OPTIMIZED COMBINATION OF 1D/2D/3D ENGINEERED TIMBER SYSTEMS

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ABSTRACT

There is a significant problem with how we conceive our built environment, the traditional nature of the construction industry lags in innovation compared to nearly every other industry. As a result, the industry is unable to quickly respond to changing social, environmental and economical contexts. Requiring new methods of construction in order to meet the demands of the present and anticipate change in the future. Within the context of TU Delft Campus and it's needed to accommodate an increasing student population and subsequently needing to maximize the use of space throughout campus. The research paper aims to explore what combination of prefabricated 1D,2D and 3D engineered timber systems generates the most optimized use of engineered timber for a hybrid building.

KEYWORDS: *Engineered Timber, 1D/2D/3D systems, Hybrid Buildings, Kit of Parts, Dimensionality*

I. INTRODUCTION

Due to a lack of innovation in the construction industry, dependency on renovations and demolitions, and an increased demand for construction. The built environment is unable to easily adapt to future social, environmental and economic contexts. Producing a significant amount of waste in order to try and upgrade the past, rather than trying to design for the future. Moreover, traditional practices are inadequate to meet the growing demand for housing (Raymond, 2021). With the world changing more than ever, there is a major problem with how we conceive our built environment.

The negative effects of the construction industry's traditional nature is evident in TU Delft's lack of on campus accommodation for students, leaving many to find housing in different cities. According to Monitor Student Housing, the forecast is that 16,500 students presently seeking accommodation will rise to 22,830 in the 2028-29 academic year (Persbureau, 2021). A table of Delft's realized student accommodation projects can be viewed in appendix 1. At the current rate of development, TU Delft will never be able to meet the accommodation of its continuously increasing population. Moreover, TU Delft has made clear that there is a significant need to maximize the use of space on campus.

The objective is to then transform the underused locations of existing parking lots into an active hybrid environment by integrating high density residential and educational uses. Maximizing the use of space throughout campus and exceeding TU Delft's need to accommodate 23,000 students by 2029, through an optimized temporary kit of parts configuration. The project will explore different spatial qualities within this high density, hybridized environment, rethinking the role of the building on campus. Refer to appendix 3 for existing parking lots to be transformed on campus.

To do so, the research paper explores how to attain this project objective using engineered timber. In particular, the research paper explores the combination of glue laminated timber and cross-laminated timber and its use in 1D, 2D and 3D systems (Refer to appendix 2 for definitions). The combination of these two timber materials is ideal, as both have similar properties making it easier to detail as they similarly respond to environmental changes (Waugh Thistleton Architects, 2018). Moreover, these two engineered timber types were selected as they are commonly used in 1D, 2D and 3D prefabricated systems for residential and educational typologies. Furthermore, the reason to utilize these engineered timber types is due to their popularity and ability to prefabricate and quickly construct new buildings. Due to the fact timber roughly weighs 20% of brick and 25% of concrete (Waugh Thistleton Architects, 2018), the lighter material makes it perfect for the application of generating temporary structures quickly with minimal impact to the existing site(s).

In order to pursue the ambition of quickly transforming single use parking lots, the following research question asks: “what configuration of prefabricated 1D, 2D and 3D systems generates the most optimized use of engineered timber for a hybrid building?” The configuration of different prefabricated systems would then allow for a kit of parts system to quicky generate different layout iterations while simultaneously meeting structure, fire and acoustical requirements. Moreover, it would then provide a greater understanding of residential and educational building requirements.

From this research question, a set of sub-questions have been developed to guide the research paper:

- *Q1. What aspects / boundary conditions influence the dimensionality of 1d/2d/3d engineered timber elements? (Like manufacturing, transport, assembly, etc.)*
- *Q2. What is the relation between 1d/2d/3d engineered timber dimensioning and structural / acoustical/ fire requirements of different programmatic functions?*
- *Q3. How to combine this input in a tool for designers, advising in early stages of design about optimized use of engineered timber in relation to designer input such as overall building shape and sizing of compartmentation*

The hypothesis of the research question(s) is that it will develop rules of thumb for existing 1D, 2D, and 3D timber systems for residential and educational typologies. Allowing for designers to make more informed decisions during the schematic and design development phase of a project. Moreover, it will create new opportunities for efficiently generating hybrid building systems for hybrid typologies.

II. METHODOLOGY

In order to address the proposed research question and following sub-questions, a series of specific literature studies were selected to act as the primary sources to develop a thorough understanding of 1D, 2D, and 3D timber systems, for residential and educational buildings with a maximum amount of 8 storeys applicable to the Netherlands context. The literature studies would then allow for the development of a series of rules of thumb for manufacturing, transportation, assembly, structural, fire, and acoustics, answering Q1 and Q2 resulting in a greater understanding of their influence on the overall dimensionality of prefabricated engineered timber systems.

A series of case studies were then selected, three residential case studies and three educational case studies, in order to address each of the 3 timber systems (1D, 2D, 3D). The case studies were selected based on a set of parameters to ensure their relevance to the project objective and to meet the requirements of the Netherlands climate. With the project objective of generating a mid-height building of ≤ 22 meters or 4-8 storeys. The case studies would need to be within this range of height to provide a good reference for structural sizing and fire class requirements (building class 4-5). A comparison of the case study’s building assemblies including exterior wall, interior wall, floor and roof, would provide further insight into sub-questions Q1 and Q2. Essentially, exploration of the selected case studies will help to test the rules of thumb developed from the literature studies to see how accurate they are in practice.

The rules of thumb would then be tested against the case studies to assess their accuracy and be further refined and compiled into a digital master table matrix resulting in the final design tool. Developing this tool will explore Q3 through the design of a website that quickly provides rules of thumb for 1D, 2D and 3D systems for both residential and educational typologies. Using existing sites such as dataholz.eu and wikihouse.cc to create an approachable representation of information for designers to quickly utilize. By coding the website, it will provide the opportunity to design a project specific representation of the results gathered in Q1 and Q2 and explore the potential functions of the design tool.

III. RESULTS

3.1. General Rules of Thumb for Engineered Timber

Through literature studies, sub-question Q1 was examined and resulted in establishing general rules of thumb that address manufacturing, transportation and assembly. These were titled ‘general’ as they can apply to both residential and educational projects. The three categories play a significant role in the preliminary planning of the project, as it establishes a set of dimensional restrictions that have a significant influence on the overall outcome of a proposed design. Effecting seams, joints, potential room sizing and spans, as well as overall on-site assembly. According to the Manual of Multi-Storey Timber Construction, it was these three general categories that had the most significant amount of impact on whether a project would be successful using CLT or Glulam (Kaufmann, et. al, 2018). In most cases, the issues in adopting engineered timber into mainstream construction practice was due to the unfamiliarity of how these categories may influence the project. Moreover, it was established that these should be taken into consideration as soon as possible to avoid having to back-track and re-adjust a project in order to be realized in engineered timber.

3.1.1. Manufacturing of 1D, 2D and 3D Systems

Manufacturing for 1D systems addresses the process of creating Glue-laminated Timber beams and columns. To form a glulam component, wood laminations (dimensional lumber) are positioned according to their stress-rated performance characteristics (Think Wood, 2020). Typically, the maximum width to be manufactured is 365mm. However, members that are wider than 365mm are manufactured in 50mm increments and become exponentially more expensive. The depth of a glulam member is a function of the number of laminations multiplied by the lamination thickness. As a result, depths typically range from: 114mm - 2128mm. In theory, the overall lengths of glulam members are only restricted by transportation and assembly requirements. Otherwise, it is up to the designer to determine the final length of the member. Refer to the appendix p.5 for a typical maximum cross-section for a glulam member.

Manufacturing for 2D systems deals with cross-laminated timber (CLT). Where the maximum panel length is 16500mm, the maximum panel width is 3500mm, and the maximum panel thickness is typically 500mm. Refer to the appendix p.5 for a graphic representation of rules of thumb for 2D systems. During the manufacturing process of CLT panels, it is best practice to integrate technical installations within the assembly, such as raised floor systems. This allows for installations to be completed with a high degree of accuracy in a controlled environment, ultimately saving time on site. However, it is recommended that the final floor and wall finishings should be added on site in order to cover up spacing tolerances between floor and wall panels.

Following similar sizing conditions of 2D manufacturing to produce 3D modules. 3D systems manufacturing is favorable because they can be designed as airtight as possible to improve acoustic and fire requirements. Due to the controlled conditions of an off-site facility rather than dealing with unexpected onsite conditions. It is best practice to integrate technical installations within the module in order to decrease time on site. According to Kieran Timberlake, the ‘wet’ construction program of a project such as kitchen, bathroom, laundry, are the most extensive areas of construction (Kieran and Timberlake, 2008). Since these programs require multiple trades to complete, refer to appendix p.5. As a result, when designing a 3D system, it is best practice to separate the modules into ‘Wet’ and ‘Dry’ construction. An example of this can be examined in the Puukuokka Housing Block case study and can clearly be seen how two modules (‘wet’ and ‘dry’) come together to form a single unit (OOPEAA, 2021). This case study can be found in appendix 20. Moreover, a summation of the manufacturing rules of thumb can be found in appendix 4.

3.1.2. Transportation of 1D, 2D and 3D Systems

Transportation of 1D and 2D systems is straightforward in that it is most cost effective if members are stacked regularly and compactly with no wasted space and no requirements for wide or long loads, as seen in appendix p.6. There are different restrictions depending on whether the truck has no escort, an escort vehicle on Urban and country roads and a police escort vehicle on Urban and country roads. These different requirements should be determined early on as it further influences the overall dimensionality of the designed prefabricated system(s) and can be found in appendix p.6.

It is advised that the transportation of 3D systems should be well considered, since 3D modules contain a lot of dead space within themselves while being transported, as opposed to stack panels, beams and columns. It is important to note that the size of the 3D module will influence the number of trips that are required to bring everything to site, the larger the module, the more trips required which increases transportation time and cost. However, it is also important to acknowledge that the increased time spent on transportation is often countered by efficient prefab production as well as efficient on-site assembly. A summation of the transportation rules of thumb can be found in appendix 5.

3.1.3. Assembly of 1D, 2D and 3D Systems

The most important strategy for designing an assembly is to simplify as much as possible to ensure easy and fast on site construction. This is because the more trades you have on site, there is the potential for more mistakes of intellectual misalignments and material and products miss fittings. As a result, striving for assemblies that require a minimum number of trades, needing little or no temporary support, requiring no special tools, and a minimal need for ladders or scaffolding will increase onsite assembly (Kaufmann, et. al, 2018).

A universal system of picking and setting is desirable as it mitigates differences in hoisting and placing equipment and will significantly increase construction time. It is then essential to design a prefabricated kit of parts to have similar sizing or ‘pick-points’ for easy assembly.

For the assembly of 1D systems, try to use standard sizing for all components wherever possible and ensure that members require simple lifting equipment. In the same light, simplify connection details between elements and use repetition of elements as much as possible. Taking these considerations into the design of members can also positively influence manufacturing and transportation.

The assembly of 2D systems are like the 1D systems rules of thumb and should try to maximize their size as much as possible, in relation to manufacturing and transportation. As the large format components enable a fast assembly and ensure the building is well braced. Moreover, just like for all systems, avoid custom sizes or one-off cuts to ensure fast construction. Furthermore, correct lapping of joints must be considered to avoid any failures.

When it comes to 3D systems, the larger the modules, the more cost-effective the structure will be. Just as 2D systems, it is imperative that 3D systems can be easily hoisted from their transport and into place. Moreover, it is recommended that along with final finishings, the final façade should be assembled on-site as well. The reason being is that the designer then has more freedom on the final aesthetic of the project and can potentially hide the regulating joints of the modules to create a seamless appearance. A prime example of this can be seen in the Puukuokka Housing Block case study in appendix 20 (OOPEAA, 2021). A summation of the assembly rules of thumb can be found in appendix 6.

3.2. Specific Rules of Thumb for Engineered Timber

The specific rules of thumb were developed from the selected literature studies and examined with the selected case studies as well. These rules of thumb can be broken down to three categories of spans, fire and acoustics. It is important to note that the research proved that there are different requirements for residential and educational typologies, primarily with fire and acoustics.

3.2.1. Structure of 1D, 2D and 3D Systems

3.2.1.1. Residential Typologies

It was found that Glulam beams and columns are not typically utilized for residential unit construction as it is more effective to go with a 2D or 3D alternative. An example from the Manual of Multi-Storey Timber suggests a series of span to depth ratios for a beam ceiling system. Refer to the section diagram and table in the appendix p.8. Moreover, a project in British Columbia, Canada known as Brock Commons, utilized a column and floor panel combination (1D/2D) for high rise student housing.

For residential 2D systems (CLT Panels), one can use the calculation L/27 to determine the overall depth of a floor panel. Where L = the span in millimeters. Some typical span to depth ratios includes Span 4m = 140mm Depth, Span 5m = 180mm Depth, Span 6m = 220mm Depth (Kaufmann, et. al, 2018). The rule of thumb was then tested against the Ansbach case study and the Dantebad case study as they both utilize CLT floor panels. In the case of Ansbach, it has roughly a CLT span of 4750mm. So, 4750/27= 176mm. In comparison to the specified 180mm thick CLT floor plate in the section detail. As for Dantebad, it has a CLT floor panel span of 4000mm. Resulting in 4000/27= 148mm in relation to the specified 140mm thick panel.

For determining spans of 3D modules of both residential and educational typologies, it is recommended to reference the rules of thumb for 2D Spans as well as 2D manufacturing and transportation to ensure an easy combination of 2D and 3D systems.

To determine the ‘ceiling’ depth of a CLT panel in a 3D Module. The ceiling panel is typically ±50% thinner than that of the CLT Floor panel in a residential module, typically a 5-Layer floor with a 3-Layer ceiling. A diagram of this clearly shows this relation in the appendix p.8. This was tested against the Puukuokka Housing Block case study and found that on average the rule of thumb was accurate for residential projects using 3D systems.

As for the wall panels for both 2D and 3D systems, it was found that they are typically 80-100mm thick (Comprising 3-Layers). However, it should be noted that this range of thickness for a CLT wall panel is optimized for 5 storeys or greater. If used for 4 storeys or less, it would be considered an unoptimized use of material. A summation of the structural rules of thumb can be found in appendix 7 and 8.

3.2.1.2. Educational Typologies

Beam geometries make use of the fact that load-bearing capacity increases exponentially with the distance between the upper and lower areas of a structurally effective cross section. As a result, the greater the span, the greater the depth of beam is required. Referring to the manufacturing rules of thumb for 1D systems, the width of the beam comes in predetermined sizes depending on the manufacturer. Therefore, a glulam beam for an office or education program, while referring to a product chart, one can use the calculation L/16 to determine the depth of a beam. Where L = the span in millimeters.

This rule of thumb was tested on the Wood Innovation and Design Centre case study where it was a 7-storey building with spans of 8000mm with 500mm deep beams. Using the rule of thumb: 8000/16 = 500mm. It is important to note that calculating for column sizes becomes extremely complicated and should preliminarily be determined through case study examples.

In order to calculate the thickness of a CLT floor panel (2D system), one can use the calculation L/47 to determine the depth of a beam. Where L = the span in millimeters.

The rule of thumb was then tested against the Wood Innovation and Design Centre case study where there are two layers of CLT panels that overlap on top of each other. For simplification, the rule of thumb was applied to the ‘bottom’ CLT panel that spans 8000mm from beam to beam. As a result, 8000/47= 170mm in relation to the 169mm specified. (Refer to appendix 8)

To determine the ‘ceiling’ depth of a CLT panel in a 3D Module. The ceiling panel is typically ±25% thinner than that of the CLT Floor panel in a residential module, typically a 3-Layer Floor and a 3-Layer Ceiling (As seen in appendix p.9). The rule of thumb was then tested on the European Frankfurt School case study and proved to be accurate floor to ceiling ratio for educational 3D systems.

For both 2D and 3D CLT wall panels, the range of depth is typically 80-150mm thick (Comprising 3 or 5 Layers). Refer to appendix 14 for interior wall assemblies for educational case studies.

3.2.2. Fire of 1D, 2D and 3D Systems

Due to the project objective of creating a multistorey building between 5 and 6 storeys, that places the project in either a Class 4 (height of the uppermost floor = 13 meters) or class 5 (height of the uppermost floor = 22 meters). In which case, buildings require longer fire resistance durations of 60 and 90 minutes for all timber systems, both residential and educational.

3.2.2.1. Residential Typologies

For residential typologies, typically the use of a 1D system is done in combination with a 2D system as seen in the Brock Commons student housing building in British Columbia, Canada. In order to meet fire requirements, the entire building is sprinkled with a 30-minute back-up water supply. Moreover, most structural wood elements are clad in multiple layers of Type X gypsum board to achieve a 2-hour fire resistance rating (Naturally: wood, 2016).

Regarding 2D systems (CLT panels), the required corridors and staircases must be kept free of fire loads by means of paneling with non-combustible cladding, as seen in the appendix p.10 graphics. The corridors and egress stairs must serve to escape potential fires and should thus have a higher fire resistance rating. In the same light, if the ceiling and floor are made of visible wood, the walls should be paneled with a non-combustible material, or if two walls are not lined, then either the ceiling or floor may be made of visible timber. In principle for 2D and potentially 3D systems, increased requirements for fire resistance can be compensated by the following measures: Increase the thickness of the CLT element, which will increase the number of layers of the CLT element resulting in the member having a protective layer. Essentially, the rule of thumb is 2cm per 30 minutes for charring and this layer must not contribute to the structural integrity of the member. Alternatively, one can clad a CLT member with fire rated gypsum board in order to meet the requirements. An example: With a non-clad, three-layer CLT element, the fire resistance REI 60 is already obtained, and with a CLT element clad with a single layer of plasterboard, the fire resistance REI 90 is obtained. As a result, the greater the thickness of the CLT panel the higher the fire resistance rating of the member. However, if a thinner member is desired then the total assembly must compensate, i.e) increased layers of plasterboard. A summation of the fire rules of thumb can be found in appendix 9 and 10.

3.2.2.2. Educational Typologies

The rule of thumb for 1D systems is that individual supports must only be designed to retain their structural integrity (R). Furthermore, the behavior of timber structural elements in fire is greatly influenced by the proportion of surface to cross section and the densities of various woods. As a result, for 1D system members to meet potential fire requirements, their cross-section may be enlarged if exposed timber is desired. Alternatively, the member can be cladded in a non-combustible material (typical one or two layers of 16mm or greater fire-resistant gypsum). Refer to appendix p.11 for a cross-sectional detail.

For all system types, most connectors are fabricated from steel and the performance of steel in high temperatures deteriorates. Typically, the connectors will be protected within a fire board or within a floor and wall assembly, refer to the appendix p.11 for an example detail of this.

The rules of thumb stated for residential 2D systems can also be applied to educational typologies. However, it is important to note that educational typologies typically require a fire resistance of 30-60 minutes, depending on overall building height and footprint. For example, the Wood Innovation and Design Centre requires 60 minutes and is considered building class 5, while the European Frankfurt School requires a 30-minute resistance rating and is considered building class 3 (Kaufmann, et. al, 2018). Often, educational typologies will utilize sprinkler systems to help attain their fire resistance rating, while adding additional layers of gypsum to walls, floors and ceilings.

The rules of thumb for fire and 3D timber systems are like that of the 2D rules of thumb. However, in both residential and educational cases, the double stacking of floors and walls should be considered.

The double stacking of CLT panels increases the fire resistance rating of the project and results in the potential for thinner CLT Panels for each module.

3.2.3. Acoustics of 1D, 2D and 3D Systems

For acoustic rules of thumb, the research was based on German context as it currently has the highest level of sound requirements for residential typologies. Resulting in these requirements becoming the typical rules of thumb for projects going forward to attain the most optimum acoustic conditions.

It is important to note that impact sound can be understood as the sound generated from foot fall, moving furniture or anything that makes direct contact with a floor slab that in turn generates sound. In order to mitigate this, detailing a raised floor system is the most effective way to reduce impact sound levels for CLT floor slabs. Typically, if a project is designed for good impact sound insulation, it will normally meet the requirements for airborne sound. Moreover, airborne sound is generated from conversation, music and other audible sources and it has a significant impact on flanking.

Flanking sound is an essential consideration and should be addressed through detailing of components by providing acoustical breaks where timber members meet and should be considered for 1D, 2D, and 3D systems. Subsequently, there are two methods to minimize this which include, vibration damping using flanking transmission barriers and separate inner cladding of load-bearing elements.

3.2.3.1 Residential Typologies

It is important to note that in general, for residential typologies the impact sound requirement should be L'n, w≤ 50 dB where the lower the value the better. Moreover, a residential unit must have an airborne sound reduction index of R'w≥ 54dB, where the higher the value the better. Typically, if a project is well designed for impact sound it will also perform well for airborne sound requirements. Refer to the appendix p.12 for a series of floor assemblies that meet these requirements.

For 2D systems, in both residential and educational typologies it is imperative that the detailing of CLT panels takes flanking into consideration during the design. Examples of this can be seen in the diagrams represented in the appendix p.12 to understand where flanking occurs and potential design implementations to mitigate this. Typically, residential floor assemblies are roughly the same depth or less than those in educational typologies. This is largely due to residential typologies typically generating a less significant amount of impact sound. On average, 2D floor assemblies utilize 30-40mm of impact sound insulation in addition to thermal insulation which can be seen in the floor assembly details in the appendix p.12 (Kaufmann, et. al, 2018). Which ultimately affects the overall dimensionality of the floor assembly. However, the wall assemblies in the residential case studies proved to be thicker, utilizing 40mm of insulation on either side of a CLT unit separation wall panel (Kaufmann, et. al, 2018). Also providing an airspace between the wall finish and the CLT member which helps to mitigate impact and airborne sound reverberations. Both of which can be referred to in the Ansbach and Dantebad case study in appendix p.36 and p.38.

In both residential and educational typologies, the prefabricated 3D module provides the opportunity to develop airtight details which result in mitigating opportunities for flanking as much as possible as seen in the appendix p.12. As a result of the stack of modules, there is a need to provide insulation in between each module, acting as a fire and acoustical separation (Waugh Thistleton Architects, 2018). In the Puukuokka Housing Block residential case study, there is an acoustical insulation infill of 60mm, essentially 30mm attached to the perimeter of each module (Kaufmann, et. al, 2018). The underside of the 3D module typically has 50mm of thermal insulation that also contributes to overall acoustic performance and works in addition to the 30mm of impact insulation found in the raised floor assembly (Kaufmann, et. al, 2018). Along with the double stacking of floors and walls, the use of 3D modules generates the thickest overall final dimensionality and can clearly be noticed in the comparison of assemblies seen in appendix 11 and 12, 3D systems.

3.2.3.2 Educational Typologies

In comparison, for educational typologies there are different functioning rooms within a project that require different levels of sound insulation. An example of this can be viewed in appendix 12, where a small classroom of less than 50 people generate a maximum impact sound level of L'n, w = 60dB.

However, often what separates residential and educational acoustic requirements is the use of drop ceilings in educational spaces. These drop ceilings provide a quiet environment to work and present within, mitigating the reverberation within the space. There is then more of a focus placed on the ceiling design of an educational space along with adding further sound insulation to the walls. Along with the typical use of beams to create larger open spaces to work within, the acoustic design of the ceiling has a major impact on the dimensionality of assemblies required to produce a well-functioning space.

The floor assemblies of 2D systems utilize the same rules of thumb as residential 2D systems, however in an educational typology context. The amount of acoustical sound insulation is considerably less in both floor and wall assemblies. Ranging from 7mm to 30mm of impact sound insulation in floor assemblies (Kaufmann, et. al, 2018). For example, in the Wood Innovation and Design Centre, there is only 7mm specified impact sound insulation. Yet the floor assembly also enables an integrated drop ceiling and raised floor that helps to contribute to overall acoustical performance. As a result, it appears that educational typologies try to minimize the assembly as much as possible and instead use off-set acoustic interventions such as drop ceilings.

For educational 3D systems, the rules of thumb are like residential 3D systems. Using the European Frankfurt School case study, there is 25mm of impact sound insulation in the floor assembly, and 60mm of thermal insulation with the floor assembly of the module and another 60mm of insulation in the ceiling, contributing to the overall acoustic performance of the classrooms (Kaufmann, et. al, 2018). As a result, looking at just the stacking of floor plates, the educational building is 87.5mm thinner than that of the Puukuokka Housing Block. It is also noticed that like the Puukuokka Housing Block, the Frankfurt School utilizes acoustical breaks where the modules connect in order to mitigate vibrations throughout the modules.

3.2.4. The Design Tool

With the collected information for the rules of thumb, the third sub-question is addressed: "*How to combine this input in a tool for designers, advising in early stages of design about optimized use of engineered timber in relation to designer input such as overall building shape and sizing of compartmentation?"*. The rules of thumb were compiled into a master table as seen in the appendix. However, there is a lot of information being presented at once, so websites such as dataholz.eu were referenced to explore how to break down information. The designed website sets out to present all the information on one page but can be filtered by the designer. Allowing one to look at only residential typologies, only 1D systems or compare systems for residential and educational typologies. Moreover, the website also presents the different types of assembles that are found in the referenced case studies, allowing for designers to understand how a system type (1D/2D/3D) comes together. They are then able to be redirected to find more information about the case study if need be. The design tool then becomes a place to quickly get information presented in a simplified way so that designers are more inclined to incorporate the researched rules of thumb in the early stages of a project, making it the best solution to combine the concluded results.

The design tool can be found at: https://timbersystemsdesigntool.netlify.app/designtool

It is important to note that the website was preliminarily coded to act as a prototype to then be further developed in the future. The website also includes further information about the case studies utilized, information on the materiality of Glue laminated timber (GLT) and Cross laminated timber (CLT), and an explanation of 1D, 2D and 3D system types. Through testing and sharing the website it, it was found that the master table page was able to be easily used while developing the graduation project, allowing to easily make more informed decisions throughout the design process. These rules of thumb, along with case study examples helps for learning about the different rules of thumb and to then see how an example of how it is used in practice, provided the designer with a greater understanding of 1D, 2D and 3D engineered timber systems.

IV. CONCLUSIONS

The stated results discovered from the selected literature and case studies have helped to develop a greater understanding of existing 1D, 2D, and 3D timber systems that utilize CLT and Glulam. From these three timber systems, it was noticed that rarely are all three utilized and even less likely be utilized to generate a hybrid building with residential and educational typologies. The combination of all three systems could result in taking the benefits each system offers and mitigate the negatives as much as possible. Moreover, it was found that 3D systems are best for a specific programmatic function or unit, either a residential unit typology or a classroom, while 1D and 2D systems can provide a great amount of flexibility for public space.

While developing the rules of thumb for 1D, 2D, 3D systems, the sub-question of "*what are other aspects / boundary conditions influencing the dimension of 1d/2d/3d engineered timber elements? (Like manufacturing, transport, assembly, etc.)"* From this question, three 'general' categories of manufacturing, transportation, assembly were explored and to be applied to 1D, 2D and 3D timber systems. It was established that all three of these categories must be taken into consideration with each of the categories overlapping with each other, effecting the overall dimensionality of prefabricated engineered timber systems. It becomes imperative when developing an engineered timber building that designers have knowledge of these categories and understand how they ultimately effect the final design of the project. The research of these systems and the general categories helps to eliminate the current issue with designers not having the background knowledge to make more informed decisions during the early stages of the project. The produced research results in a more streamline approach to engineered timber buildings, rather than developing a proposal only to re-adjust it later in order to meet CLT or Glulam restrictions that fall within the established three general categories that can essentially be applied to any building typology.

As the research progressed towards the specific programmatic typology of residential and education. Three primary categories were established in order to answer the sub-question of "*What is the relation between 1d/2d/3d engineered timber dimensioning and structural / acoustical/ fire requirements of different programmatic functions"*. The answer to this question for residential and educational programmatic functions is that in order to meet these requirements the designer essentially has two options. Option 1 is to simply increase the CLT member's depth or the Glulam member's cross section in order to meet structure and fire requirements. Option 2 addresses fire and acoustical requirements which is to maintain the timber element as thin or as small as structurally possible and to then increase the overall assembly such as fire-resistant gypsum board or acoustical insulation. For residential projects, 2D and 3D systems were typically a larger assembly than that of the educational case studies. The CLT members of residential projects typically ranged from 140mm-180mm for the floor plates and the CLT walls ranged from 80mm-100mm. In comparison to educational buildings where 2D and 3D system CLT floor plates ranged from 80mm-170mm, while the CTL walls ranged from 80mm-150mm. For the purposes of a hybrid building typology, structural members should have the same depths and then have different assembly types to meet the different residential and educational requirements.

The overall research question: "*what configuration of prefabricated systems generates the most optimized use of engineered timber for a hybrid building?"*. Through the results of the paper and developed design tool allow for designers to make more informed decisions to select systems that best fit their programmatic functions. Utilizing rules of thumb for all three prefabricated systems in a hybrid building typology will result in an optimized building design proposal that is further developed than other schematic engineered timber designs.

With the results providing a greater understanding of 1D/2D and 3D timber systems, it allows designers to go into a new project with the ability to make more informed decisions which will then save time during design development. Rather than creating a design and then having to go back and adjust later in the process.

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APPENDIX

Personal Information

Benjamin Bomben

Student Number: 5511585

Studio

Architectural Engineering Design

Tutor: Anne Snijders Research

Tutor: Pieter Stoutjesdijk

Focus

Context: TU Delft Campus

Technology: Make

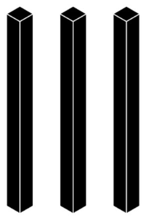
Design Program: Open Building

Appendix 1: Realized Student accomodation from 2017- Now

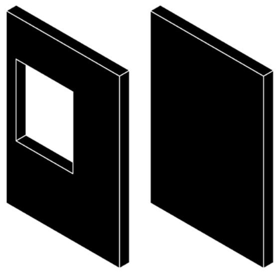
Location	Units	Year of completion	Developer
Prof. Schermerhornstraat	332	2017	Duwo
Kanaalweg 3a	47	2017	Duwo
Deltares/Stieltjesweg	665	2017	Duwo
Prof. Schoemakerstraat 97	289	2017	Camelot
Van Bleyswijkstraat	25	2017	Villex
A. Veerstraat 1-15	118	2017	Xior
Abtswoude (tijdelijk)	110	2018	SHS
Phoenixstraat	100	2018	Xior
The Student Hotel	240	2020	The Student Hotel
Campus 015 Pauwmolen	143	2021	Camelot
Balthasar van der Polweg	136	2023	Duwo
Totaal	2205		

Source: https://www.delta.tudelft.nl/article/shortfall-1500-student-rooms-delft

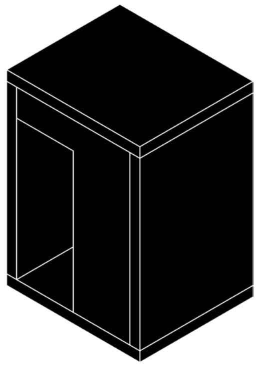
Appendix 3: Engineered Timber System Definitions:



1D Systems
Linear timber members such as columns and beams. Typically made of Glue laminated timber

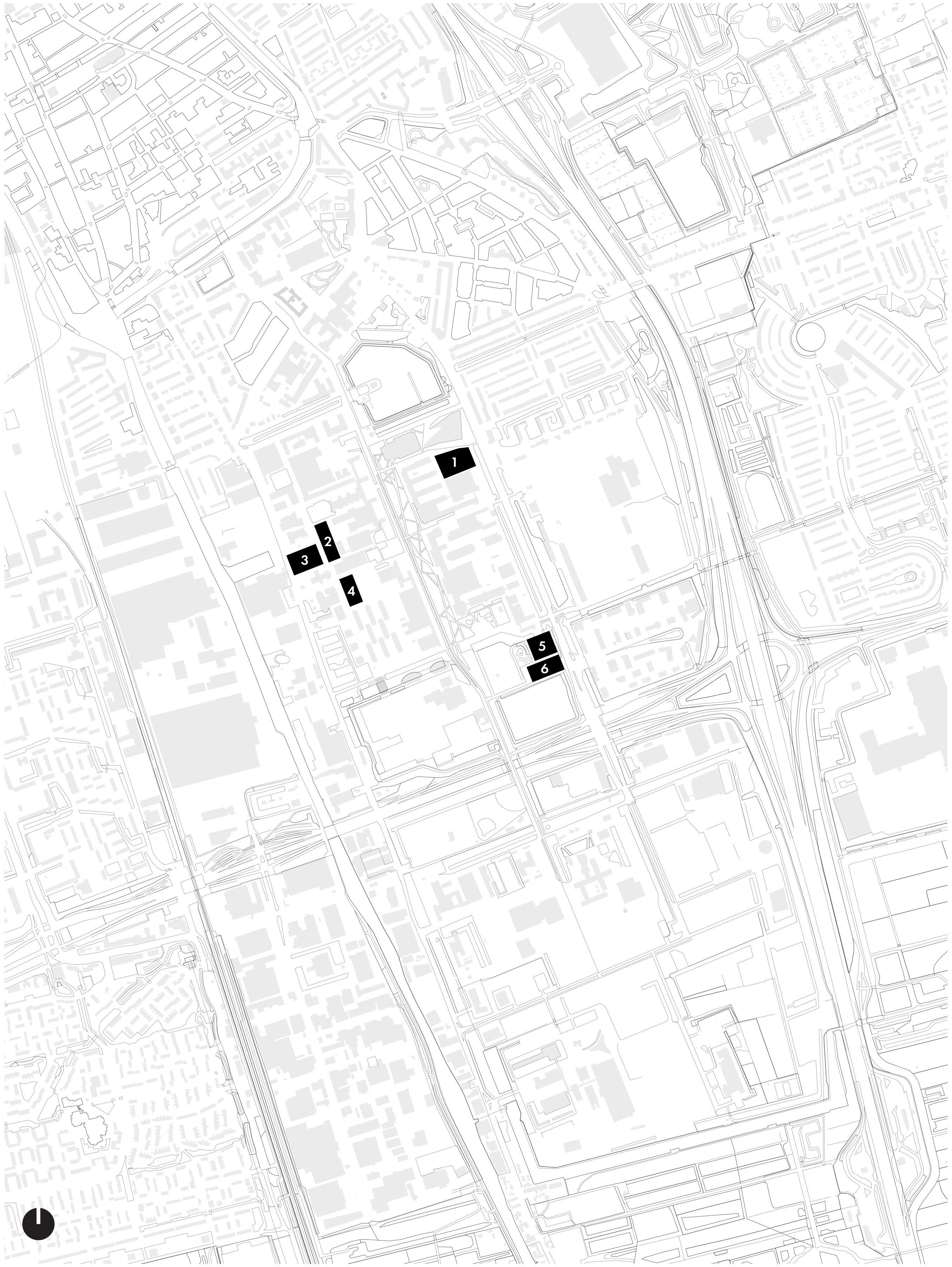


2D Systems
Typically cross laminated timber (CLT) floor and wall panels.



3D Systems
A prefabricated assembly of 2D CLT members to create a module to be brought and place at site.

Appendix 3: Existing Parking Lot on Delft Campus to be Utilized



Parking Lot Areas

Total Area: 28738m²

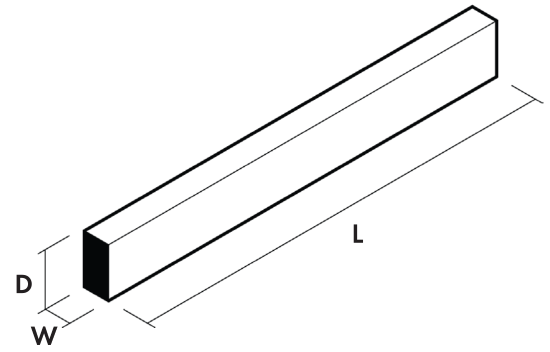
1: 6410m²
2: 3810m²
3: 4013m²
4: 3451m²
5: 3865m²
6: 3324m²

RULES OF THUMB

Appendix 4: Manufacturing Rules of Thumb:

1D Systems: Glue Laminated Timber Cross Section:

- D = Depth: 114mm - 2128mm typ.
- W = Width: 365mm typ.
  However, if a greater width is desired, then it can be manufactured in 50mm increments, i.e) 415mm, 465mm, etc... Memberss then become exponentially more expensive.
- L = Length: Determined by the desired span from the designer. Should take transporation and assembly rules of thumb into consideration.



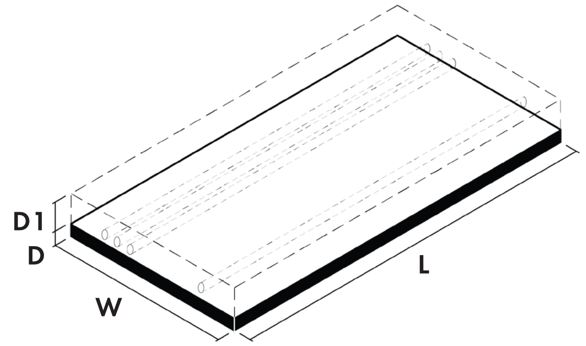
2D Systems: Cross Laminated Timber Panels:

- D = Depth: 500mmmm typ.
- D1 = Depth of Assembly: 60mm-215mm typ.
- W = Width: 3500mm Maximum
- L = Length: 16500mm Maximum

Typically CLT panels with a depth from 60mm-100mm consist of 3-layers.

Where as CLT panels with a depth from 120mm-180mm consist of 5-layers.

In order to attain its structural properties, CLT panels always need to have an odd number of layers. i.e) 3-Layers, 5-Layers, 7-Layers, etc...

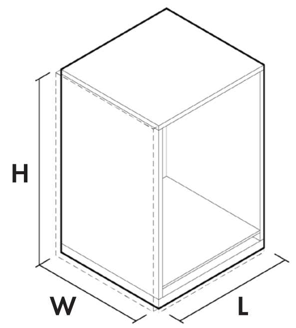


3D Systems: CLT Modules:

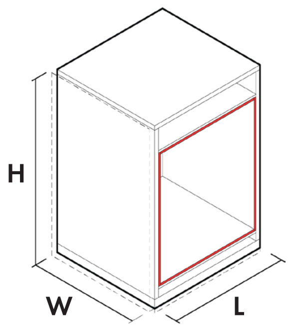
- H = Height: ±3000mmmm typ.
- W = Width: Dependent on transportation and assembly rules of thumb
- L = Length: 16500mm Maximum

Note that the 2D manufacturing of CLT panels also has an influence on the dimensionality of 3D modules.

Within the 'wet' module, the red represents finishing for wet conditions and below the ceiling CLT member is a drop ceiling for mechanical installations. Alternatively this can be located against one of the walls of the module or in the raised floor system



'Dry' Module

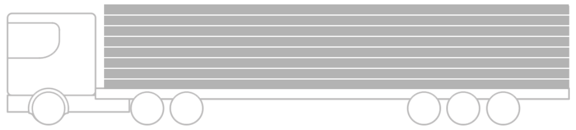


'Wet' Module

Appendix 5: Transportation Rules of Thumb:

1D Systems:

- Transporting a 1D system is most cost effective if they are stacked regularly and compactly with no wasted space and no requirements for wide or long loads.
- The same rule applys to 2D panels as well.
- To ensure trasnportation is most effective, prefabricated members should be as typical as possible, avoiding custom or one-off memebrs.



Correct

Incorrect

Source: Waugh Thistleton Architects. (2018). 100 Projects UK CLT.

2D Systems:

Transport Sizes with no additional requirements:

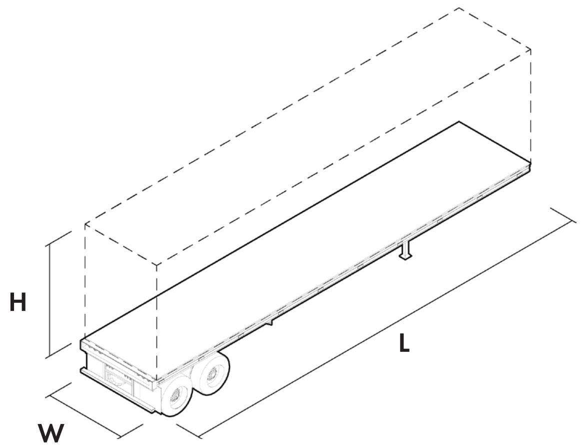
- H = Maximum Height: 4m
- W = Maximum Width: 2.55m
- L = Length of Rigid lorries: 12m

Transport Sizes if there is an escort vehicle on Urban and country roads:

- H = Maximum Height: 4m
- W = Maximum Width: 3m
- L = Length of Articulated Lorries: 16.5m

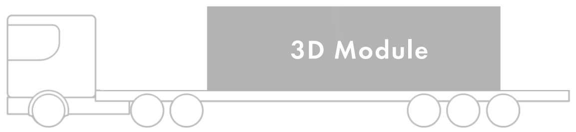
Transport Sizes if there is a Police escort vehicle on Urban and country roads:

- H = Maximum Height: 4m
- W = Maximum Width: 3.5m
- L = Length of Road Trains: 18.75m



3D Systems:

Transportation of 3D modules follows the same size conditions as 2D systems. However, since 3D modules contain a lot of dead space within themselves while being transported, as opposed to stack panels, beams and columns. Depending on the size of the 3D module, the more trips are required to bring everything to site, affecting overall construction time. However, this is to be balanced with assembly rules of thumb.

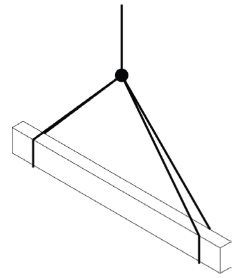


Source: Waugh Thistleton Architects. (2018). 100 Projects UK CLT.

Appendix 6: Assembly Rules of Thumb:

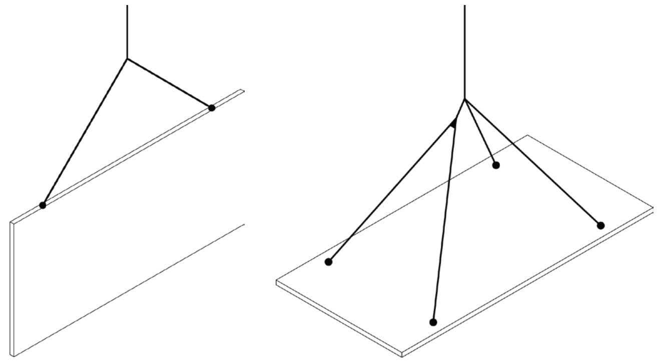
1D Systems:

- Try to use standard sizing for all components wherever possible in order to simplify on site assembly, resulting in faster construction.
- Requires simple lifting equipment.
- Simplify connection details between elements.
- Typically uses wrap around straps for beams.



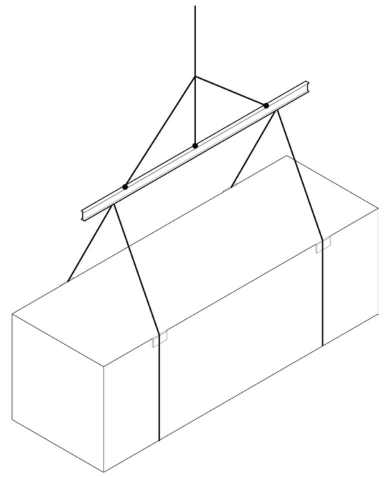
2D Systems:

- The large format components enable a fast assembly and ensure the building is well braced
- Avoid custom sizes/ one-off cuts to ensure fast construction.
- Depending on the final design. The pick points used to life the panels into place may be exposed. The designer should then take this into consideration into the final design.
- However, if the facade and other final finishing are completed on site, then these pick point will be hidden within the assembly.



3D Systems:

- The larger the modules, the more cost-effective this structure will be.
- In some cases, the ceiling can be completely omitted from the module so that when stacked, the underside of the floor becomes the ceiling. The same idea can be applied to the walls of the module. i.e) Two 3m wide modules come together to create a 6m room.
- It is ideal to separate 'wet' modules from 'dry' modules to increase construction speed.
- To optimize the use of the factory setting, integration of technical installation can increase on site construction speed.



Appendix 7: Residential Typologies:

Structure Rules of Thumb:

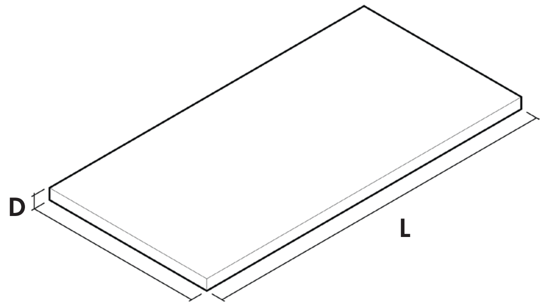
1D Systems:

- The use of 1D systems are rarely utilized in Residential construction as 2D and 3D systems are better optimized for those typologies.
- Instead of using 1D systems, it is recommended to use 2D, 3D or a combination of both for multiple residential units where repetition of units is likely to occur

2D Systems:

CLT Floor Spans for Residential Program:

- One can use the calculation **L/27 = D** to determine the depth (D) of a panel.
- Where L = the span in millimeters
- Some typical span to depth ratios include (Manual of multi storey timber):
- Span 4m = 140mm Depth
- Span 5m = 180mm Depth
- Span 6m = 220mm Depth



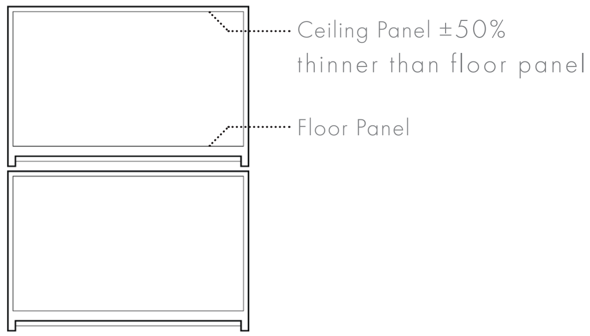
3D Systems:

For determining spans of 3D modules, it is recommended to reference the rules of thumb for 2D Spans as well as 2D manufacturing and transportation to ensure an easy combination of 2D and 3D systems

- For 3D modules, use 2D rule of thumb to calculate for the floor panel first.

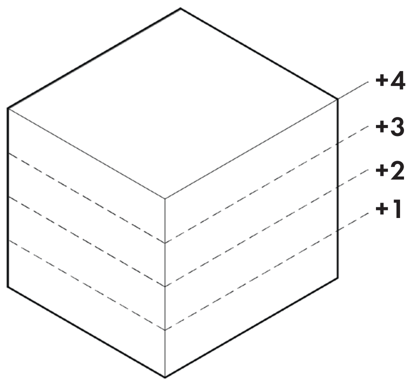
To determine the 'ceiling' depth of a CLT panel in a 3D Module:

- The ceiling panel is typically **±50% thinner** than that of the CLT Floor panel in a residential module



Overall Building Height:

It is important to note that a CLT solultion 4 storey's or less would use moer CLT than required. Therefore it is recommended to go 5 storey's or higher when proposing an engineered timber project that utilizes CLT.



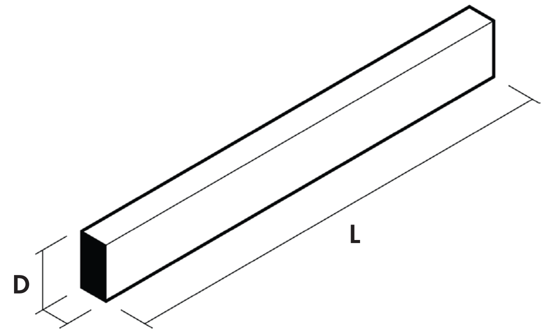
Appendix 8: Educational Typologies:

Structure Rules of Thumb:

1D Systems:

Glulam Beam Depth calculation for Office/ Education Program:

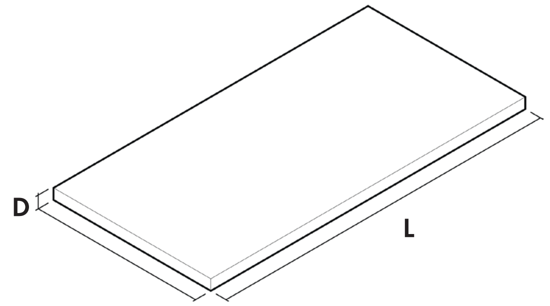
- One can use the calculation **L/16 = D** to determine the depth of a beam. Where L = the span in millimeters



2D Systems:

CLT Floor Spans for Residential Program:

- One can use the calculation **L/47 = D** to determine the depth (D) of a panel.
- Where L = the span in millimeters



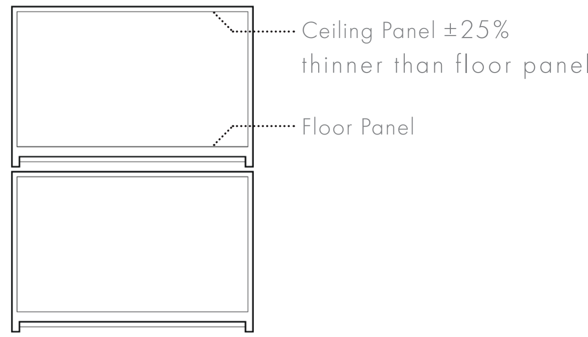
3D Systems:

For determining spans of 3D modules, it is recommended to reference the rules of thumb for 2D Spans as well as 2D manufacturing and transportation to ensure an easy combination of 2D and 3D systems

- For 3D modules, use 2D rule of thumb to calculate for the floor panel first.

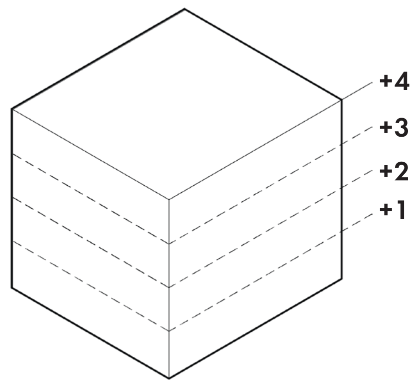
To determine the 'ceiling' depth of a CLT panel in a 3D Module:

- The ceiling panel is typically **±25% thinner** than that of the CLT Floor panel in a residential module



Overall Building Height:

It is important to note that a CLT solultion 4 storey's or less would use moer CLT than required. Therefore it is recommended to go 5 storey's or higher when proposing an engineered timber project that utilizes CLT.



Appendix 9: Residential Typologies:

Fire Rules of Thumb:

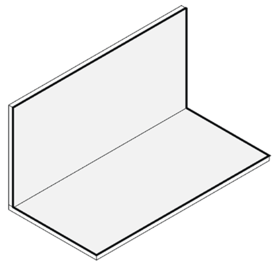
Class 4 (height of the uppermost floor = 13 meters) and class 5 (height of the uppermost floor = 22 meters) buildings require longer fire resistance durations of 60 and 90 minutes because fires are harder to extinguish in taller buildings.

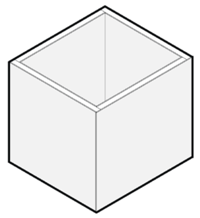
2D Systems:

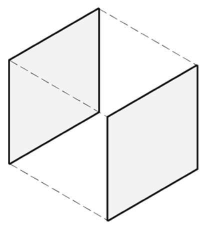
- The required corridors and staircases must be kept free of fire loads by means of paneling with non-combustible cladding.
- If the ceiling and floor are made of visible wood, the walls should be paneled with a non-combustible material, or if two walls are not lined, then either the ceiling or floor may be made of visible timber.

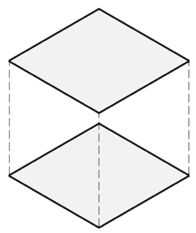
In principle, increased requirements for fire resistance can be compensated by the following measures:

- Increase the thickness of the CLT element
- Increase the number of layers of the CLT element
- Clad CLT member with fire rated gypsum board


Corridor


Stair Egress


Clad CLT Walls in Gypsum

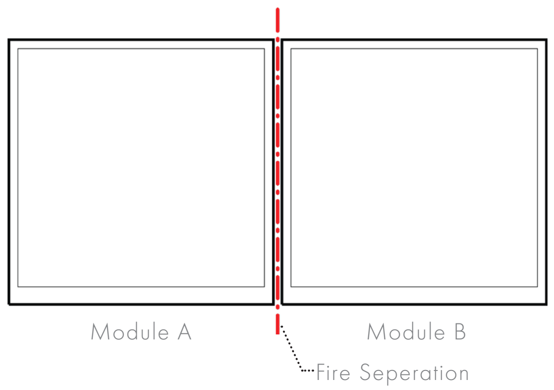

Clad CLT floor & ceiling in Gypsum

3D Systems:

For 3D systems, follow the rules of thumb stated for 2D systems. However, for 3D systems:

- The double stacking of CLT panels increases the fire resistance rating of the project
- Resulting in the potential for thinner CLT Panels

Important to keep in mind of the double stacking of floor to ceiling and wall to wall



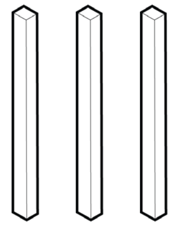
Appendix 10: Educational Typologies:

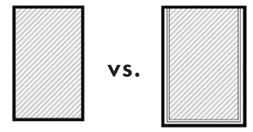
Fire Rules of Thumb:

In the case of educational typologies, typically a fire rating of 30 - 60 minutes is required. Often time, educational buildings will also add sprinkler installations to help improve their fire rating. For the purposes of combining residential and educational typologies, a fire rating of 60min or greater will be attained.

1D Systems:

As a result of Glue laminated timber being rarely used in multi-storey residential units, there are no specific fire rules of thumb for this condition. As stated previously, it is recommended to utilize 2D, 3D or a combination of both for residential units.


Individual Support Members



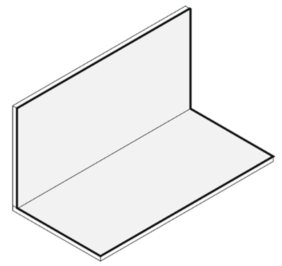
Exposed Timber vs. Timber w/ fire resistance cladding

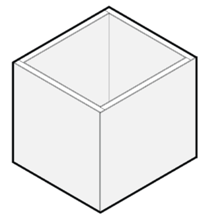
2D Systems:

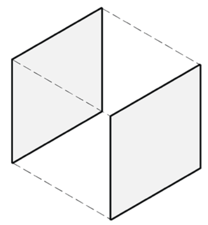
- The required corridors and staircases must be kept free of fire loads by means of paneling with non-combustible cladding.
- If the ceiling and floor are made of visible wood, the walls should be paneled with a non-combustible material, or if two walls are not lined, then either the ceiling or floor may be made of visible timber.

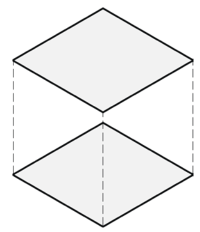
In principle, increased requirements for fire resistance can be compensated by the following measures:

- Increase the thickness of the CLT element
- Increase the number of layers of the CLT element
- Clad CLT member with fire rated gypsum board


Corridor


Stair Egress


Clad CLT Walls in Gypsum

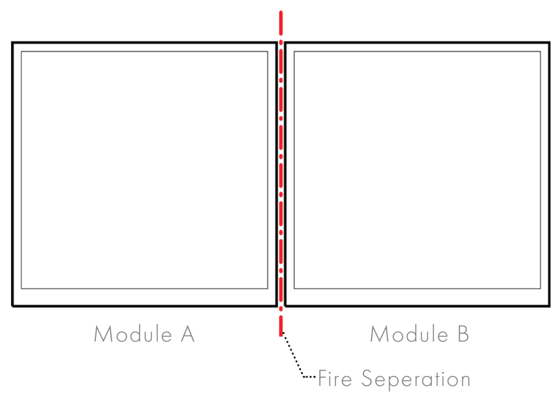

Clad CLT floor & ceiling in Gypsum

3D Systems:

For 3D systems, follow the rules of thumb stated for 2D systems. However, for 3D systems:

- The double stacking of CLT panels increases the fire resistance rating of the project
- Resulting in the potential for thinner CLT Panels

Important to keep in mind of the double stacking of floor to ceiling and wall to wall



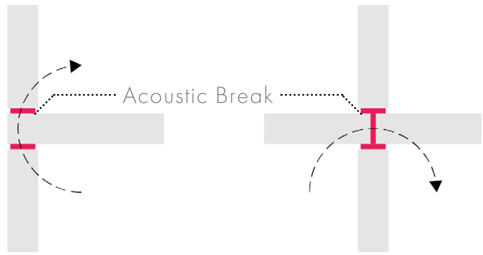
Appendix 11: Residential Typologies:

Acoustic Rules of Thumb:

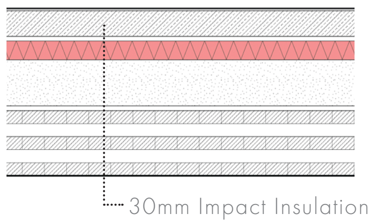
It is important to note that in general, for residential typologies the impact sound requirement should be L'n, w≤ 50 dB where the lower the value the better. Moreover, a residential unit must have an airborne sound reduction index of R'w≥ 54dB, where the higher the value the better. Typically, if a project is well designed for impact sound it will also perform well for airborne sound requirements

2D Systems:

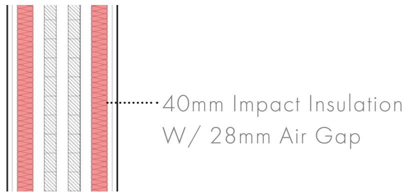
- For 2D systems, in both residential and educational typologies it is imperative that the detailing of CLT panels takes flanking into consideration during the design. To mitigate this, there must be an acoustical break between CLT panel members. Typically 5mm-10mm thick.
- On average, 2D floor assemblies utilize **30mm-40mm** of impact sound insulation in addition to thermal insulation
- Providing an airspace between the wall finish and the CLT member helps to mitigate impact and airborne sound reverberations



Flanking Example



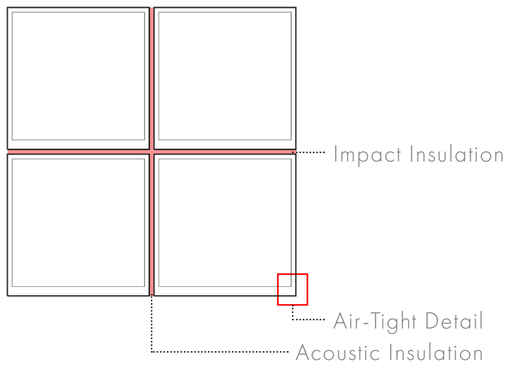
Dantebad Case Study | Typical Floor Assembly

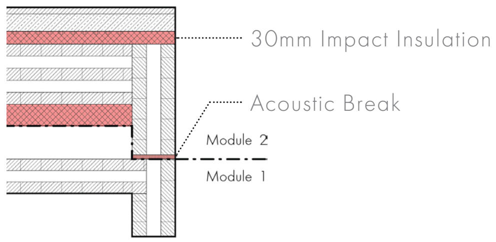


Ansbach Case Study | Typical Interior Wall Assembly

3D Systems:

- 3D module provides the opportunity to develop airtight details
- Use of insulation to separate modules
- Acoustic breaks/ seals where modules connect to mitigate impact sound
- Double stacking of CLT walls helps to improve the acoustical rating.





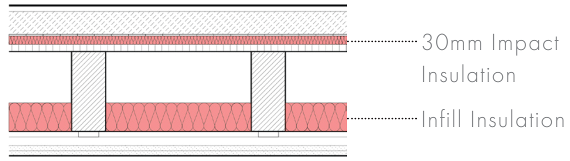
Ansbach Case Study | Module Floor Assembly

Appendix 12: Educational Typologies:

Acoustic Rules of Thumb:

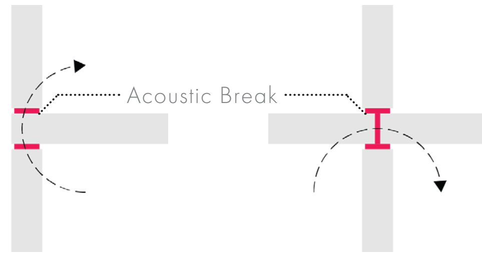
1D Systems:

- Mitigating impact sound as much as possible with assembly
- Use of acoustic breaks
- Accommodating for Airborne sound is achieved through the infill of insulation between members
- Utilizing acoustic tiles or drop ceiling in a beam system

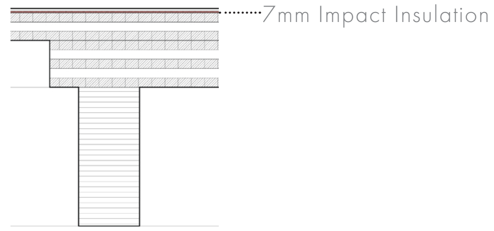


2D Systems:

- For 2D systems, in both residential and educational typologies it is imperative that the detailing of CLT panels takes flanking into consideration during the design. To mitigate this, there must be an acoustical break between CLT panel members. Typically 5mm-10mm thick.
- On average, 2D floor assemblies utilize **7mm-30mm** of impact sound insulation in addition to thermal insulation
- Providing an airspace between the wall finish and the CLT member helps to mitigate impact and airborne sound reverberations



Flanking Example

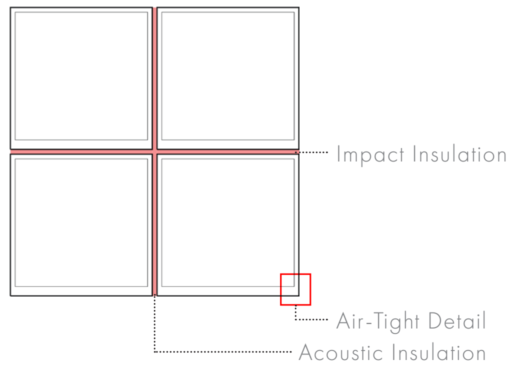


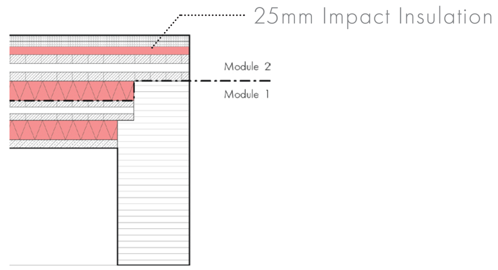
Wood Innovation Centre| Floor Assembly

Frankfurt School Case Study | Interior Wall Assembly

3D Systems:

- 3D module provides the opportunity to develop airtight details
- Use of insulation to separate modules
- Acoustic breaks/ seals where modules connect to mitigate impact sound
- Double stacking of CLT walls helps to improve the acoustical rating.



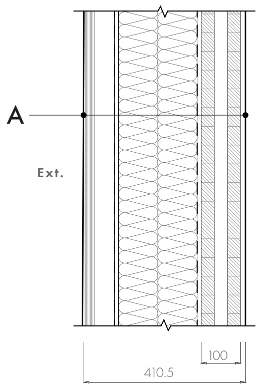


Frankfurt School Case Study | Module Floor Assembly

CASE STUDY ASSEMBLIES

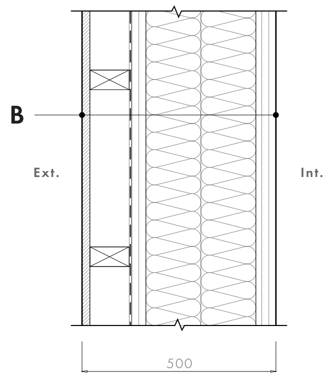
Appendix 13: Exterior Wall Assemblies:

Residential Assemblies:



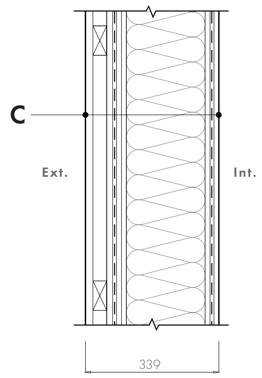
Exterior Wall Assembly A:
Puukuokka Housing Block

- Wood shell: spruce, painted larch, untreated 28mm
- 50mm Wooden substructure with rear ventilation
- Planking membrane (liner) (sd ≤ 0.3 m)
- 200mm Mineral wool
- Extra airtight foil vaporbarrier
- 100mm CLT
- 12.5mm Fire-resistant gypsum plasterboard



Exterior Wall Assembly B:
Ansbach Housing

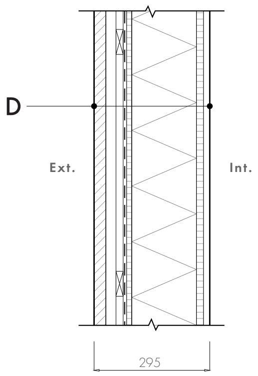
- 20mm Wood Silver Fir Exterior Wall Paneling
- 100mm Softwood Battens (50/100) - Rear Ventilation
- Diffusion-open Facade Membrane
- 18mm Gypsum Board
- 18mm Gypsum Board
- 280mm (2x140) Mineral Wool Insul.
- 60/280mm Construction Wood
- 15mm OSB
- 18mm Gypsum Board (x2)



Exterior Wall Assembly C:
Dantebad Housing

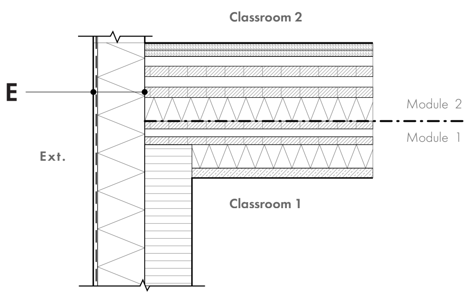
- 19mm Wood Larch Exterior Wall Paneling
- 35mm Softwood Battens 12.5mm
- 15mm Softwood Battens, Vapor
- Permeable Facade Membrane
- 12.5mm Gypsum Fiber Board
- 12.5mm Gypsum Fiber Board
- 60/200 Construction Wood
- 200mm Mineral Wool
- 12.5mm Gypsum Fiber Board
- Vapor Barrier
- 12.5 Gypsum Fiber Board

Educational Assemblies:



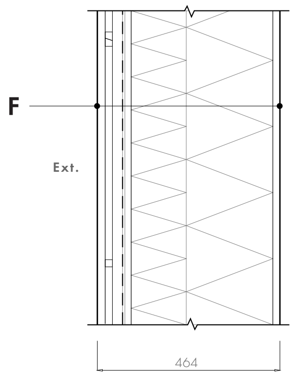
Exterior Wall Assembly D:
Wood Innovation &
Design Centre

- Timber boarding, cedar, heat-treated, in different widths 30 mm
- Plywood strip, weatherproof 13 mm
- Vapor barrier
- Wood fibreboard 13 mm,
- thermal insulation 165 mm
- Wood fibreboard 18 mm,
- Plasterboard 16 mm



Exterior Wall Assembly E:
European School Frankfurt

- Aluminum sheet, lacquered 1 mm
- Wind paper
- mineral wool 120 mm

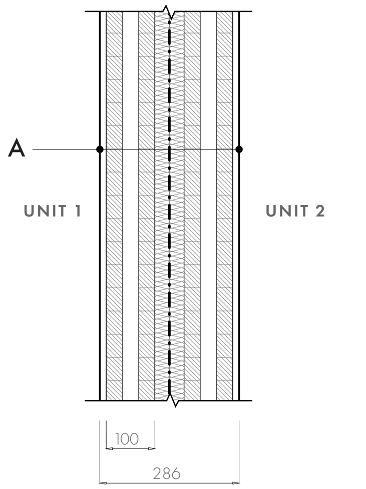


Exterior Wall Assembly F:
Schmuttertal Gymnasium

- Timber battens, horiz. 40mm
- Wind paper
- Wood fibreboard, permeable, waterproof 16mm
- Supporting structure, spruce, filled with thermal
- Insul. mineral wool 140mm
- Supporting structure, filled with mineral wool 220mm
- OSB panel (vapor retarder),
- Glued joinings 18 mm

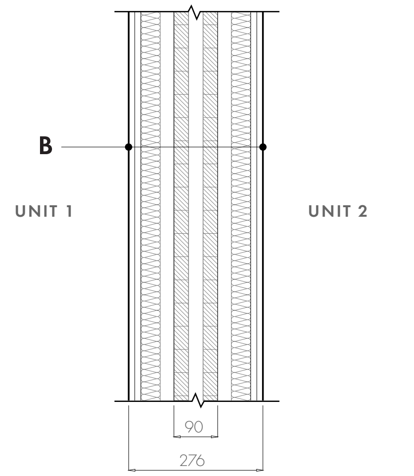
Appendix 14: Interior Wall Assemblies:

Residential Assemblies:



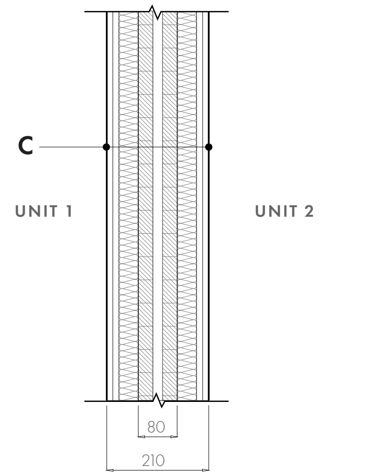
Interior Wall Assembly A:
Puukuokka Housing Block

- 13mm Gypsum Board
- 100mm CLT Wall Panel
- 60mm Insulation
- 100mm CLT Wall Panel
- 13mm Gypsum Board



Interior Wall Assembly B:
Ansbach Housing

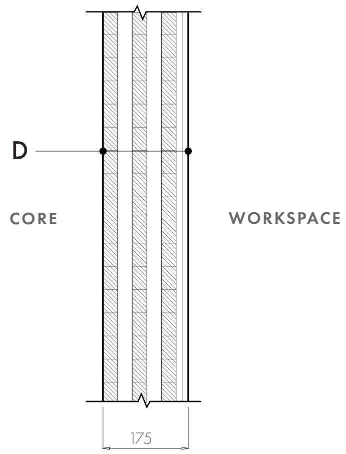
- 12.5mm Gypsum Fiber Board
- 12.5mm Gypsum Fiber Board
- 40mm Insulation Mineral Wool, 27mm Metal Profiles
- 28mm Air Gap
- 90mm Cross Laminated Timber
- 28mm Air Gap
- 40mm Insulation Mineral Wool, 27mm Metal Profiles
- 12.5mm Gypsum Fiber Board
- 12.5mm Gypsum Fiber Board



Interior Wall Assembly C:
Dantebad Housing

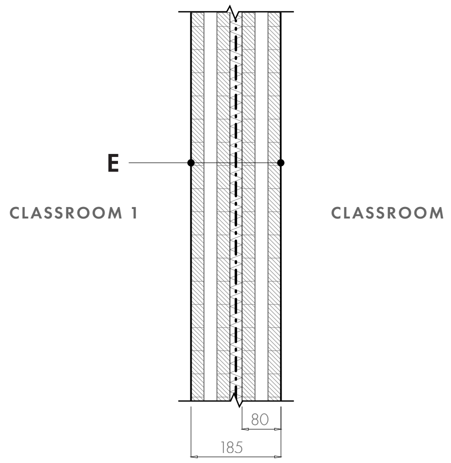
- 12.5mm Gypsum Fiber Board
- 12.5mm Gypsum Fiber Board
- 40mm Insulation Mineral Wool
- 80mm Cross Laminated Timber
- 40mm Insulation Mineral Wool
- 12.5mm Gypsum Fiber Board
- 12.5mm Gypsum Fiber Board

Educational Assemblies:



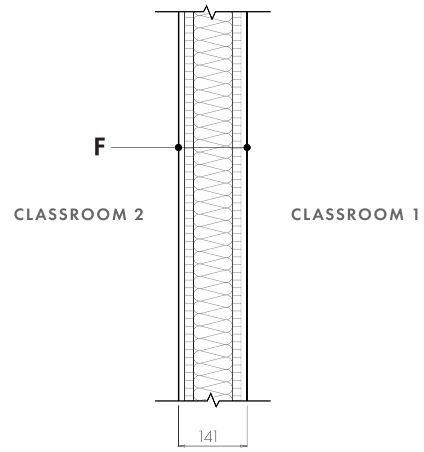
Interior Wall Assembly D:
Wood Innovation &
Design Centre

- 150mm CLT Core Wall Panel
- 12.5mm Gypsum Board
- 12.5mm Gypsum Board



Interior Wall Assembly E:
European School Frankfurt

- 80mm CLT Wall Panel
- 25mm Acoustic Insulation
- 80mm CLT Wall Panel

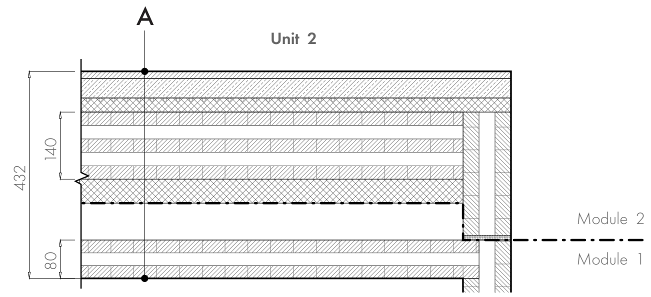


Interior Wall Assembly F:
Schmuttertal Gymnasium

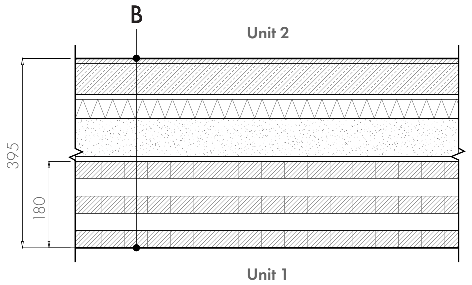
- Gypsum fibreboard 12.5 mm
- OSB panel 18 mm
- Supporting structure, spruce 80/60 mm, filled with
- thermal insulation, mineral wool 80 mm
- OSB panel 18 mm

Appendix 15: Floor Assemblies:

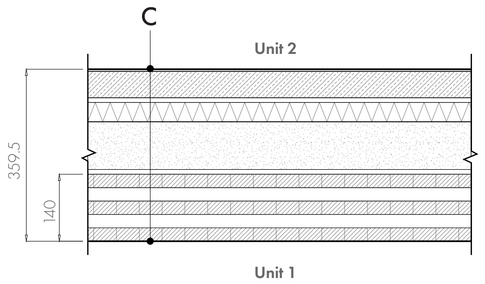
Residential Assemblies:



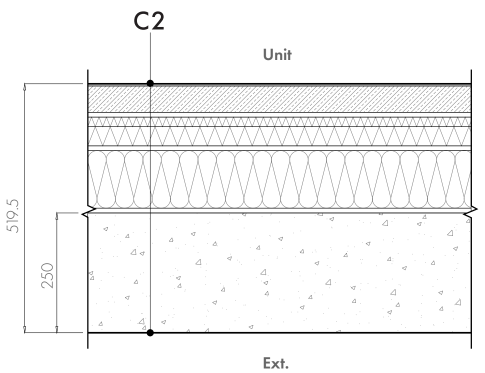
Floor Assembly A:
Puukuokka Housing Block
- 15 mm Flooring: oak parquet
- 40 mm Screed
- 30 mm Impact sound insulation with underfloor heating
- 140 mm CLT panel
- 50 mm Cavity insulation: glass wool
- 77 mm Air space
- 80 mm CLT panel



Floor Assembly B:
Ansbach Housing
- 10 mm Mosaic parquet
- 65 mm Heating screed
- Separating layer of PE foil
- 40mm Impact sound insulation
- 80 mm Bonded chipping infill
- Emergency seal: elastomer bitumen membrane
- 180 mm CLT, spruce



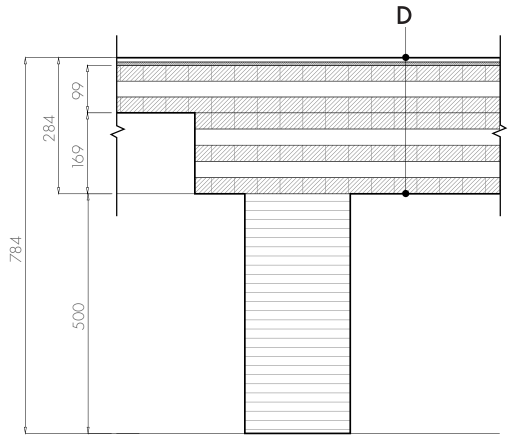
Floor Assembly C:
Dantebad Housing
- 2.5 mm Floor covering: linoleum
- 2 mm putty substrate preparation
- 55 mm Cement screed
- separating layer: PE foil 2x 0.2 mm
- 40 mm Impact sound insulation
- 100 mm latex-bonded chipping infill
- 140 mm CLT, industrial grade



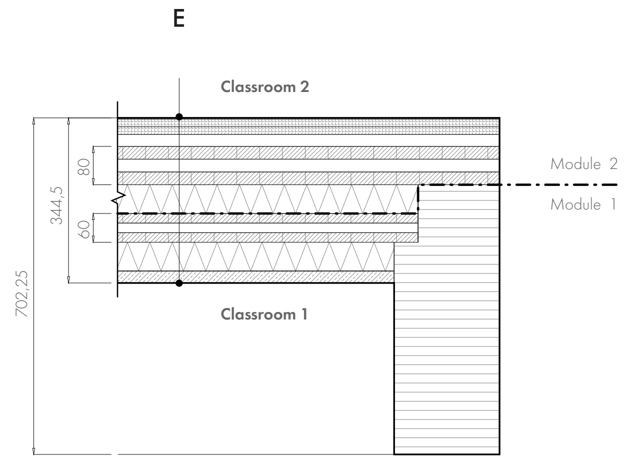
Floor Assembly C2:
Dantebad Housing
- 2.5 mm Floor covering: linoleum
- 2 mm putty substrate preparation
- 55 mm Cement screed
- separating layer: PE foil 2≈ 0.2 mm
- 20 mm Impact sound insulation: mineral fiber
- 40 mm Thermal insulation EPS
- vapor barrier
- 120 mm Thermal insulation EPS
- 250 mm reinforced concrete floor

Appendix 16: Floor Assemblies:

Educational Assemblies:



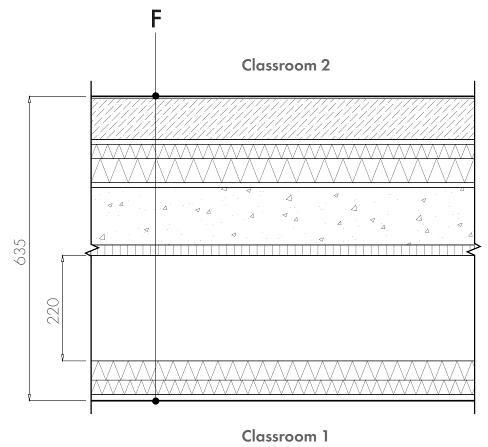
Floor Assembly D:
Wood Innovation & Design Centre
- Flooring, carpet 9 mm
- 7 mm Impact sound insulation
- 99 mm CLT, three layers
- 169 mm CLT, five layers



Floor Assembly E:
European School Frankfurt

Module 1:
- linoleum 2.5 mm,
- chipboard, glued 2≈ 16 mm,
- 25 mm Impact sound insulation panel
- 80 mm CLT
- 60 mm Thermal insulation mineral wool

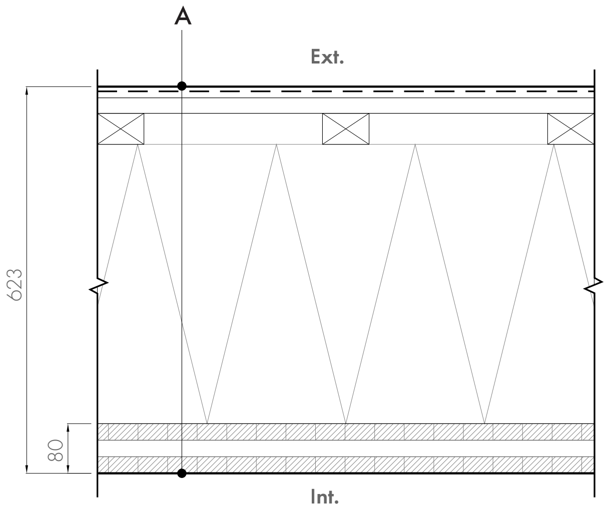
Module 2:
- 60 mm CLT
- 60 mm Thermal insulation, mineral wool
- 25 mm wood-wool acoustic panel
- 560/220 mm LVL beam, beech



Exterior Floor Assembly F:
Schmuttertal Gymnasium
- 5 mm Mineral coating
- 85 mm Heating screed
- Separation layer, PE foil
- 30 mm Impact sound insulation
- 50 mm Leveling insulation
- Separation layer PE foil, two-ply
- 98 –120 mm Reinforced concrete
- 22 mm Ceiling element battens OSB panel
- Frame of joists 2≈ 180/320 mm
- Filled with acoustic element:
- 40 mm Thermal insulation,
- Wood-wool acoustic panel, magnesite-bonded

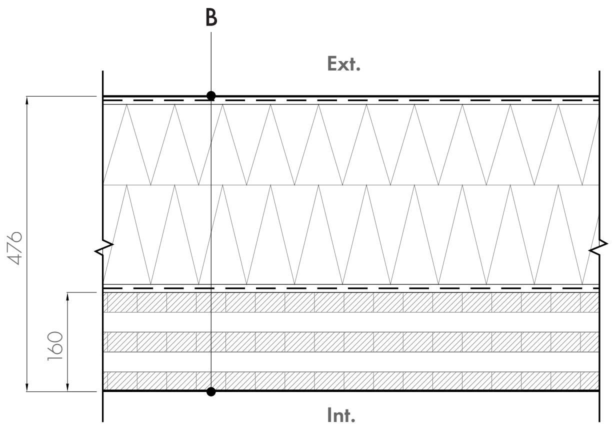
Appendix 17: Roof Assemblies:

Residential Assemblies:



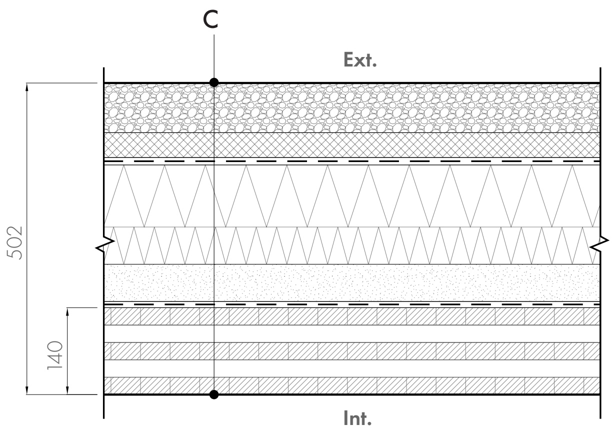
Exterior Floor Assembly A:
Puukuokka Housing Block

- Sealing: bitumen
- 18 mm OSB panel
- Battens with rear ventilation,
- 450 mm Heat insulation: blow-in insulation
- 80 mm CLT



Exterior Wall Assembly B:
Ansbach Housing

- Sealing membrane w/ fleece underneath
- 50 – 130 mm EPS thermal insulation
- 160 mm EPS thermal insulation
- Emergency waterproofing / vapor barrier
- 160 mm CLT panel: spruce

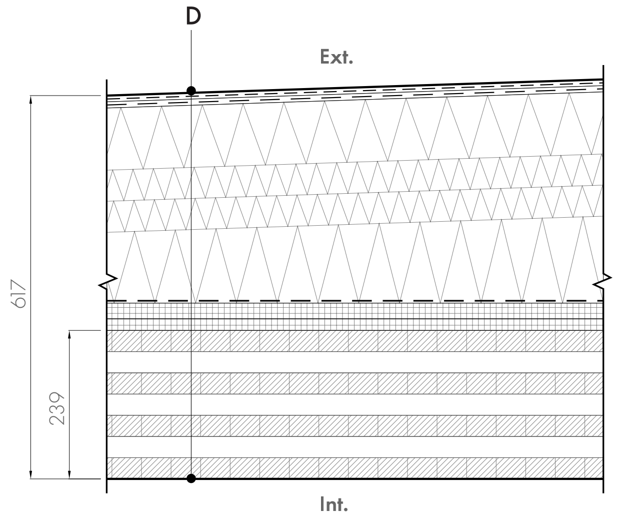


Exterior Wall Assembly C:
Dantebad Housing

- Extensive vegetation or gravel surface
- 40 mm Drainage element,
- 6 mm protective mat
- Sealing: bitumen double-layered,
- 20 – 200 mm EPS insulation in gradient
- 60 mm Thermal insulation PU,
- 60 mm latex-bonded chipping infill
- Vapor barrier (emergency seal),
- 140 mm CLT

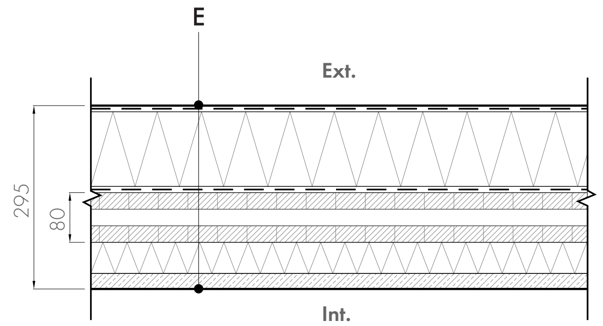
Appendix 18: Roof Assemblies:

Educational Assemblies:



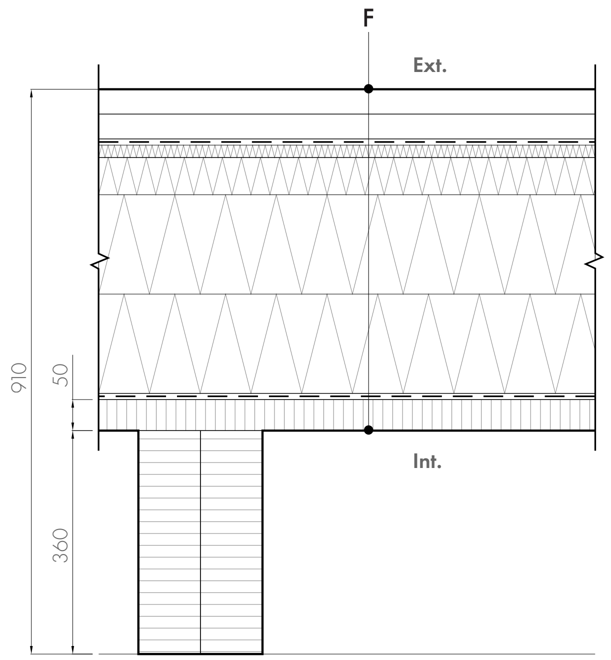
Exterior Floor Assembly D:
Wood Innovation & Design Centre

- Sealing, bitumen, two layers
- Thermal insulation, mineral wool, bitumen-coated 100 mm
- 2x 50 mm Thermal insulation PIR
- 100 – 140 mm Gradient insulation EPS approx.
- Vapor barrier,
- 25 mm plywood board
- 19 mm Plywood board
- 239 mm Cross laminated timber, seven layers



Exterior Floor Assembly E:
European School Frankfurt

- Waterproofing, plastic membrane
- Gradient insulation, EPS min. 120 mm
- Vapor barrier
- 80 mm CLT
- 50 mm Thermal insulation, mineral wool
- 25 mm Wood-wool acoustic panel



Exterior Floor Assembly F:
Schmuttertal Gymnasium

- 40 mm Greening, extensive substrate
- 40 mm Drainage filled w/substrate
- 10 mm Waterproofing, EPDM
- 20 mm Thermal insul.
- 60 mm Timber battens, between them thermal insul
- 160 mm Thermal insul.
- 100/160 mmTimber battens,
- between them thermal insul. 160 mm
- Prefabricated roof element
- Waterproofing
- Bitumen membrane
- 50 mm Lightweight wood-wool panels in edge area and support area
- 100/360 mm Rafters, glued laminated timber, spruce, glazed white

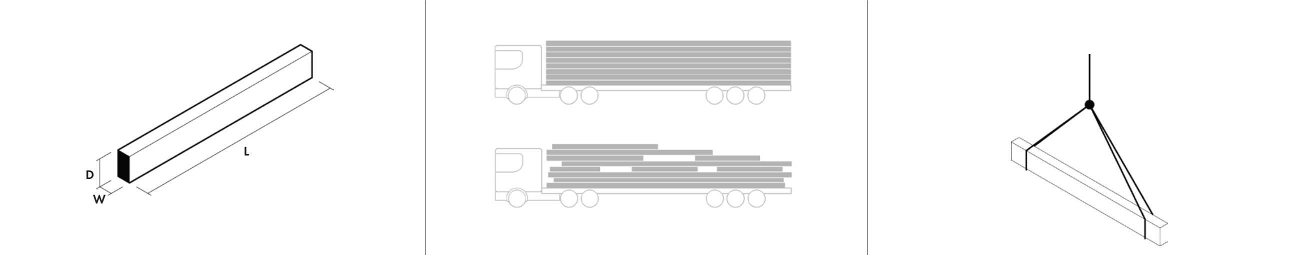
DESIGN TOOL

The design tool was developed as a webpage for designers to easyily access rules of thumb for existing 1D, 2D and 3D engineered timber systems. Acting as an initial 'master' sheet for rules of thumb address, manufacturing, transportation, assembly, structure, fire and acoustics. The designer can then use a filter to simplify the presented information to focus on the system or typology they want to address.

Specify Timber System (1D,2D,3D) or (Res, Edu)

TIMBER SYSTEM	MANUFACTURING	TRANSPORTATION	ASSEMBLY	STRUCTURE	FIRE	ACOUSTICS

1D RES.



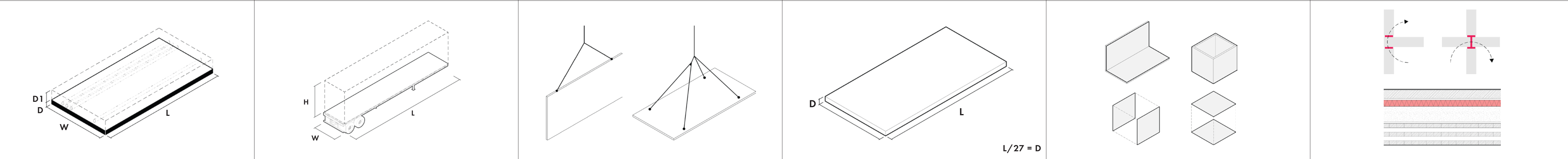
Structure:

- The use of 1D systems are rarely utilized in Residential construction as 2D and 3D systems are better optimized for those typologies.
- Instead of using 1D systems, it is recommended to use 2D, 3D or a combination of both for multiple residential units where repetition of units is likely to occur

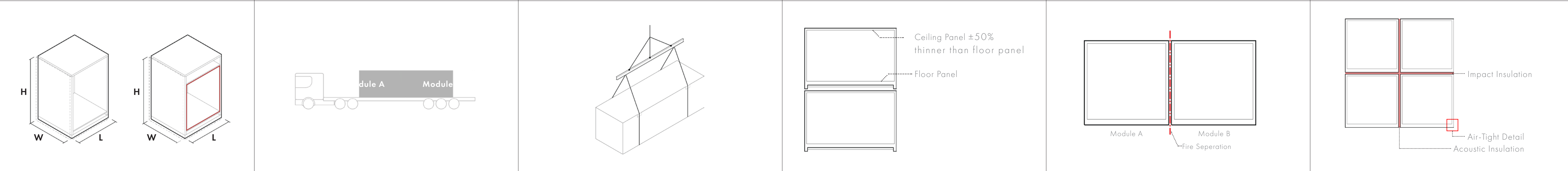
Fire: Class 4 (height of the uppermost floor = 13 meters) and class 5 (height of the uppermost floor = 22 meters) buildings require longer fire resistance durations of 60 and 90 minutes because fires are harder to extinguish in taller buildings.

Acoustics: It is important to note that in general, for residential typologies the impact sound requirement should be L'n, w≤ 50 dB where the lower the value the better. Moreover, a residential unit must have an airborne sound reduction index of R'w≥ 54dB, where the higher the value the better. Typically, if a project is well designed for impact sound it will also perform well for airborne sound requirements

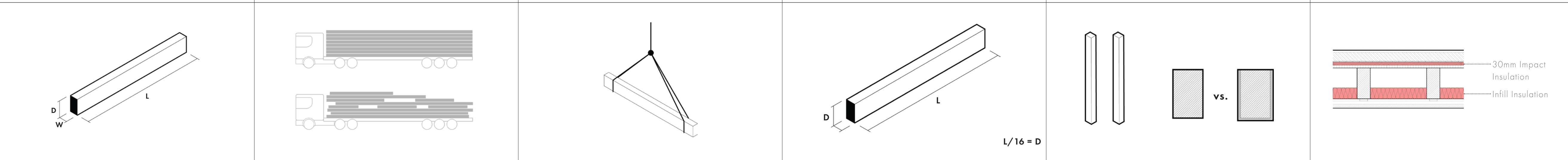
2D RES.



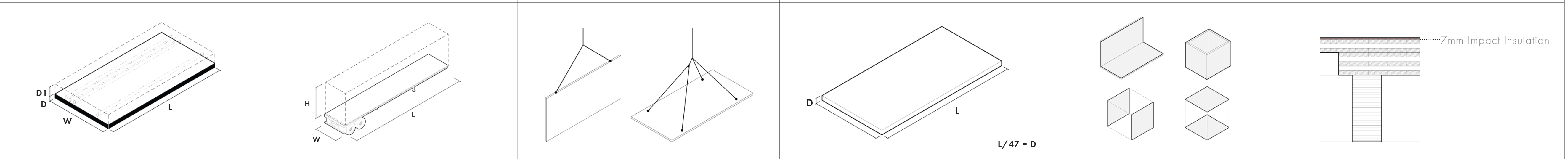
3D RES.



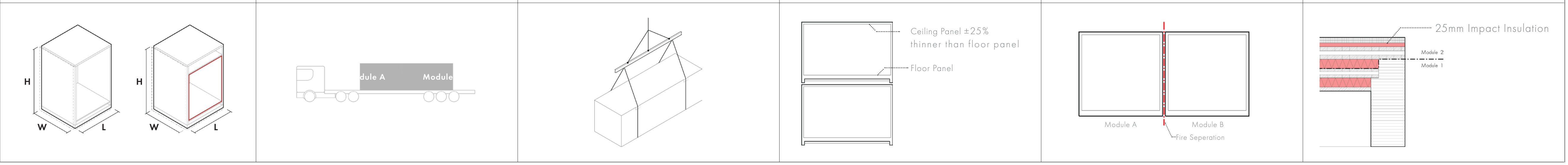
1D EDU.



2D EDU.

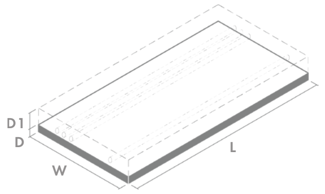
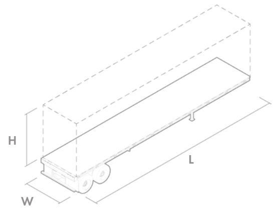
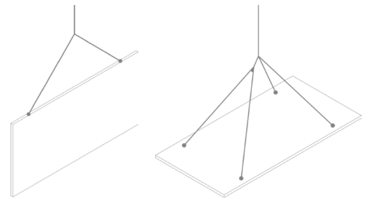
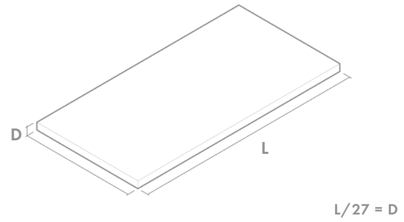
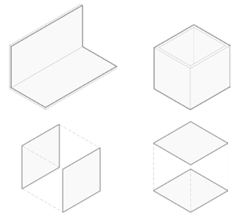
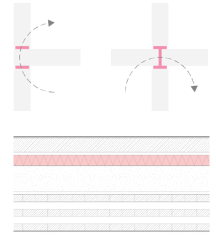
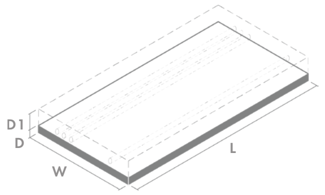
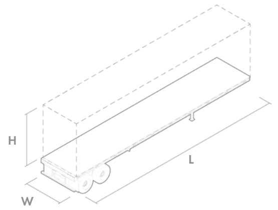
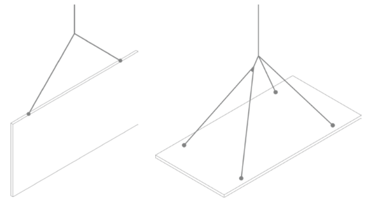
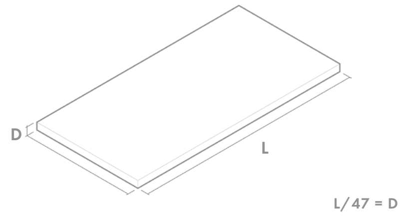
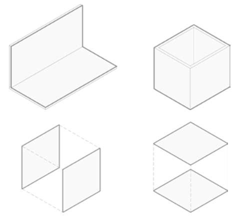
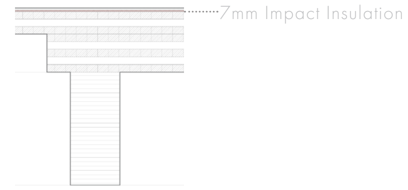


3D EDU.

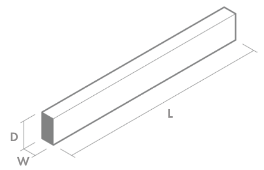
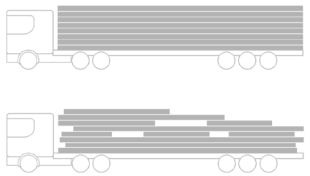
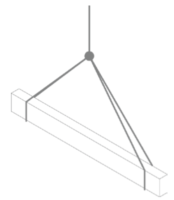
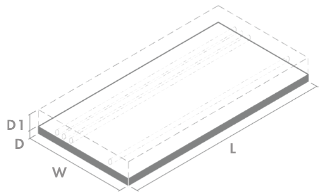
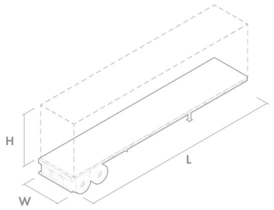
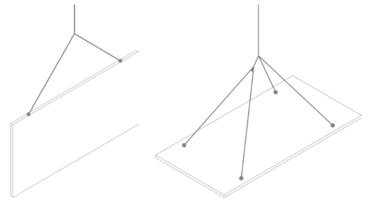
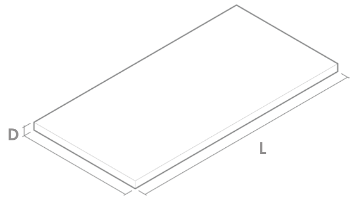
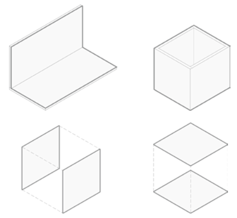
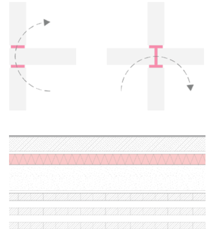
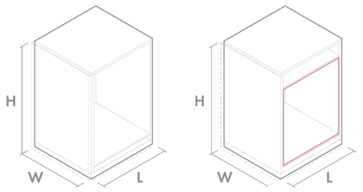
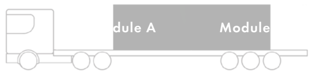
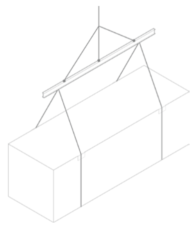
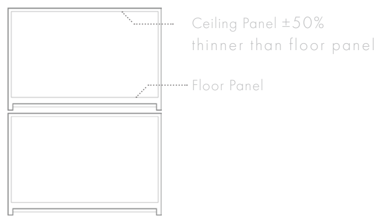
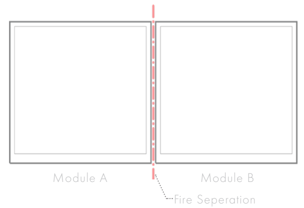
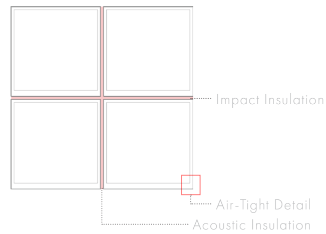


2D

Use search filter to isolate timber systems
to compare typology rules of thumb

TIMBER SYSTEM	MANUFACTURING	TRANSPORTATION	ASSEMBLY	STRUCTURE	FIRE	ACOUSTICS
2D RES.						
2D EDU.						

RES — Use search filter to isolate typology

TIMBER SYSTEM	MANUFACTURING	TRANSPORTATION	ASSEMBLY	STRUCTURE	FIRE	ACOUSTICS
1D RES.				• The use of 1D systems are rarely utilized in Residential construction as 2D and 3D systems are better optimized for those typologies. • Instead of using 1D systems, it is recommended to use 2D, 3D or a combination of both for multiple residential units where repetition of units is likely to occur	Class 4 (height of the uppermost floor = 13 meters) and class 5 (height of the uppermost floor = 22 meters) buildings require longer fire resistance durations of 60 and 90 minutes because fires are harder to extinguish in taller buildings.	It is important to note that in general, for residential typologies the impact sound requirement should be L'n, w≤ 50 dB where the lower the value the better. Moreover, a residential unit must have an airborne sound reduction index of R'w≥ 54dB, where the higher the value the better. Typically, if a project is well designed for impact sound it will also perform well for airborne sound requirements
2D RES.				 L/27 = D		
3D RES.						

Appendix 19: Design Tool Alternative Representation:

Specify Timber System (1D,2D,3D) or (Res, Edu)

TIMBER SYSTEM	MANUFACTURING	TRANSPORTATION	ASSEMBLY	STRUCTURE	FIRE	ACOUSTICS
1D RES.	• D = Depth: 114mm - 2128mm typ. • W = Width: 365mm typ. However, if a greater width is desired, then it can be manufactured in 50mm increments, i.e) 415mm, 465mm, etc... Memberss then become exponentially more expensive. • L = Length: Determined by the desired span from the designer. Should take transporation and assembly rules of thumb into consideration.	• Transporting a 1D system is most cost effective if they are stacked regularly and compactly with no wasted space and no requirements for wide or long loads. • The same rule applys to 2D panels as well. • To ensure trasnportation is most effective, prefabricated members should be as typical as possible, avoiding custom or one-off memebrs.	• Try to use standard sizing for all components wherever possible in order to simplify on site assembly, resulting in faster construction. • Requires simple lifting equipment. • Simplify connection details between elements. • Typically uses wrap around straps for beams.	• The use of 1D systems are rarely utilized in Residential construction as 2D and 3D systems are better optimized for those typologies. • Instead of using 1D systems, it is recommended to use 2D, 3D or a combination of both for multiple residential units where repetition of units is likely to occur	Class 4 (height of the uppermost floor = 13 meters) and class 5 (height of the uppermost floor = 22 meters) buildings require longer fire resistance durations of 60 and 90 minutes because fires are harder to extinguish in taller buildings.	It is important to note that in general, for residential typologies the impact sound requirement should be L'n, w≤ 50 dB where the lower the value the better. Moreover, a residential unit must have an airborne sound reduction index of R'w≥ 54dB, where the higher the value the better. Typically, if a project is well designed for impact sound it will also perform well for airborne sound requirements
2D RES.	• D = Depth: 500mmmm typ. • D1 = Depth of Assembly: 60mm-215mm typ. • W = Width: 3500mm Maximum • L = Length: 16500mm Maximum Typically CLT panels with a depth from 60mm-100mm consist of 3-layers. Where as CLT panels with a depth from 120mm-180mm consist of 5-layers. In order to attain its structural properties, CLT panels always need to have an odd number of layers. i.e) 3-Layers, 5-Layers, 7-Layers, etc...	Transport Sizes with no additional requirements: • H = Maximum Height: 4m • W = Maximum Width: 2.55m • L = Length of Standard Semi-Trailer: 13.5m Transport Sizes if there is an escort vehicle on Urban and country roads: • H = Maximum Height: 4m • W = Maximum Width: 3m • L = Length of Standard Semi-Trailer: 13.5m Transport Sizes if there is a Police escort vehicle on Urban and country roads: • H = Maximum Height: 4m • W = Maximum Width: 3.5m • L = Length of Standard Semi-Trailer: 13.5m	• The large format components enable a fast assembly and ensure the building is well braced • Avoid custom sizes/ one-off cuts to ensure fast construction. • Depending on the final design. The pick points used to life the panels into place may be exposed. The designer should then take this into consideration into the final design. • However, if the facade and other final finishing are completed on site, then these pick point will be hidden within the assembly.	CLT Floor Spans for Residential Program: • One can use the calculation **L/27 = D** to determine the depth (D) of a panel. • Where L = the span in millimeters • Some typical span to depth ratios include (Manual of multi storey timber): • Span 4m = 140mm Depth • Span 5m = 180mm Depth • Span 6m = 220mm Depth	• The required corridors and staircases must be kept free of fire loads by means of paneling with non-combustible cladding. • If the ceiling and floor are made of visible wood, the walls should be paneled with a non-combustible material, or if two walls are not lined, then either the ceiling or floor may be made of visible timber. In principle, increased requirements for fire resistance can be compensated by the following measures: • Increase the thickness of the CLT element • Increase the number of layers of the CLT element • Clad CLT member with fire rated gypsum board	• For 2D systems, in both residential and educational typologies it is imperative that the detailing of CLT panels takes flanking into consideration during the design. To mitigate this, there must be an acoustical break between CLT panel members. Typically 5mm-10mm thick. • On average, 2D floor assemblies utilize **30mm-40mm** of impact sound insulation in addition to thermal insulation • Providing an airspace between the wall finish and the CLT member helps to mitigate impact
3D RES.	• H = Height: ±3000mmmm typ. • W = Width: 3500mm Maximum • L = Length: 16500mm Maximum Note that the 2D manufacturing of CLT panels also has an influence on the dimensionality of 3D modules. Within the 'wet' module, the red represents finishing for wet conditions and below the ceiling CLT member is a drop ceiling for mechanical installations. Alternatively this can be located against one of the walls of the module or in the raised floor system	Transportation of 3D modules follows the same size conditions as 2D systems. However, since 3D modules contain a lot of dead space within themselves while being transported, as opposed to stack panels, beams and columns. Depending on the size of the 3D module, the more trips are required to bring everything to site, affecting overall construction time. However, this is to be balanced with assembly rules of thumb.	• The larger the modules, the more cost-effective this structure will be. • In some cases, the ceiling can be completely omitted from the module so that when stacked, the underside of the floor becomes the ceiling. The same idea can be applied to the walls of the module. i.e) Two 3m wide modules come together to create a 6m room. • It is ideal to separate 'wet' modules from 'dry' modules to increase construction speed. • To optimize the use of the factory setting, integration of technical installation can increase on site construction speed.	For determining spans of 3D modules, it is recommended to reference the rules of thumb for 2D Spans as well as 2D manufacturing and transportation to ensure an easy combination of 2D and 3D systems • For 3D modules, use 2D rule of thumb to calculate for the floor panel first. To determine the 'ceiling' depth of a CLT panel in a 3D Module: • The ceiling panel is typically **±50% thinner** than that of the CLT Floor panel in a residential module	For 3D systems, follow the rules of thumb stated for 2D systems. However, for 3D systems: • The double stacking of CLT panels increases the fire resistance rating of the project • Resulting in the potential for thinner CLT Panels Important to keep in mind of the double stacking of floor to ceiling and wall to wall	• 3D module provides the opportunity to develop airtight details • Use of insulation to separate modules • Acoustic breaks/ seals where modules connect to mitigate impact sound • Double stacking of CLT walls helps to improve the acoustical rating.
1D EDU.	• D = Depth: 114mm - 2128mm typ. • W = Width: 365mm typ. However, if a greater width is desired, then it can be manufactured in 50mm increments, i.e) 415mm, 465mm, etc... Memberss then become exponentially more expensive. • L = Length: Determined by the desired span from the designer. Should take transporation and assembly rules of thumb into consideration.	• Transporting a 1D system is most cost effective if they are stacked regularly and compactly with no wasted space and no requirements for wide or long loads. • The same rule applys to 2D panels as well. • To ensure trasnportation is most effective, prefabricated members should be as typical as possible, avoiding custom or one-off memebrs.	• Try to use standard sizing for all components wherever possible in order to simplify on site assembly, resulting in faster construction. • Requires simple lifting equipment. • Simplify connection details between elements. • Typically uses wrap around straps for beams.	Glulam Beam Depth calculation for Office/ Education Program: • One can use the calculation **L/16 = D** to determine the depth of a beam. Where L = the span in millimeters	As a result of Glue laminated timber being rarely used in multi-storey residential units, there are no specific fire rules of thumb for this condition. As stated previously, it is recommended to utilize 2D, 3D or a combination of both for residential units.	• Mitigating impact sound as much as possible with assembly • Use of acoustic breaks • Accommodating for Airborne sound is achieved through the infill of insulation between members • Utilizing acoustic tiles or drop ceiling in a beam system
2D EDU.	• D = Depth: 500mmmm typ. • D1 = Depth of Assembly: 60mm-215mm typ. • W = Width: 3500mm Maximum • L = Length: 16500mm Maximum Typically CLT panels with a depth from 60mm-100mm consist of 3-layers. Where as CLT panels with a depth from 120mm-180mm consist of 5-layers. In order to attain its structural properties, CLT panels always need to have an odd number of layers. i.e) 3-Layers, 5-Layers, 7-Layers, etc...	Transport Sizes with no additional requirements: • H = Maximum Height: 4m • W = Maximum Width: 2.55m • L = Length of Standard Semi-Trailer: 13.5m Transport Sizes if there is an escort vehicle on Urban and country roads: • H = Maximum Height: 4m • W = Maximum Width: 3m • L = Length of Standard Semi-Trailer: 13.5m Transport Sizes if there is a Police escort vehicle on Urban and country roads: • H = Maximum Height: 4m • W = Maximum Width: 3.5m • L = Length of Standard Semi-Trailer: 13.5m	• The large format components enable a fast assembly and ensure the building is well braced • Avoid custom sizes/ one-off cuts to ensure fast construction. • Depending on the final design. The pick points used to life the panels into place may be exposed. The designer should then take this into consideration into the final design. • However, if the facade and other final finishing are completed on site, then these pick point will be hidden within the assembly.	CLT Floor Spans for Residential Program: • One can use the calculation **L/47 = D** to determine the depth (D) of a panel. • Where L = the span in millimeters	• The required corridors and staircases must be kept free of fire loads by means of paneling with non-combustible cladding. • If the ceiling and floor are made of visible wood, the walls should be paneled with a non-combustible material, or if two walls are not lined, then either the ceiling or floor may be made of visible timber. In principle, increased requirements for fire resistance can be compensated by the following measures: • Increase the thickness of the CLT element • Increase the number of layers of the CLT element • Clad CLT member with fire rated gypsum board	• For 2D systems, in both residential and educational typologies it is imperative that the detailing of CLT panels takes flanking into consideration during the design. To mitigate this, there must be an acoustical break between CLT panel members. Typically 5mm-10mm thick. • On average, 2D floor assemblies utilize **7mm-30mm** of impact sound insulation in addition to thermal insulation • Providing an airspace between the wall finish and the CLT member helps to mitigate impact and airborne sound reverberations
3D EDU.	• H = Height: ±3000mmmm typ. • W = Width: 3500mm Maximum • L = Length: 16500mm Maximum Note that the 2D manufacturing of CLT panels also has an influence on the dimensionality of 3D modules. Within the 'wet' module, the red represents finishing for wet conditions and below the ceiling CLT member is a drop ceiling for mechanical installations. Alternatively this can be located against one of the walls of the module or in the raised floor system	Transportation of 3D modules follows the same size conditions as 2D systems. However, since 3D modules contain a lot of dead space within themselves while being transported, as opposed to stack panels, beams and columns. Depending on the size of the 3D module, the more trips are required to bring everything to site, affecting overall construction time. However, this is to be balanced with assembly rules of thumb.	• The larger the modules, the more cost-effective this structure will be. • In some cases, the ceiling can be completely omitted from the module so that when stacked, the underside of the floor becomes the ceiling. The same idea can be applied to the walls of the module. i.e) Two 3m wide modules come together to create a 6m room. • It is ideal to separate 'wet' modules from 'dry' modules to increase construction speed. • To optimize the use of the factory setting, integration of technical installation can increase on site construction speed.	For determining spans of 3D modules, it is recommended to reference the rules of thumb for 2D Spans as well as 2D manufacturing and transportation to ensure an easy combination of 2D and 3D systems • For 3D modules, use 2D rule of thumb to calculate for the floor panel first. To determine the 'ceiling' depth of a CLT panel in a 3D Module: • The ceiling panel is typically **±25% thinner** than that of the CLT Floor panel in a residential module	For 3D systems, follow the rules of thumb stated for 2D systems. However, for 3D systems: • The double stacking of CLT panels increases the fire resistance rating of the project • Resulting in the potential for thinner CLT Panels Important to keep in mind of the double stacking of floor to ceiling and wall to wall	• 3D module provides the opportunity to develop airtight details • Use of insulation to separate modules • Acoustic breaks/ seals where modules connect to mitigate impact sound • Double stacking of CLT walls helps to improve the acoustical rating.

CASE STUDY SELECTION

The case studies were selected based on a set of parameters to ensure their relevance to the project objective and to meet the requirements of the Netherlands climate. With the project objective of generating a mid-height building of ≤ 22 meters or 4-8 storeys. The case studies would need to be within this range of height to provide a good reference for structural sizing and fire class requirements (building class 4-5).

Residential Case Study | Puukuokka Housing Block:

Source: *https://oopeaa.com/research/modular-timber-construction/*

Architect: OOPEAA

Location: Jyväskylä, FInland

Designed: 2015

Number of Storeys: 8

Total Construction Area: 18,650 m²

Apartments: 14,000 m²

Shared Facilities: 4,650 m²

Total Construction Time: 6 months

5 Months of prefabrication

2 Months of on site construction time

Timber System Used: Primary 3D with a secondary 2D

The project is characterized by its innovative use of room modules: Each apartment contains a module with a bedroom, living room and loggia on the facade side, while a second module on the inside contains the bathrooms, kitchens and other rooms. Essentially comprised of a 'wet' module and 'dry' module

Fire Safety Building Class: Between 5 & High Rise

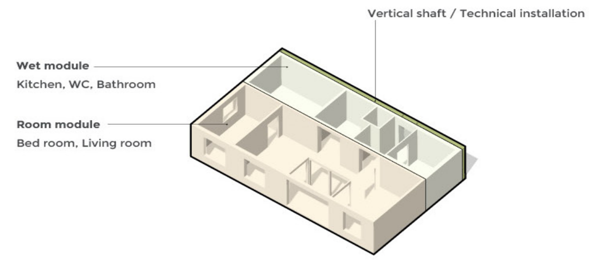
Resulting in a requirement for fire resistance durations of 60 and 90 minutes because fires are harder to extinguish in taller buildings

The walls of the apartments and stairwells are clad in plasterboard. The surface of the wood remains visible on the ceilings of the apartments and stairwells
A sprinkler system is part of the fire safety concept.

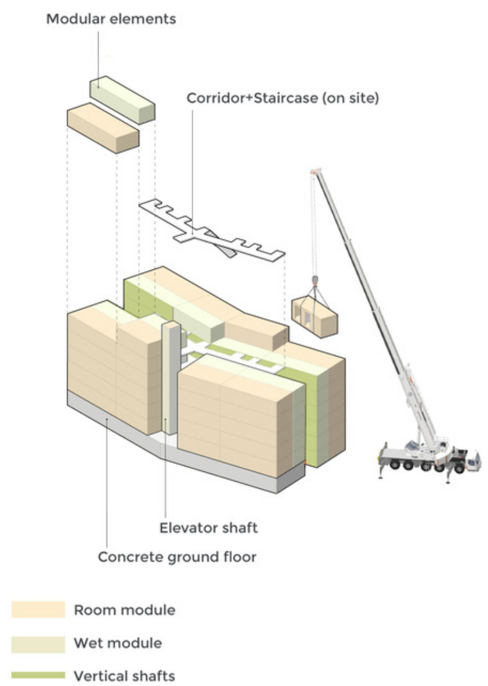
Appendix 20: Case Study Selection:

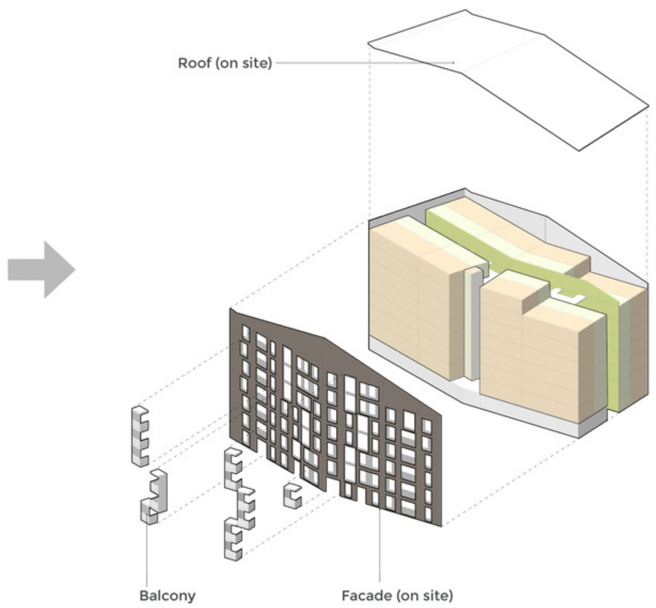
Residential Case Study | Puukuokka Housing Block:

Typical floor plan



Modular elements





Source: *https://oopeaa.com/research/modular-timber-construction/*

Residential Case Study | Ansbach Housing:

Source: *https://www.dataholz.eu/nwendungen/olzbauprojekte/energieeffizienter-wohnungsbau-ansbach-de.htm*

Architect: Deppisch Architekten

Location: Ansbach, Germany

Designed: 2013

Number of Storeys: 4

GFA: 3,667 m²

Total Living Space: 2,400 m2

Total Construction Time: 13 months

4 Months of Timber and Facade construction

Timber System Used: Primary 2D systems, 1D vertical

- The ceiling elements penetrate the outer shell on the longitudinal side, resulting in a very simple continuous balcony construction
- Thanks to the structural-physical properties of wood, there is no danger of condensate formation; a groove on the underside of the ceiling panel prevents moisture from moving from the outside to the inside of the wood and reduces thermal bridges.

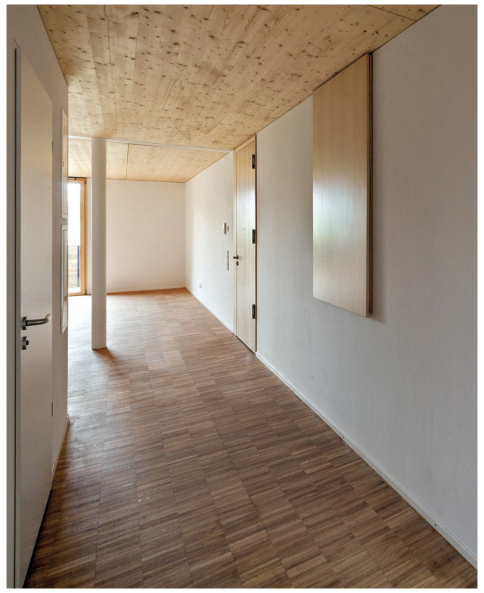
Fire Safety Building Class: 3-4 Building of medium height

Ground floor is made of concrete in order to meet fire requirments of a class 3 building. Resulting in the total building height of timber to be 3 storeys instead of the total 4.

- K260 encapsulation with highly fire-retardant insulation was required for the exterior walls.
- The ceiling panels for the balconies, which pass uninterrupted from the inside to the outside, act as a type of firewall on the long sides, as they separate the outer walls of each storey from the storeys above and below
- The small size of the residential units, each of which has a maximum area of 100m2, and the solid timber construction of the ceilings, which have no cavities, also helped this part of the design meet regulations.

Appendix 21: Case Study Selection:

Residential Case Study | Ansbach Housing:



Source: *https://www.dataholz.eu/nwendungen/olzbauprojekte/energieeffizienter-wohnungsbau-ansbach-de.htm*

Residential Case Study | Dantebad Housing:

Source: *https://www.nagler-architekten.de/projekt-daten/projekt-ansicht/wohnen-am-dantebad/*

Architect: Florian Nagler Architects

Location: Munich, Germany

Designed: 2016

Number of Storeys: 5

GFA: 4,630 m2

Floor Space: 3,540 m²

Total Construction Time: 7 months

2 months for Timber construction

Timber System Used: Primary 2D system with 'wet' 3D Modules (Bathroom Unit)

- In order to maintain most of the existing parking spaces, a construction of reinforced concrete columns and beams was erected first, and the actual residential development was then built in timber on top of that
- After the external walls and apartment partitions were installed, prefabricated bathrooms were lowered into the residential units by a crane and closed with the wooden ceiling

Fire Safety Building Class: 4 Building of medium Height

- The building falls into class 4, which requires the upper storeys to be fire-resistant for 60 minutes.
- The reinforced concrete "table" at the car park level has a fire-resistance period of 90 minutes to protect the residential floors above it from the fire load of the cars parked below.
- The two stairwells guarantee two structurally independent escape routes. On upper floors they are constructed from timber and they have a layer of plasterboard on both sides, so they are considered to be substitute firewalls with a fire-resistance time of 60 minutes.

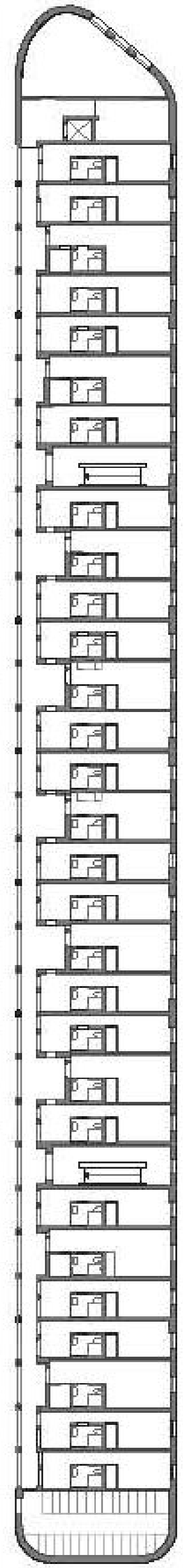
Acoustics:

- Interior walls have a double layer of gypsum fibreboard on both sides to provide the necessary soundproofing.

Residential Case Study | Dantebad Housing:

3D system W/C Module being lifted into place

Source: *Manual of MultiStorey Timber Construction*



Typical Floor Plan

Educational Case Study | Wood Innovation & Design Centre:

Source: *https://www.archdaily.com/630264/wood-innovation-design-centre-michael-green-architecture*

Architect: Michael Green Architecture

Location: Prince George, Canada

Designed: 2014

Number of Storeys: 7

GFA: 4,820 m^2

Total Construction Time: 15 months

5 months for Timber construction

Timber System Used: Primary 2D system

- The construction system is a skeletal structure based on a square grid measuring about 8 x 8 metres, with a central access core providing reinforcement to the structure
- Composite constructions were avoided to allow for easy demolition and end-of-life recycling.
- Lying on the main beams are two layers of alternating cross laminated timber elements, still visible, with thicknesses of 10 or 17 cm and widths of about 120 to 160 cm. The resulting cavities are used as installation zones.

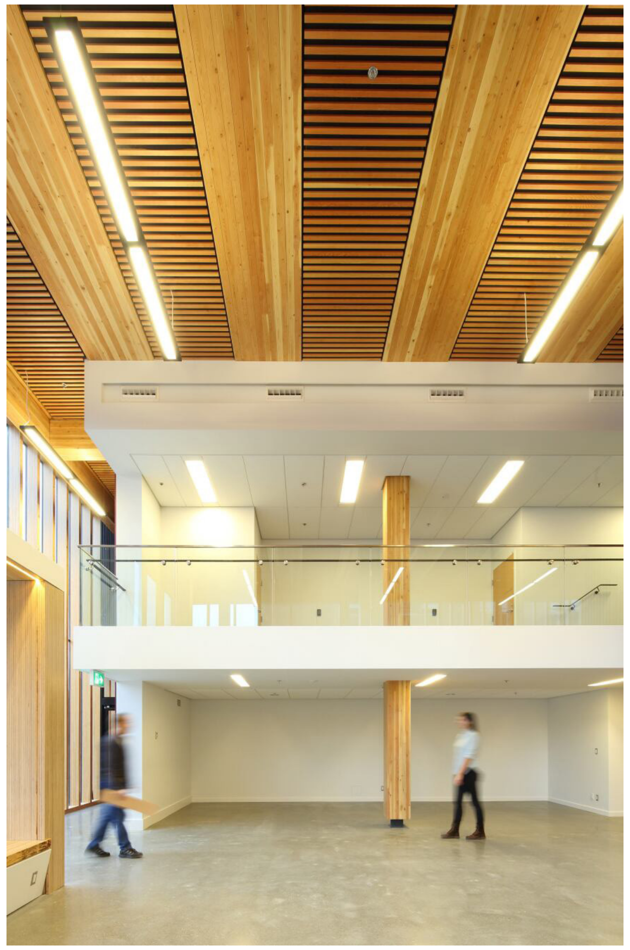
Fire Safety Building Class: 5 Building of medium height

- It is dimensioned to withstand 60 minutes of fire before burn-up. Sprinklers offer additional protection. The wooden post-andbeam facade is mostly glazed, alternating with opaque elements made of natural or precharred horizontal boards.

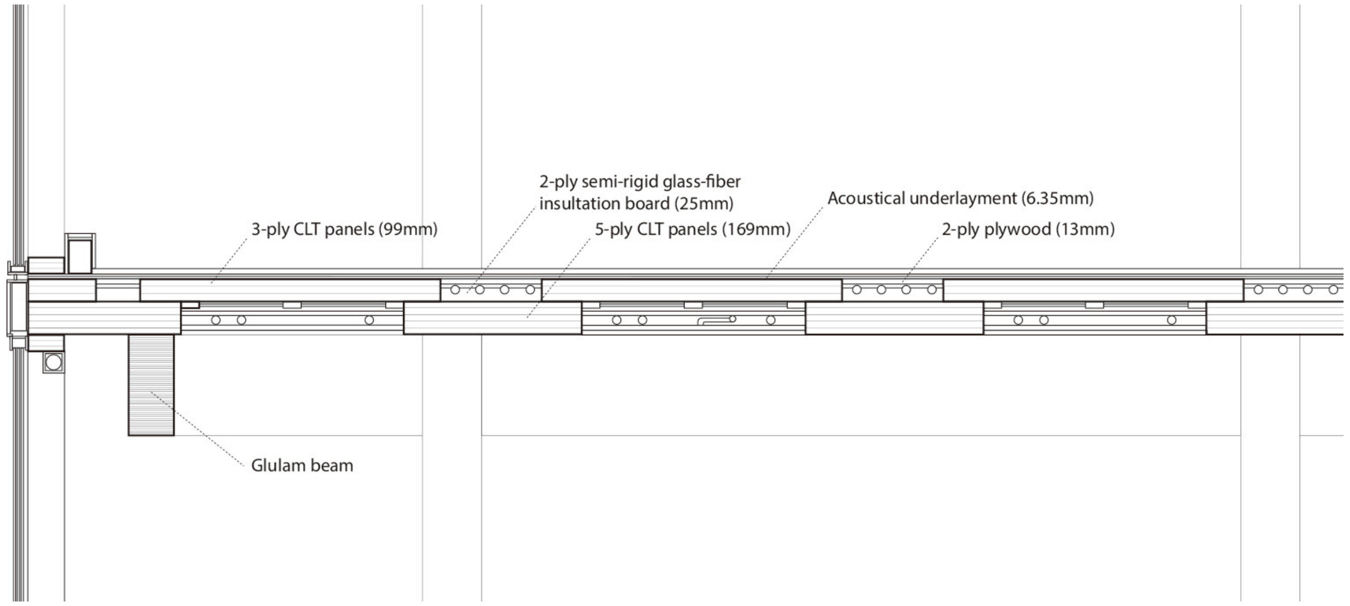
Acoustics:

- Installation zones in the ceilings are effectively acoustically closed at the ceiling.
- Impact sound insulation is provided by carpet on a soft underlay.v
- Air bourne sound insulation was not of major concern in this project.

Educational Case Study | Wood Innovation & Design Centre:



Source: *https://www.archdaily.com/630264/wood-innovation-design-centre-michael-green-architecture*



Typical Floor Section Assembly

Source: *Manual of MultiStorey Timber Construction*

Educational Case Study | European School Frankfurt:

Source: *https://nkbak.de/en/europaeische-schule-frankfurt/*

Architect: NKBAK

Location: Frankfurt am Main, Germany

Designed: 2015

Number of Storeys: 3

GFA: 1,215 m^2

Total Construction Time: 8 months

3 months for Timber construction

Timber System Used: Primary 3D system

- The building is defined by module sizes of 3 x 9 metres, which relate to the classroom depths
- The load-bearing walls of the modules are made of cross laminated timber, while the ceiling slabs of the corridors are suspended between the modules or placed on skeleton constructions made of glued laminated timber.
- Cross laminated timber ceilings and floors handle the span of 3 metres in the transverse direction.

Fire Safety Building Class: 3 - Lowrise Building

- The engineers had to prove that the three-storey building could withstand fire for 30 minutes.
- An excellent escape route design with three staircases ensures that each classroom has two independent directions of escape at all times.
- This also made it possible to have visible wooden surfaces on the walls.
- Only in the stairwells did these surfaces have to be given a fire-protection coating.

Acoustics:

- The double CLT Walls and floors resulting from the modules help with both impact and air bourne sound insulation.

Appendix 24: Case Study Selection:

Educational Case Study | European School Frankfurt:

Source: *https://nkbak.de/en/europaeische-schule-frankfurt/*

Educational Case Study | Schmuttertal Gymnasium:

Source: *https://www.hkarchitekten.at/de/projekt/schmuttertal-gymnasium-diedorf/*

Architect: ARGE

Location: Diedorf, Germany

Designed: 2015

Number of Storeys: 3

GFA: 16,046 m^2

Total Construction Time: 24 months

6 months for Timber construction

Timber System Used: 1D & 2D Systems

- The clear organisation of the visible skeleton construction makes it possible to react flexibly to new teaching concepts now and in the future.
- Because there are no suspended ceilings, the installations are vertically oriented and integrated in the deep corridor walls of the classrooms

Fire Safety Building Class: 3 - Lowrise Building

- Due to the minimised storey heights resulting from the chosen structures, the building falls into class 3, which requires it to be fire-resistant for just 30 minutes

Acoustics:

- Acoustic elements made of lightweight wood-wool panels alternating with visible wooden surfaces characterise the interiors

Educational Case Study | Schmuttertal Gymnasium:

Source: *https://www.hkarchitekten.at/de/projekt/schmuttertal-gymnasium-diedorf/*

THANK YOU

Personal Information

Benjamin Bomben

Student Number: 5511585

Studio

Architectural Engineering Design

Tutor: Anne Snijders Research

Tutor: Pieter Stoutjesdijk

Focus

Context: TU Delft Campus

Technology: Make

Design Program: Open Building

REFLECTION

The research results have played a significant role in the development of the architectural project. Dealing with 1D, 2D and 3D systems, the graduation research has been continually referenced to make more informed decisions and proved to be a useful tool during the schematic phase of the project, helping to determine the sizing of CLT elements, influencing the overall composition of the design. Once the design began to develop, it was realized that the combination of all three systems can provide a great amount of flexibility for residential and educational typologies.

However, what proved to be a challenge was the ambition to maintain the existing function of a parking lot. The existing parking space is 5 x 2.5 meters in size, influencing the proportions of the entire site resulting in the building having to fit within this proportioning system while still functioning as a quality residential building. It was important that the proportions of the kit of parts (1D, 2D and 3D) fit within the existing parking lot proportions as that would result in the ability to construct on top of any parking lot throughout Delft Campus. After a lot of trial and error through physical and digital model making, a proportioning system was determined for the 1D, 2D and 3D parts. Allowing for a variety of floor plans to be quickly generated and reconfigured upon further iteration. For example, if an additional fire stair is needed, then one would simply take out a 3D module part or 2D CLT floor part and replace it with the fire stair. This way of working allowed for the ability to establish a kit of parts that could continuously be developed throughout the term. Once the proportioning was determined, it became easy to generate large scale plans in a short amount of time simply by repeating elements. The aim was then to generate the most ambitious of options and from that, exceptions within the kit of parts would emerge and new parts would be designed and implemented. It was discovered that every 'part' in the project is a repeating element, avoiding any one off custom pieces in order to attain the design. This repeatability can then be transformed into reconfigurability, allowing for completely different design opportunities using the same kit of parts. Moreover, it allows for the project to take over different parking lots throughout campus, with each parking lot having site specific conditions that the kit of parts is able to respond to.

The different possibilities that the kit of parts can generate results in small, medium, large and extra large configurations, allowing for specific responses depending on the context of that time. Allowing for the buildings to grow and shrink rather than producing a static product. The opportunities go even further with the parts once you start utilizing them for other applications. For example, the parts can be utilized to develop spaces on top of existing buildings, or can quickly generate communities in brownfield sites, the opportunities become limited by the designers ideas rather than being limited by the parts. The transferability of the project can go beyond parking lots, just as it can only focus on residential typologies or only educational typologies as well as different scales of each. Flexibility becomes a major component of what the designed kit of parts can offer. As the project has developed, the complications of combining all three timber systems (1D, 2D, and 3D) has been realized. It becomes difficult when switching back and forth between 1D/2D and 3D, with the goal of attaining maximum flexibility. Although it does appear to be possible, the combination of the two systems may result in using more material than needed. However, throughout the project development and research, it must be acknowledged that every system has its drawbacks and must try to be mitigated as much as possible. The significant benefit of combining all three systems has resulted in being able to quickly iterate and develop the project, allowing for the building to consist of typical details that can quickly be rearranged as needed.

Throughout the graduation project, exploration has gone from generating ambitious sketches of building ideas to researching existing tools and techniques within 1D, 2D and 3D timber systems and establishing rules of thumb for each. To then explore the proportional implications of the parking lot and how that dictates the sizing of the timber elements within each system while referring back to the established rules of thumb. While along the way constantly testing through physical model iterations to gain a greater understanding of how things come together and function. Going back and forth from different scales between 1:1000 to 1:5 has provided a great deal of insight in order to figure out specific design aspects and functionality of the project. Then exploring materiality and quality of space through visualizations to see how the expression of the different parts contributes to the architectural quality of the project. I believe that exploring all of these different aspects and using a range of different approaches to do so enables the design to develop in such a way that may not be possible through only one means of exploration.

The graduation project topic itself explores a pressing issue of the lack of housing that is provided on Delft campus along with its need to maximize the use of space. Which relates to the ambitions of the architecture track to positively influence the built environment in such a way that is innovative and relevant. Moreover, the project relates to the overall master program, addressing the need for housing as well as exploring how the development of different parts from different systems (1D, 2D, 3D) come together, figuring out the detailing of each component, essentially creating a large scale meccano set.

Going forward, there is a great potential to develop the kit of parts further, solving the issues of the 1D to 3D transitions to create a truly highly adaptable built environment. The parts can be pushed further to create different housing or educational typologies, not limited to existing parking lots but to be placed within different contexts. The current proportioning allows for the building to be configured in a way that meets the designers needs, the parts are no more limiting than a typical structural grid. Breaking the norm of what prefabricated construction can produce, building in contexts otherwise designed for a single purpose and to react to site specific conditions.