floor component (mark EE)					0,3759	m^3	10	3,759
galley floor component (mark EF)					0,3759	m^3	10	3,759
galley floor component (mark EG)					0,3759	m^3	10	3,759
Floors 2 - 7								
floor component (mark DA)	2,6	1,8	0,15	260 cm x 180 cm x 15 cm	0,702	m^3	47	32,994
floor component (mark DB)	2,6	1,8	0,15	260 cm x 180 cm x 15 cm	0,702	m^3	0	0
floor component (mark DC)	2,6	1,8	0,15	260 cm x 180 cm x 15 cm	0,702	m^3	8	5,616
floor component (mark DD)	2,6	1,8	0,15	260 cm x 180 cm x 15 cm	0,702	m^3	0	0
floor component (mark DE)	2,6	1,8	0,15	260 cm x 240 cm x 15 cm	0,702	m^3	0	0
floor component (mark DF)	1,5	1,8	0,15	150 cm x 180 cm x 15 cm	0,405	m^3	2	0,81
floor component (mark DG)	1,5	1,8	0,15	150 cm x 180 cm x 15 cm	0,405	m^3	9	3,645
floor component (mark DH)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	20	5,4
floor component (mark DJ)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	1	0,27
H-portals (mark BB)	2,1	1,2	3,98	210 cm x 120 cm x 398 cm	10,0296	m^3	220	2206,512
H-portals (mark BA)	2,3	0,6	3,98	230 cm x 60 cm x 398 cm	5,4924	m^3	220	1208,328
T-column (mark AA)	2,36	0,4	3,98	236 cm x 40 cm x 398 cm	3,75712	m^3	700	2629,984
Floor 8								
floor component (mark DG)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	576	155,52
floor component (mark DF)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	0	0
H-portals (mark BB)	2,1	1,2	3,98	210 cm x 120 cm x 398 cm	10,0296	m^3	44	441,3024
H-portals (mark BA)	2,3	0,6	3,98	230 cm x 60 cm x 398 cm	5,4924	m^3	44	241,6656
Floor 9								
floor component (mark DG)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	576	155,52
floor component (mark DF)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	0	0
H-portals (mark BB)	2,1	1,2	3,98	210 cm x 120 cm x 398 cm	10,0296	m^3	44	441,3024
H-portals (mark BA)	2,3	0,6	3,98	230 cm x 60 cm x 398 cm	5,4924	m^3	44	241,6656
Floor 10								
floor component (mark DG)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	576	155,52
floor component (mark DF)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	0	0
H-portals (mark BB)	2,1	1,2	3,98	210 cm x 120 cm x 398 cm	10,0296	m^3	44	441,3024
H-portals (mark BA)	2,3	0,6	3,98	230 cm x 60 cm x 398 cm	5,4924	m^3	44	241,6656
Floor 11								
floor component (mark DG)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	576	155,52
floor component (mark DF)	1	1,8	0,15	? cm x 180 cm x 15 cm	0,27	m^3	0	0
H-portals (mark BB)	2,1	1,2	3,98	210 cm x 120 cm x 398 cm	10,0296	m^3	44	441,3024

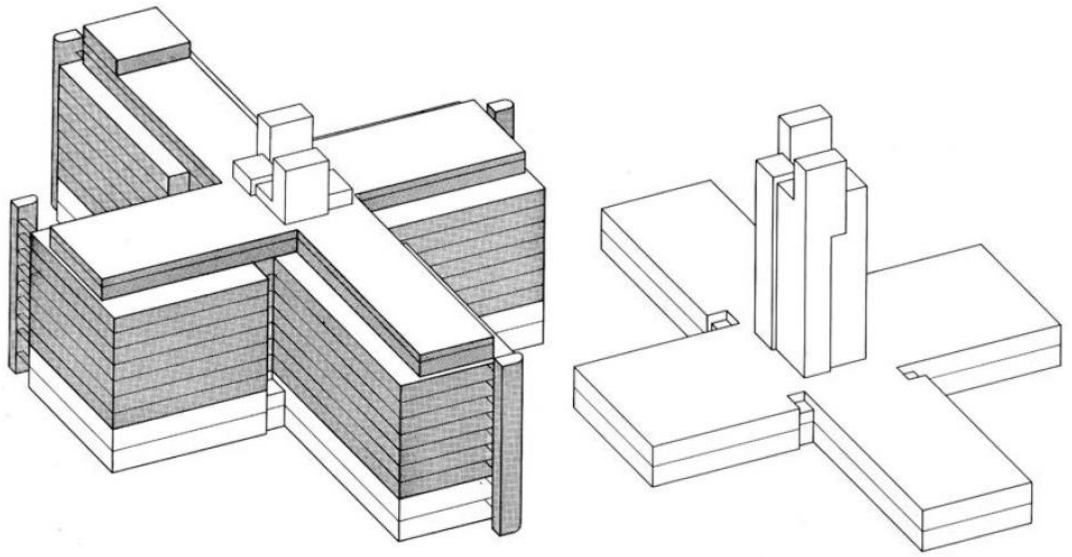
Appendix N : Calculations of Concrete in the Kruytgebouw



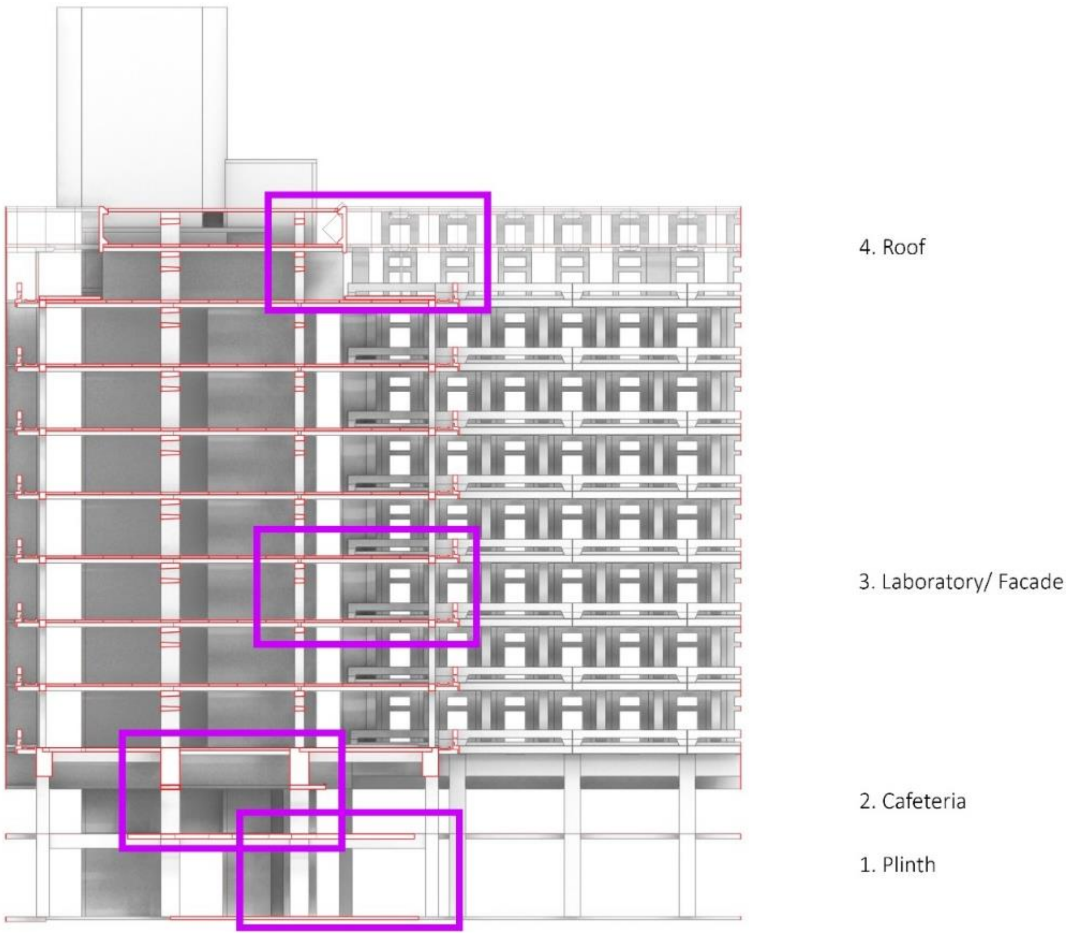
Appendix O : A glimpse into the current interior conditions of the Hugo R. Kruytgebouw.



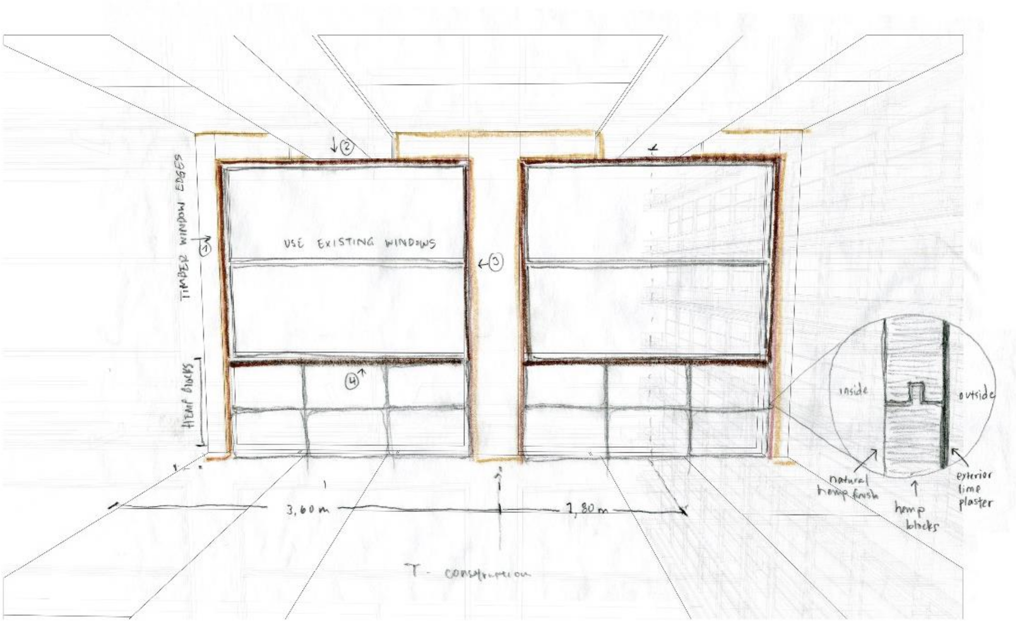
Appendix P : The supporting structure that is left following the undressing of the Kruytgebouw (ABT, 2019, p. 7).



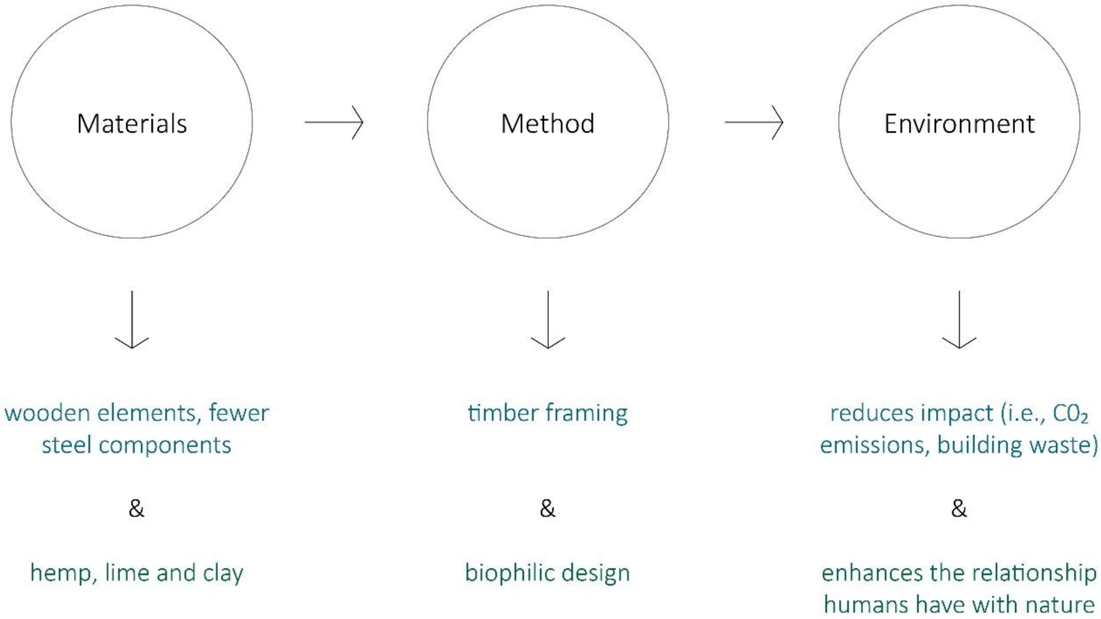
Appendix Q : Prefabricated concrete elements are shown in grey while in-situ concrete elements are shown in white (ABT, 2019, p. 7).



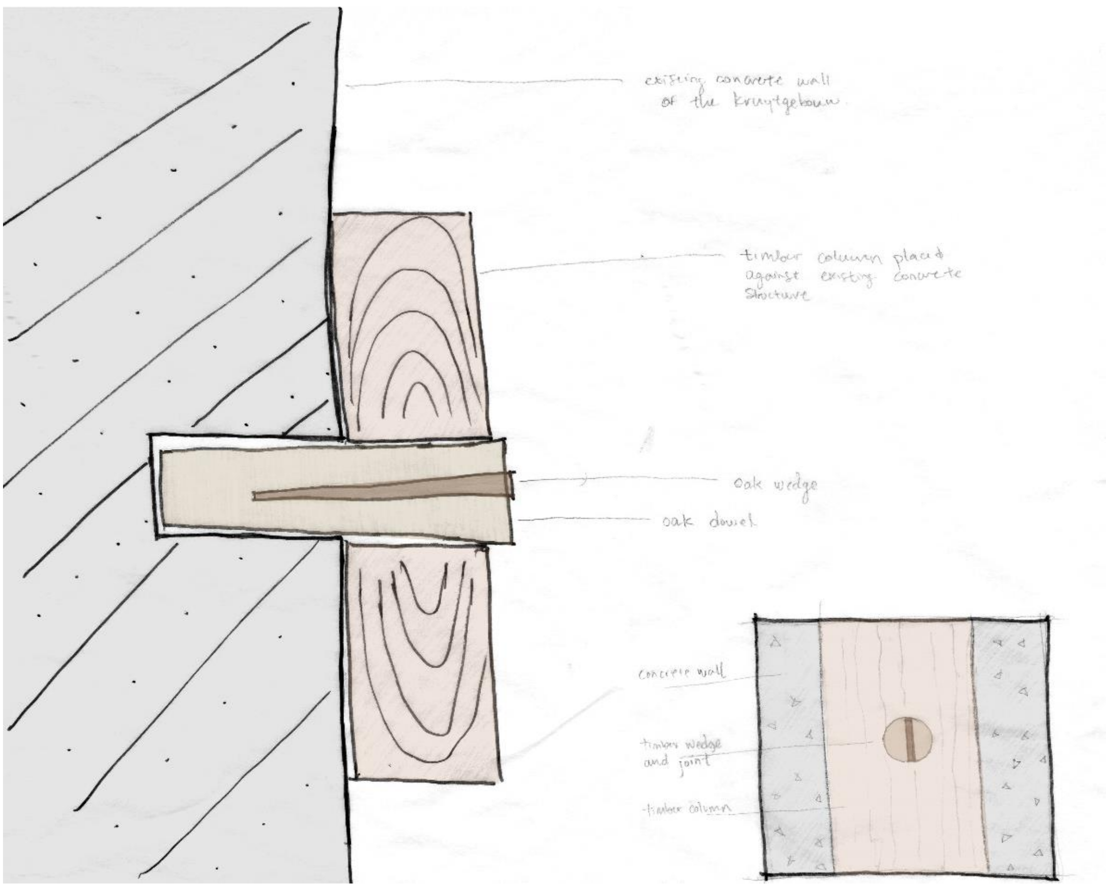
Appendix R : The main points of interest where new timber extensions will be added.



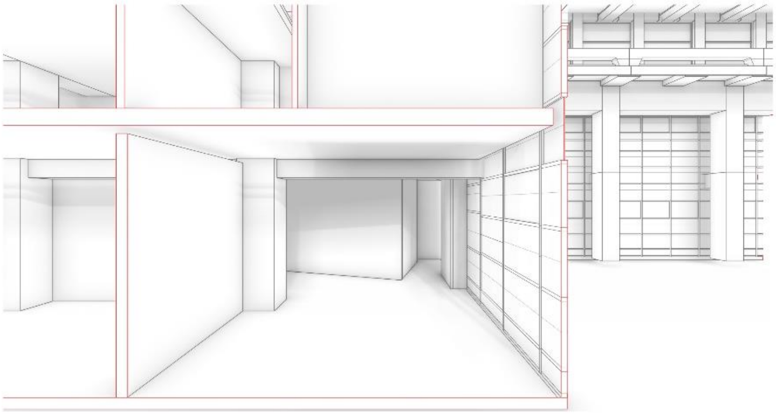
Appendix S : Impressions of a laboratory renovation strategy in the Kruytgebouw. Yellow is used to indicate the main ‘H’ and ‘T’ pre-fabricated concrete elements which are part of the remaining concrete structure.



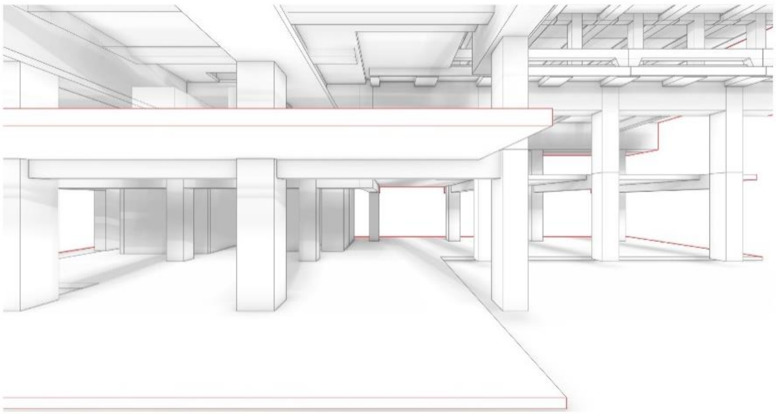
Appendix T : Design strategy diagram for the redevelopment of the Hugo R. Kruytgebouw.



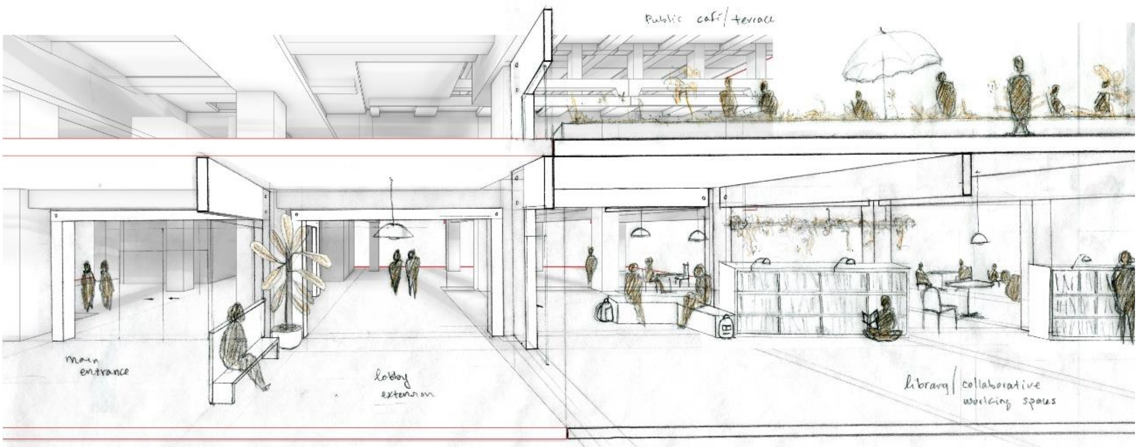
Appendix U : Potential technique used to join new timber elements with the existing concrete structure of the Kruytgebouw. A similar method is used to build boat frames with tree-nails (wooden nails).



Existing Plinth

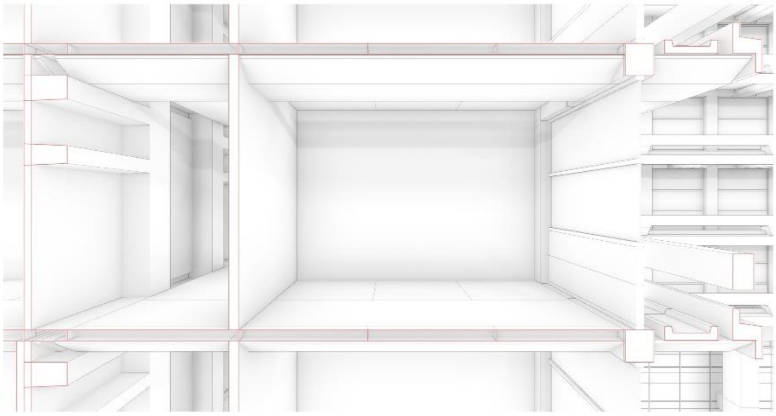


Deconstructed Plinth

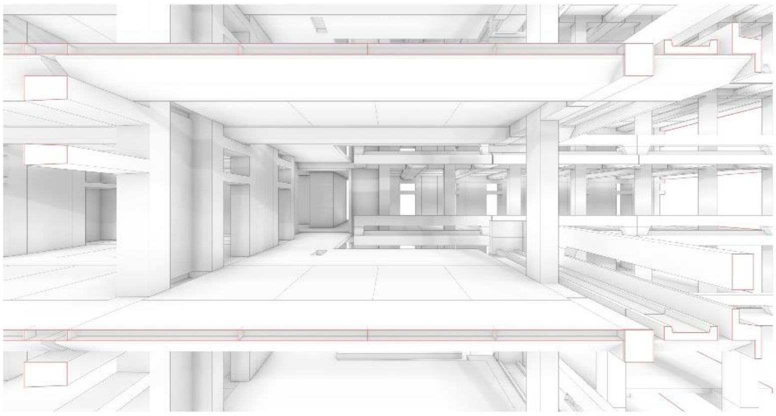


Re-Designed Plinth

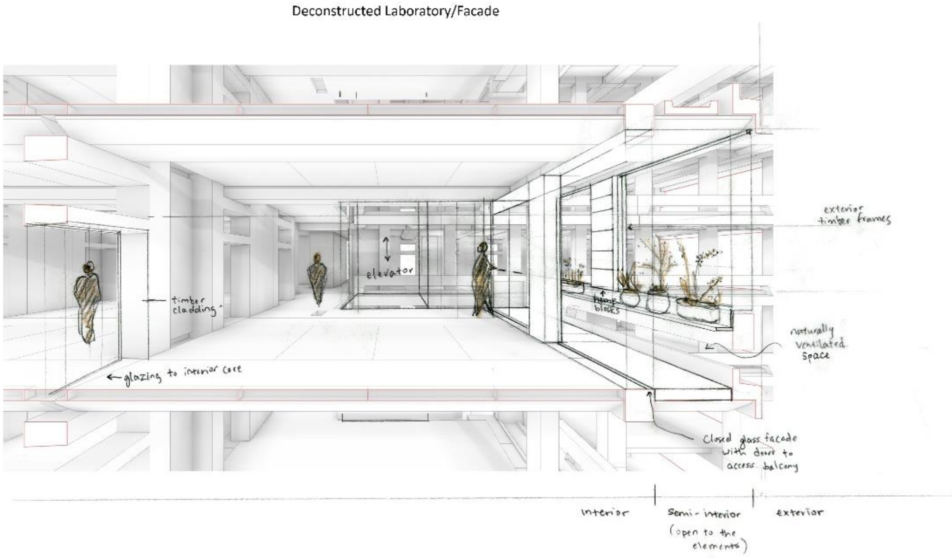
Appendix V : Transformation of the Kruytgebouw's Plinth.



Existing Laboratory/Facade

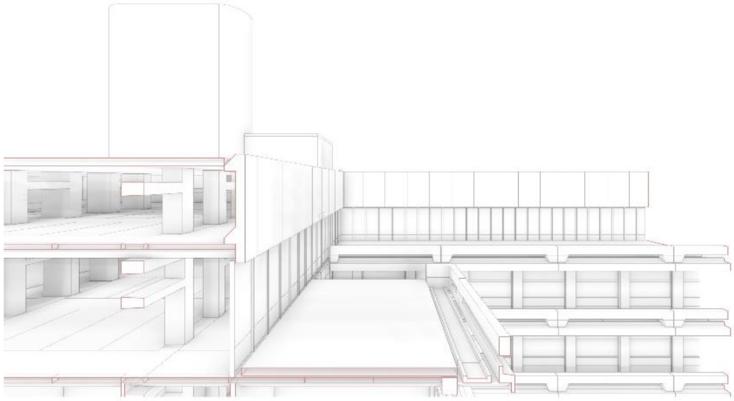


Deconstructed Laboratory/Facade

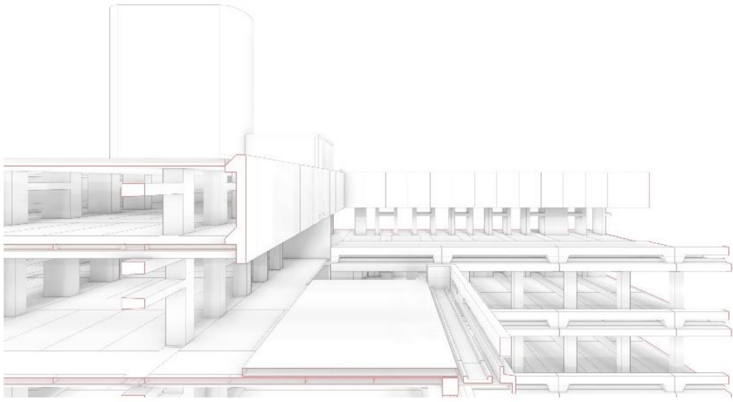


Re-Designed Laboratory/Facade

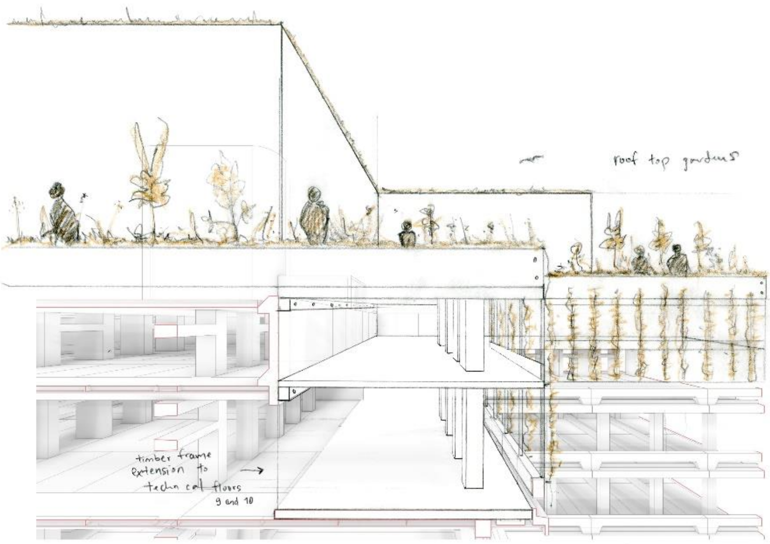
Appendix W : Transformation of a laboratory in the Kruytgebouw.



Existing Roof



Deconstructed Roof



Re-Designed Roof

Appendix X : Transformation of the Kruytgebouw's Roof.