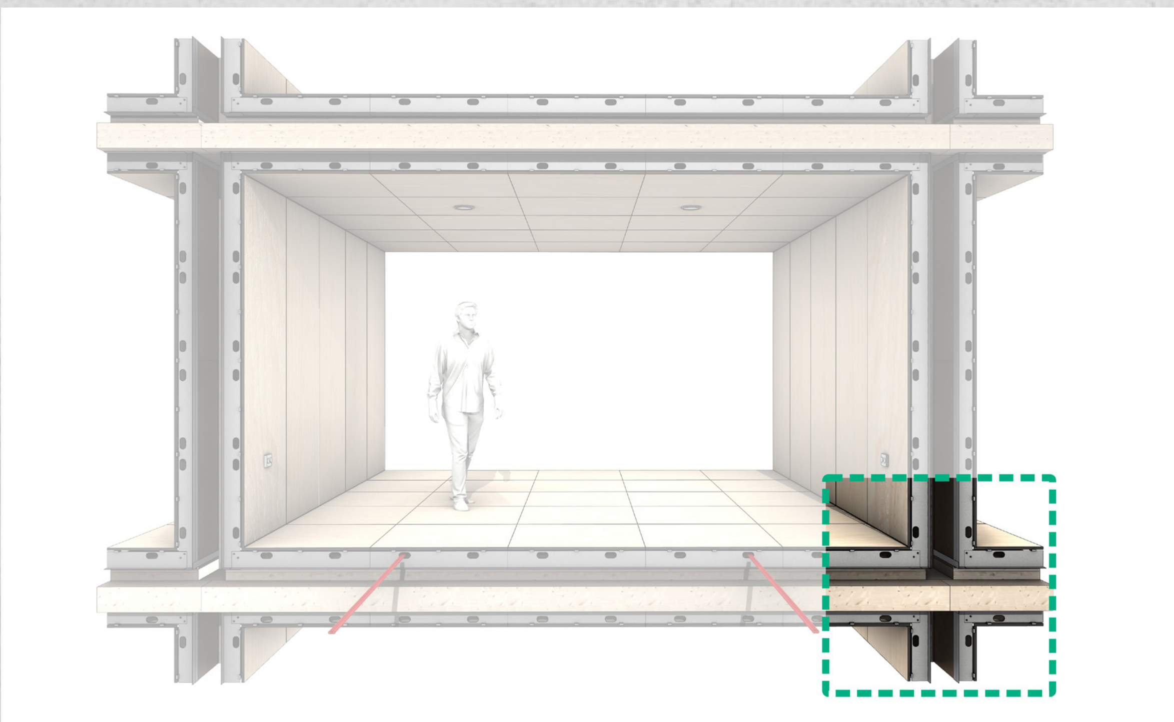
COMPONENTISED INTERNAL WALLS FOR MULTI-RESIDENTIAL APPLICATIONS

CRC #28 FINAL REPORT



CONTENTS

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1. EXECUTIVE SUMMARY

This report outlines the findings from a scoping study into Componentised and Connected Internal Walls for Multi-residential applications. The research identified a set of multi-scalar issues associated with business-as-usual (BAU) approaches to internal walls including defects and rectification costs; on-site waste (up to 18% in the case of plasterboard); and associated incidents leading to common injuries. A literature review into the benefits of prefabrication indicated that componentised wall systems could help address these key issues.

The scoping study developed a framework for assessing the efficacy of componentised wall alternatives. The design-led research identified knowledge gaps that impede the take-up of prefabrication within existing design, manufacture, assembly and delivery processes. These inputs and processes will be the focus of a second stage of research development, and include: new modes of reporting with industry to quantify tangential costs associated with common issues such as defects and OH&S; strategies for overcoming barriers such as ingrained procurement practices; on site tolerance issues; and lack of digital integration from design through to manufacture. The report recommends that future research include partners across the supply chain to establish workable responses to these barriers.

Overview of research question

Typical internal wall systems in multi-residential buildings are commonly achieved through multi-layer plasterboard wall systems. Elements in these wall systems are handled, cut and assembled on site and require multiple trades to complete the structural, services and finishing required. These wall systems are labour intensive, and involve wasteful on-site processing – quality control is difficult to achieve. The described performance requirements for internal walls including fire and sound separation rely on skilled trades and supervision - when these fail, significant and costly legacy issues arise. Componentised wall systems which address these issues are common in other sectors such as commercial fitouts - so why aren't these being pursued for internal walls in residential construction?

Team and approach

Project #28 is a collaboration between Monash University's Urban Lab and Future Building Initiative, with engineering input from the University of Melbourne and working closely with industry partner Lendlease. We utilised three key methods:

- industry consultation through interviews and workshops
- a literature review including a survey of existing componentised wall systems and lifecycle assessment tools
- a design research approach to put forward scenarios for review and discussion.

Literature review

Our literature review supported industry feedback on key issues with business-as-usual wall construction.

Defects

- Significant and growing costs are associated with defects rectification annually.[1] A large portion of serious defects include those relating to issues with passive fire separation, i.e. faults in fire-seals within inter-tenancy walls.[2]
- Findings are limited in their accuracy and relevance by the way defects are reported and catergorised. Future research could establish methods of analysing project data to support a more nuanced understanding.

OH&S

- Installation of plasterboard has been directly linked to OH&S injuries, primarily with musculo-skeletal disorders (MSDs).[3] MSDs account for the most common of series injuries (16%) within the construction sector.[4]
- Research suggests that off-site manufacturing reduces OH&S incidents by reducing exposure to common risks.[5]

Plasterboard waste and lifecycle assessment (LCA)

- Significant waste (between 12% to 18%)[6] is built in to the installation of standard plasterboard wall panels.
- Suppliers report that pre-cut plasterboard solutions are available - why don't contractors explore these?
- Existing LCA tools and data operate on overall building scales and systems; assessing internal walls in isolation requires new data and approaches.

Summary of findings

By testing the design research led scenarios, or provocations, we found that shifts towards componentisation could address many of the BAU issues identified, but significant barriers to adoption remain. The following opportunities, barriers and recommendations reflect results from the design research led scenarios.

OPPORTUNITIES

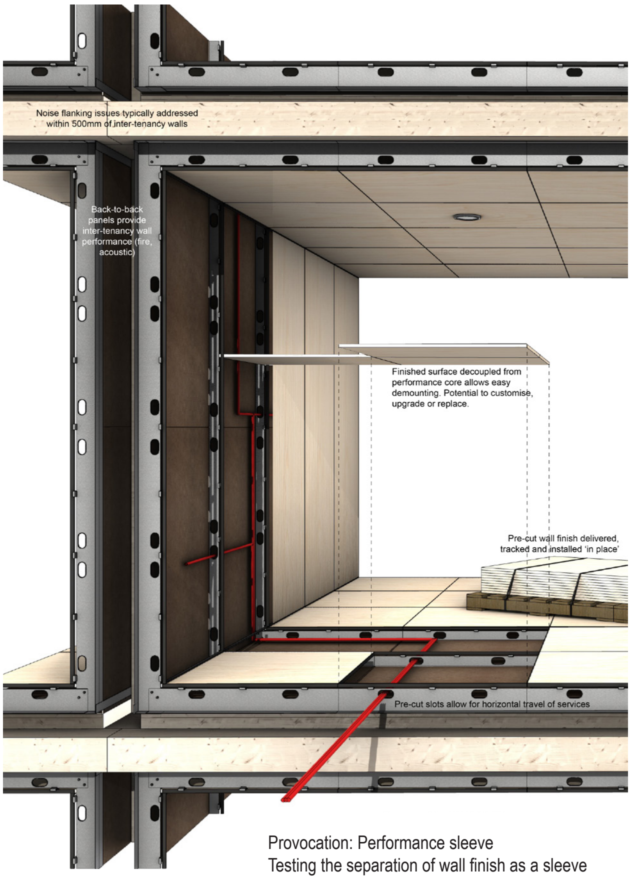
- Componentised wall systems could reduce the time, complexity and waste of on site construction, offering considerable cost advantages.
- Any shift to off-site construction would reduce OH&S incidents (namely musculo-skeletal disorders) linked directly to handling plasterboard on site.
- Initiatives such as utilising a 'performance sleeve' (refer 5.2 *Lessons from provocations* below) could significantly reduce serious defects associated with failures in fire and sound separation.
- The use of bio-materials to replace common walling materials (for example strawboard replacing Hebel) has the potential to reduce carbon footprint, or even carbon capture, creating important contributions to sustainability.
- The introduction of a fully off-site product for walls allows for repair, flexibility and replacement, enabling significant value to be retained over time. This may be particularly suited to scenarios such as a build-to-rent.

BARRIERS TO ADOPTION

- Lack of digital integration with services, suppliers and manufacturers raises questions about industry readiness for off-site solutions.
- Costing models for internal walls do not currently factor in tangential costs such as defect rectification and decanting. Until they do so, a shift to componentised walls is unlikely to stack up financially.
- BAU internal fitout does not require walls to be craned etc while pre-assembled solutions may, raising the possibility of implications for BAU critical path planning.
- Current practice builds in tolerances to account for deviation from documented design due to inaccuracies. How can the precision of off-site manufacture come together with variation on site?
- Pre-assembly and/or off-site integration of services would require a location, transport and personnel - i.e. a third party. Who would this be?

RECOMMENDATIONS

- Improve collection and analysis of data to quantify costs associated with internal walls including evidence-based analysis of defects, OH&S, digital integration, supply chain mapping and critical path planning.
- Investigate digital processes including survey existing BIM platforms used by partners, exemplars and examples.
- Expand design research and prototype testing into different building typologies and structural systems, including testing junction details.
- Expand the research to involve partners across the supply chain to understand how workable solutions to barriers in componentised walls might be overcome.



Provocation: Performance sleeve
Testing the separation of wall finish as a sleeve over main performance wall. Reduced duration and complexity of trades on site.

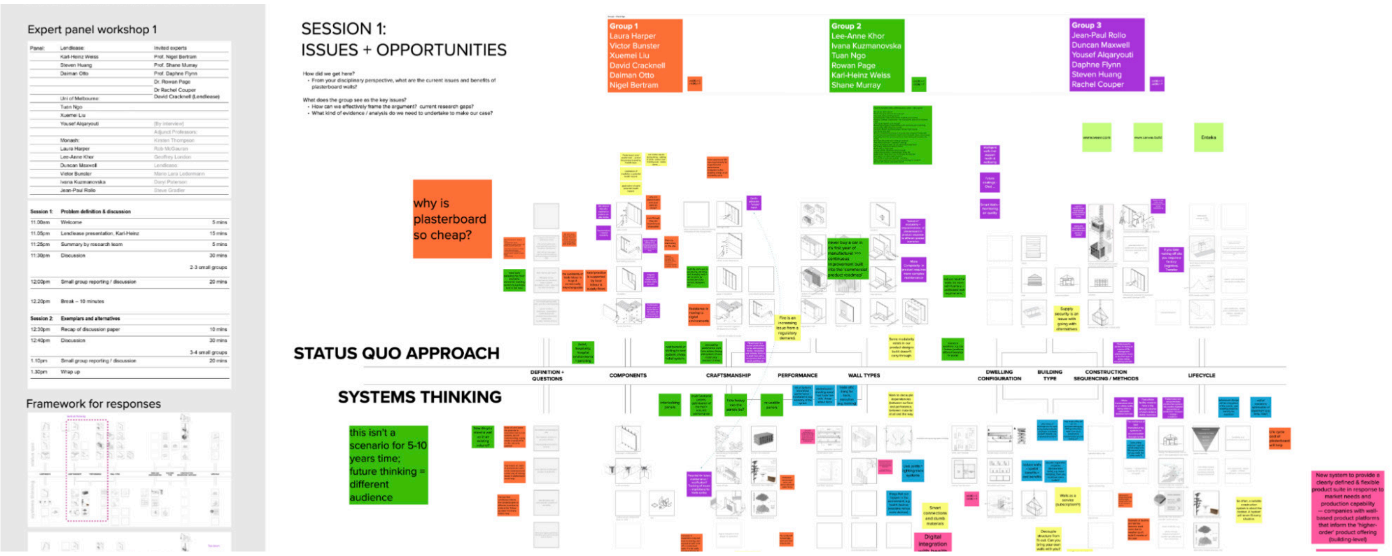
2. RESEARCH APPROACH

Research for project # 28 was undertaken through three key methods. Industry consultation was gathered through a series of discussions, workshops and interviews. This provided anecdotal, first hand experiences of the problems associated with internal walls in an Australian context which informed our subsequent research approach. A literature review was undertaken to establish a foundation for gathering industry feedback about on-site issues with internal walls (such as reported OH&S incidents), as well as to identify documented barriers to achieving higher levels of prefabrication. Part of this literature review included a survey of existing componentised wall products and alternatives. Finally, design research methods were employed to propose scenarios or ‘provocations’ which responded to existing problems. Analysis of these scenarios with industry partners enabled us to reveal the interconnected and complex issues which currently form barriers to the use of componentised wall systems in multi-residential applications.

2.1 Industry consultation

Industry expertise and multidisciplinary academic inputs were sought throughout the project through structured workshops as well as recorded interviews. Two half-day workshops, conducted via zoom, included selected personnel from within the Lendlease team as well as an invited panel consisting of academic experts, practising architects and designers. An introductory paper was issued to participants (CRC28 EP1 Report) and discussion was structured around prepared visual materials via online collaboration tool MURAL. Expert panel 1 (EP1) focused on a discussion of issues and opportunities. We presented work through a multi-scalar mapping of issues across the construction process comparing common BAU approaches to alternatives that we had identified and studied. Participants responded through written feedback which was recorded, organised and disseminated back to the panel. EP2, conducted in a similar format, focused on LCA with specific discussion on new business models such as Build-to-rent and their potential to shift equations of costs. Outcomes of workshops are detailed in Appendix 7.4.

A series of interviews were planned for the scoping study - these were only partially completed. COVID lockdowns and restrictions posed significant hurdles for planned in-person events including interviews, site visits and visits to supplier and manufacturer plants. The record of transcripts from interviews is not available to the public.

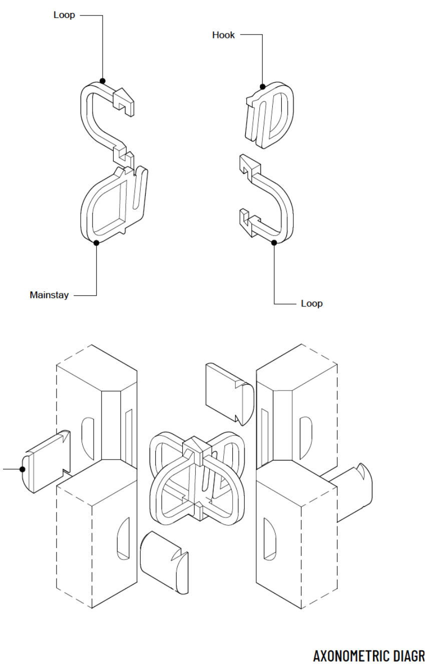


Discussion board from Expert Panel 1. (Refer Appendix 7.4, EP1)

2.2 Literature review and case study analysis

A literature review was undertaken to survey existing relevant research. A key focus was on understanding existing research into barriers to the adoption of componentised systems. Identified papers were summarised and key issues drawn out to construct a diagram of barriers to adoption that exist across the industry. A key finding of the literature review was that although significant research exists about barriers to the adoption of prefabrication more broadly, specific literature addressing internal walls was harder to find. Literature also provided an evidence base to support anecdotal experiences reported from industry. For example, significant recent research into quantities and types of defects in the construction industry can assist in quantifying the scope of this issue. Future research recommendations include understanding how project data is currently reported and accounted for within partner organisations, and if possible, to design methods for collecting this kind of data to support future research evidence.

A key research activity was a survey of pre-existing approaches to componentised wall systems. In line with the design research led approach, the initial survey of precedents is broad and draws on examples across time and industries. It examines not only the details and materials of particular wall systems, but also the factors and conditions that make them viable and suitable for particular applications at particular times. A full list of systems and themes studied to date is included in Appendix 7.2



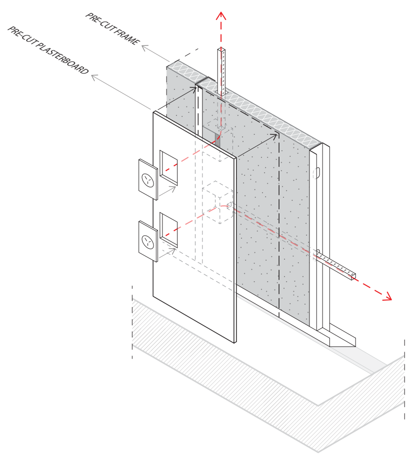
An example of the drawings undertaken of existing componentised wall system. Detail from student examination of 'Packaged House System, Konrad Wachsmann and Walter Gropius, 1939'.
(Refer Appendix 7.2)

2.3 Design research and provocations

Design research focuses on an open-ended exploration of options rather than solutions based approaches driven by current constraints. Design research is described as learning through doing - by applying ideas to real world situations and context, the issues and opportunities can be both revealed and communicated to others.[7]

An initial use of design research was tested through the integration of a Masters of Architecture design studio and studies unit. The brief to students ran in parallel to the research project, providing students with the opportunity to work with a real-world issue and to have input from industry partners. The studio work, typically representing a more 'blue-sky' approach to the issue was also presented to industry partners and acted as a useful discussion point to develop themes and ideas.

We also used a design research led approach to propose a series of four scenarios, or provocations, which were then presented to industry partners and relevant academics for review. These provocations were also tested, on paper, by University of Melbourne in terms of performance certification. The provocations serve as a way to communicate both the challenges and potential of componentised wall systems. For example, provocation 1 examined small changes in BAU construction and exposed hidden issues in the procurement process, such as existing trade subcontracts that prevented initiatives like off-site cutting to take place.



Sketch detail of provocation 1, which tried to understand barriers to simple improvements to BAU such as pre-cutting of plasterboard.

3. PROBLEM DEFINITION

Internal wall systems in multi-residential construction continue to rely on labour intensive and wasteful on-site processing despite advances in prefabrication in other aspects of this type of construction. Described performance requirements for internal walls rely heavily on skilled trades and supervision - when these fail, significant and costly legacy issues[8] arise. Quality in execution, services integration, services penetration through walls, cracks in joints and subsequent performance issues have been identified by industry partner Lendlease as having significant costs that are not currently factored into project costing models. Further research also identified significant waste production (industry average of plasterboard waste generated on site is circa 18%), associated OH&S incidents relating to handling and cutting of plasterboard and implications of construction sequencing as internal walls hit the critical path at the end of construction. Together, these issues point to a multi-scalar set of issues impacting internal walls.

3.1 Overview of internal wall systems

Internal partitioning in multi-residential construction is typically achieved with plasterboard wall systems which consist of a stud frame (either timber or steel) with a layer of plasterboard which forms the surface finish. Insulation and other layers are included depending on performance requirements. These walls are non-load bearing and can be either within a single apartment (intra-tenancy), between two adjacent dwellings (inter-tenancy) or adjoining a common area. Additionally they may hold services or not. The range of performance requirements for different internal wall applications has been met by varying the way frames, insulation/cores and surfaces are configured. Put simply, the amount, thickness, spacing and treatment of materials may change, but the underlying logic of drywall construction remains unchanged (See adjacent Figure 'Summary of internal non-load bearing wall types').

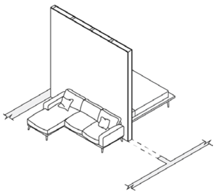
The classification of wall types and performance requirements does not necessarily pair with the spatial hierarchies of multi-residential building typologies, such as common access areas or dwelling ownership. More stringent performance requirements are set between bedrooms than for partitioning of private and common space, for example. A comprehensive analysis of performance requirements was undertaken for this project (Appendix 7.3).

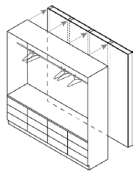
The make-up of typical plasterboard walls requires processing materials on site, and complex assembly processes involving tools, equipment and trades. On-site activities include measurement, cutting, positioning and fixing of plasterboard surfaces, which are susceptible to damage at each stage. Movement between multiple 'workstations' (e.g. for dust containment), double handling for on-site adjustments, as well as uncovering and re-finishing work for the coordination of trades, present time and cost redundancies and generate a considerable amount waste (discussed further below). Proprietary wall systems are accompanied by increasingly onerous dimensional accuracy and fixing techniques nominated by suppliers to meet performance requirements. An example is the standard Hebel inter-tenancy wall detail (refer p.9). The technical rigidity of constraint-driven wall solutions, combined with the complexity of on-site processing and delivery, leads to a number of compliance failures.

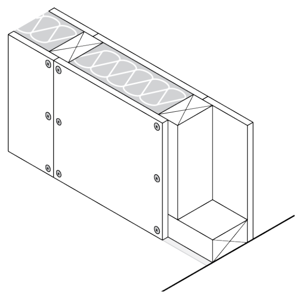
Summary of internal non-load bearing wall types in multi-residential construction including overview of performance requirements which are applied depending on the location of walls within the building.

Wall type | **Typical construction** | **Performance requirements**

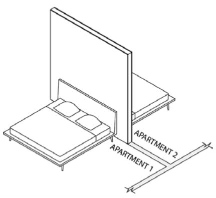
Partition (within dwelling)

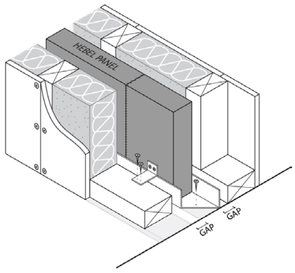

Partition


joinery

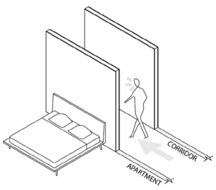


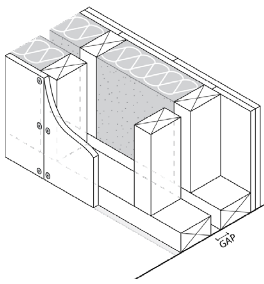
Inter-tenancy

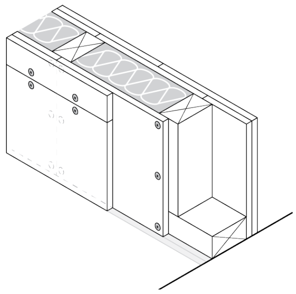




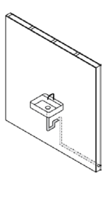
Common areas, corridor

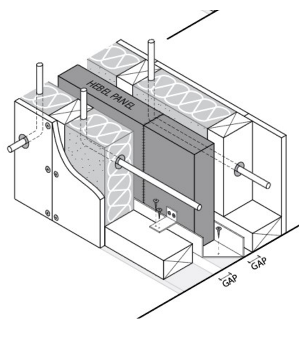


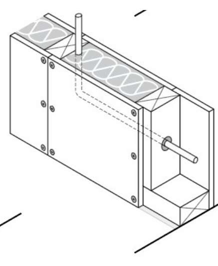




Services, 'wet' walls







Acoustic separation

The acoustic privacy required by various spaces is dependent upon:

- the noise level generated within the source room
- the degree to which legibility is acceptable within the receiving room or space.
- Wall System Ratings must be considered in conjunction with Background Noise Levels.

Fire resistance Level (FRL)

Determined with respect to the structural adequacy, insulation, and integrity performance criteria. In non-load bearing walls, the latter two criteria govern the fire performance, as studs are capable of withstanding the self-weight of the wall system. FRL improvement achieved by:

- gap clearance and emissivity
- reduction of plasterboard degradation
- confinement of plasterboard moisture.

Thermal comfort

The energy required to heat and cool residential buildings has significant environmental impacts. Maintaining "comfortable" thermal conditions with active systems (ventilation and air-conditioning) is the largest sector in energy consumption in most of the developed world (Griffiths et al 1988). In multi-residential projects, an average Nationwide House Energy Rating Scheme (NatHERS) rating of 7 Stars or greater is required.

Air tightness (transfer of smells)

Minimise uncontrolled movement of air through the walls, roof, floor and joinery to achieve healthy indoor air quality and energy efficiency. Reduced air infiltration:

- saves energy required for heating/ cooling appliances
- eliminates contamination of the indoor air
- prevents mould and mildew in the construction from internally driven moisture
- enables controlled ventilation.

* Lendlease predominantly employs steel framed drywall systems. Non load-bearing masonry walls are another typical construction system in multi-residential applications, outside the scope of this study.

3.2 Common failures and defects

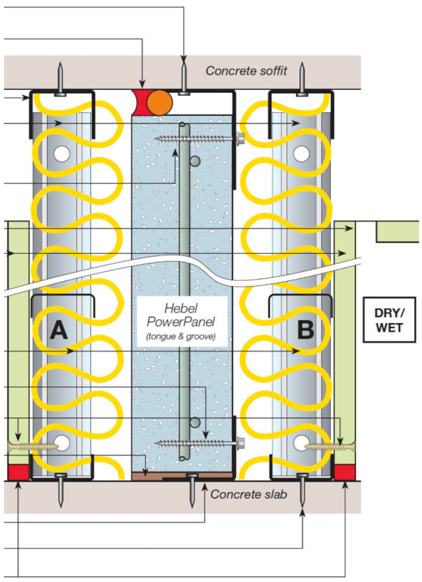
Defects are an inevitable occurrence post construction on every building site and are an accepted part of the building process.[9] A construction defect is defined as 'a defect in the workmanship, design and/or in the materials or systems used on a project that results in a failure of a component part of a building or structure, which, in turn causes damage to the property or person'.[10]

Successful installation of plasterboard wall systems relies on skilled trades. Performance requirements are dependent on the order of material layers, the number and type of fixings, the correct application of fire and acoustic seals around penetrations and at junctions, and the continuity of insulation. Performance can be compromised through small variations to multiple aspects of the system. Compounding the complexity of internal wall systems are the multiple trades and therefore people who are part of completing the system. Installation of studs, services rough-in, installation of plasterboard, services finishing and painting are often installed by separate teams which attend site in sequence.

A significant amount of research exists documenting the frequency, type, severity and causes of defects in the construction industry.[11] Sandayake et al. (2022) documented a rapid increase in research attention to the issue of defect rectification in the construction industry in the past two decades. Defects have been the subject of mainstream media attention, particularly in NSW and the ACT where sustained public attention has influenced building defects reform.[12]

Understanding what percentage of defects relate to internal walls is difficult given the way in which defects are recorded, documented and analysed. In their comprehensive Examination of Building Defects in Residential Multi-owned Properties, Johnston and Reid (2019) outlined the complexity of classifying and organising defects and the different ways in which defects are reported.[13] Their own data, drawn from defect audit reports provided by multiple building consultants / auditing companies, provided some insights into defects that can be linked to internal walls. For example they found 13% of defects (the second largest category after building envelope) related to defects with fire separation. Within the category of fire separation, about half (45%) were the result of passive fire protection measures - namely improperly installed fire seals and fire collars within intra-tenancy walls.[14] This is just one of the many potential defects raised by industry partners in relation to plasterboard walls. Defects relating to failure of sound separation for example, which Lendlease noted as a common (and difficult to fix) building defect, were not separately catergorised in Johnston and Reid.

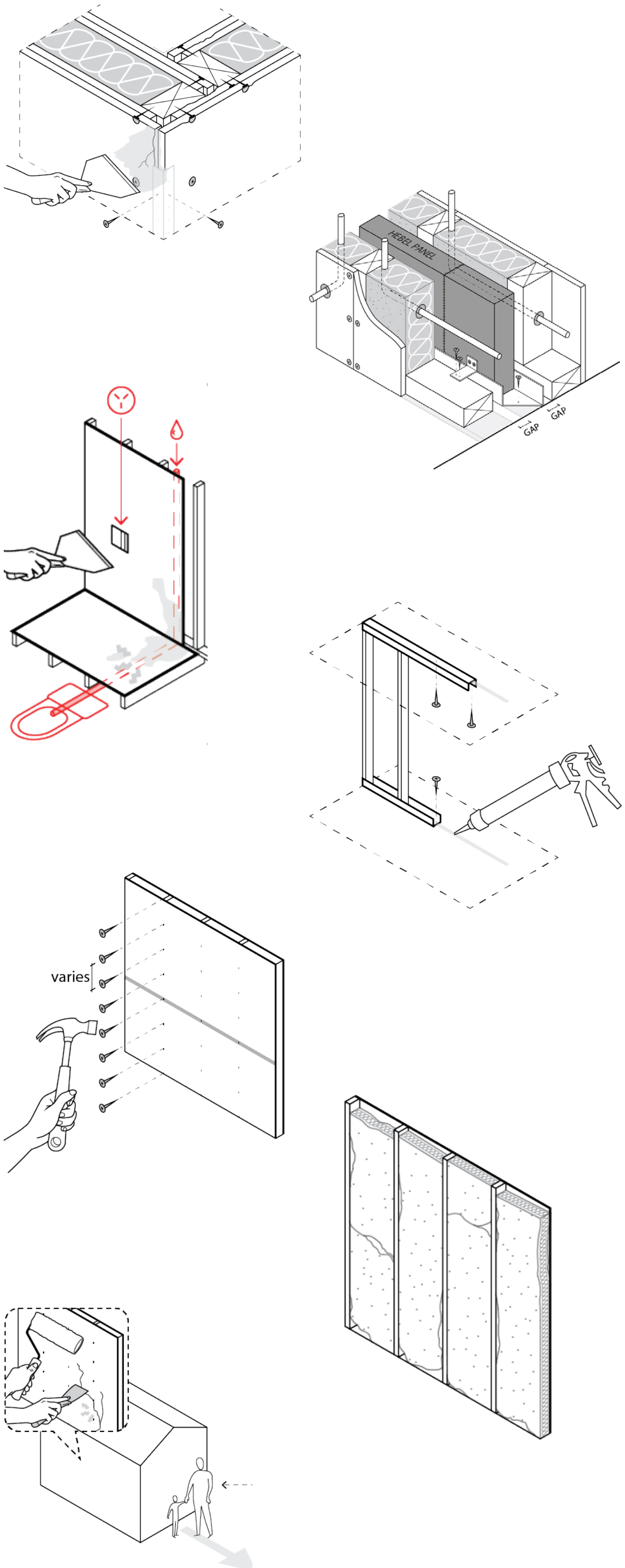
It is clear that existing research supports industry reports relating to defects within internal walls, however it is difficult to apply this research directly to internal walls. Future research should aim for a more targeted approach to quantifying these issues, for example through an analysis of defects data within an organisation, or by project.



Standard inter-tenancy wall detail. Source: Hebel Design and Installation Guide for High-rise apartments.

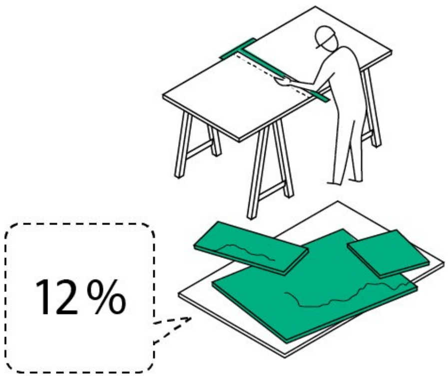
Common causes of failures and defects in business as usual internal wall construction.

- **Corner + connection details:** Staggered corner joints misaligned; plasterboard often doesn't run through. Leads to thermal and acoustic performance failures, and potential for physical/visual defects to emerge.
- **Cavities:** Specific spacing dimensions for Hebel panels to achieve acoustic performance; level of accuracy / lack of tolerance leads to common spacing errors. Incorrect installation leads to cavities acting as sound amplifiers.
- **Services:** Integration within wall system construction, as well as subsequent penetrations required, are a common source of errors/wall damage requiring rectification and cost imposts. Access to concealed services presents challenges for maintenance and adaptations over a dwelling's life span.
- **Material delivery:** Redundancies exist in the distribution of materials to active building levels and work locations. Vertical transport platforms deliver goods and equipment to a central loading point, from where they are manually carried up/down to adjacent floors (nom. 2 or 3 levels) and manually manoeuvred to relevant workstations (e.g. cutting occurs in a separated area for dust containment). The multiple movement patterns and handling present inefficient operational costs and risks damage to panels.
- **Acoustic seals to top/bottom plates:** Frequently omitted requiring costly rectification of performance defects (often only observed post-occupancy).
- **Panel joints:** Vertical or horizontal joints. To achieve performance requirements, product manuals call for a specific number of screws per panel, with nominated spacing dimensions. Divergence from specifications is very common.
- **Insulation gaps:** Smallest compromise impacts performance to such an extent that it may as well not be installed.
- **Decanting Costs:** Costs associated with rectifying these defects include not only the repair of the walls themselves but also the costs of decanting and re-housing residents temporarily.



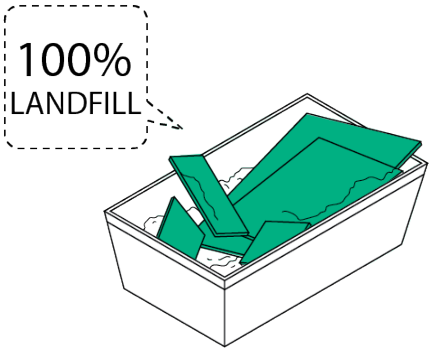
3.3 Waste and lifecycle

Plasterboard is typically purchased in standard sheet sizes - a commonly utilised sheet size is 1200mm wide by 2400mm high. The mismatch between standard sizes and variation on building sites inevitably leads to a gap where waste is produced. Estimates of the amount of plasterboard wasted through off-cuts on site vary. In the USA this has been estimated at 12%.[15]



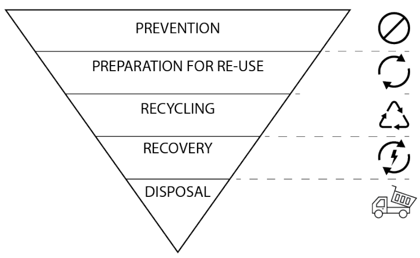
The National Waste report 2020 estimated Australia produces 74.1 million tonnes (Mt) of waste per year, 44% (or 27Mt) of which is linked to the construction and demolition (C&D) sector.[16] While other wastes have declined in the past decade, waste associated with C&D have risen, linked to rapid levels of development in major cities. While over 80% of C&D waste is recycled (largely demolition and excavation waste used for road base and fill for civil projects), the construction industry remains a key contributor to material entering into the waste processing system. In contrast to other core waste, C&D waste consists of both used waste (demolition waste) as well as off-cuts of material which have never been used such as plasterboard.

Waste reduction or prevention is seen as the most effective form of mitigating waste. The Waste Hierarchy establishes a set of priorities for actions that can be taken to mitigate waste.[17] At the top of the inverted pyramid is waste reduction, followed by re-use, then repair, recycle, recovery and disposal. The factors at the top of the pyramid tend to have the lowest impact on the environment while the lower priority actions, although important, each have significant impacts and waste associated with them. For example, energy required to recycle materials, and to transport materials to waste recovery centres, reduces the overall benefits of recycling. Research has documented that off-site manufacturing and digitisation of building more broadly has great potential to promote more efficient use of materials and produce less waste.[18]



This project comes at a time when both industry and government are investing significantly in methods for mitigating waste. For example, in 2018, Federal, state and local governments agreed on the 2018 National Waste Policy and in 2019 this was followed by the 2019 National Waste Action Plan which outlines a strategy for moving Australia towards a circular economy by 2030 including waste reduction targets and significant commitments to investing in recycling technologies. The Federal Government's $190 million Recycling Modernisation Fund is an example.[19] Industry are also investing in developing circular economy approaches. Examples of this include CSR Plasterboard take-back scheme,[20] and the cross-industry joint venture announced by Asahi Beverages, the PACT Group and Cleanaway group for a new plastics recycling facility to process their own and others' product waste.[21] Factors for this investment are varied and linked to both expectations of investors and the public, as well as to global influences. Australian exports of waste products intended for recycling have fallen sharply in recent years, linked to new import restrictions from China and other Asian nations implemented in 2017.[22]

Lendlease have their own targets for carbon reduction but more work is required to understand how these could be considered as a project cost.



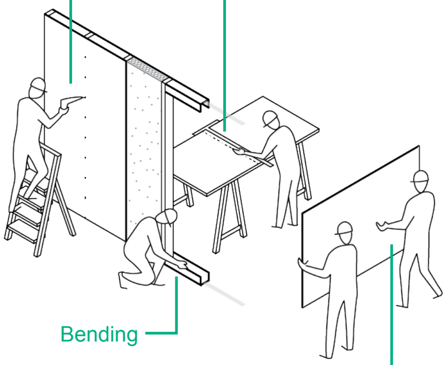
The Waste Hierarchy. Source: Waste Framework Directive, European Commission

3.4 Health and safety

The construction industry is one of the highest risk workplaces in Australia. According to Safe Work Australia, the construction industry records three workplace fatalities per 100,000 workers and 8.1 serious claims per million hours worked.[23] Many workplaces have targets for reduction in OH&S incidents on site.

Plasterboard has been identified by Safe Work Australia as being a key contributor to musculo-skeletal disorders (MSDs) due in large part to its ubiquitous use on almost every building site.[24] Workers compensation data highlights that MSDs are the most common serious non-fatal injuries (16%) within the construction sector, and dominate claims for workers compensation.[25]

MSDs are largely caused by hazardous manual tasks including lifting, picking up and lowering heavy objects and materials. In standard sheet sizes, plasterboard is bulky and is frequently handled manually in confined spaces, making movement and lifting awkward. Installation of plasterboard on ceilings was identified as a particularly difficult manual task requiring both installation at heights as well as lifting and handling - all tasks associated with high risk of injury.



The potential for off-site manufacturing to reduce incidents with OH&S is often reported as one of primary benefits of this mode of construction. The logic is that many incidents happen in the variable and unpredictable conditions of on-site construction and that the controlled environment of the factory will therefore reduce incidents which occur. However Odo and Rankin (2022) noted a lack of quantifiable data to support the improved safety of off-site construction.[26] In their 2022 study, Odo and Rankin compared on-site and off-site construction occurring simultaneously on a mid-rise building utilising both methods. They developed a model for assessing risks associated with types of activities across the whole of the supply chain - a method which allows for a direct comparison between off-site and on-site construction. These activities were assigned a risk likelihood, severity and exposure drawn from statistical OH&S incident reporting.[27] The findings demonstrated that workers in on site situations have a much higher exposure to common activities with statistically quantifiable OH&S risks, demonstrating the overall improvements to OH&S of manufacturing off site.

The research into OH&S demonstrates that more work needs to be done to quantify both the risks associated with BAU approaches to internal walls, as well as to understand and communicate the potential improvements to OH&S of off-site construction. Future research in this project should learn from the model develop by Odo and Rankin (2022) as a start to begin processes within organisations to link the costs of OH&S to innovations in construction methodology.

4. EXEMPLARS AND ALTERNATIVES

We reviewed, documented and analysed over 70 examples of componentised wall systems from contemporary and historical sources. We developed themes through the analysis and categorisation of these exemplars which focus attention on the key attributes of different componentised walls including: digital integration across the supply chain; integration of walls with floor and ceiling systems; removable / replaceable wall panels and many more. These themes correspond to challenges identified with BAU approaches and have informed the development of the four design research provocations. They also inform the recommendations of this report for future research.

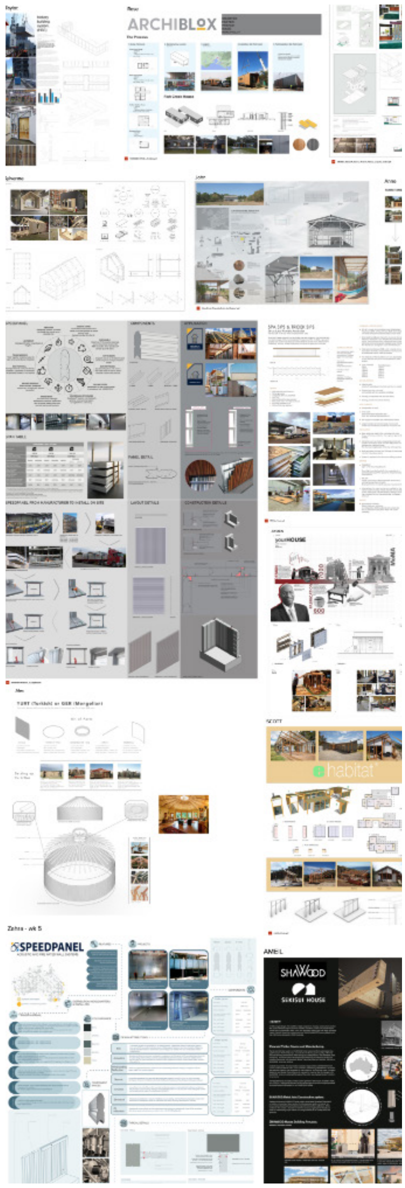
4.1 Methodology for review of exemplars and alternatives

An important aspect of base research for this project was the broad selection of componetised wall systems, details and materials for analysis, as well as a consistent and rigorous approach to understanding the factors and conditions informing each situation. The study of a large number of precedents was undertaken through a series of themes including:

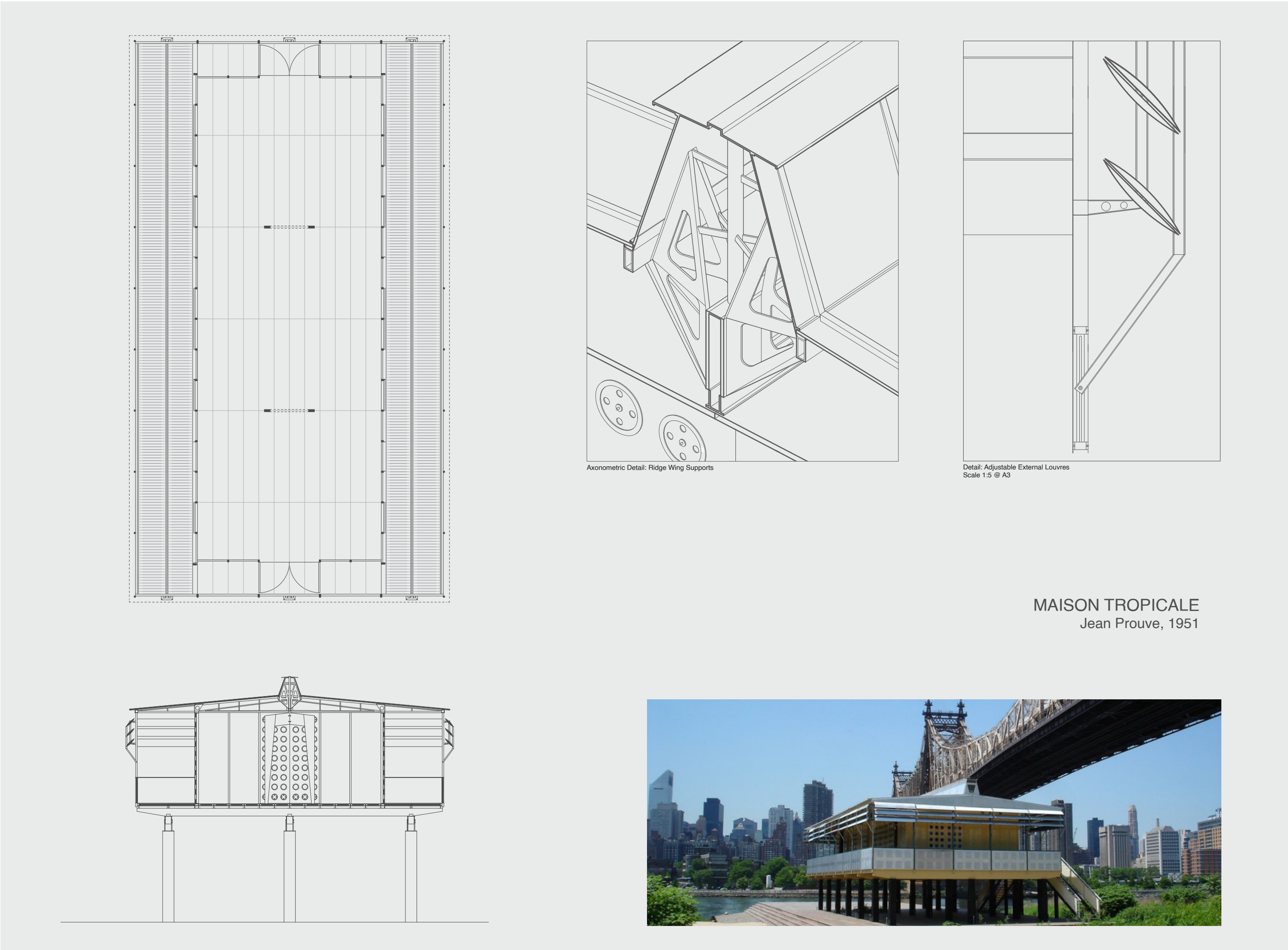
- pioneers of prefabrication including 20th century experimental post-war modular design
- modular furniture and partition systems from other industries such as office fitouts and hospital design
- commercially available modular systems including modular pods, demountable buildings and relief housing
- contemporary experimental approaches including architectural designs and advanced manufacturing.

The survey of precedents was run in parallel with, and informed the curriculum for, the Masters of Architecture studies unit, 'Wall Party!'. The students' research provided an initial survey of examples which then enabled the research team to test methods of documentation, comparison and categorisation and create a refined list.

We developed a written and drawn database which details the systems studied and how they perform against specific aspects of design and construction. (Refer Appendix 7.2 for full database.) The process of categorisation helped to draw out and understand common design questions that modular and componentised approaches to walls must solve. For example, how does a standard dimension deal with corner situations? The following section shows examples of categories developed through comparison and analysis of the systems, and particular precedent examples which demonstrate different approaches to these categories. These are not a full list of categories nor precedents but rather an example of the way in which a range of precedents from different applications and time periods become relevant when exploring particular aspects of modular wall design. The full and visual database is presented in Appendix 7.3.



A sample of the open ended database collected by students. (Refer Appendix 7.2)

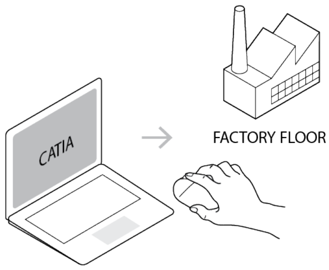


Documentation of componentised house system Maison Tropicale by Jean Prouve, 1951. Drawings by Masters of Architecture students Annabelle Low, Anne Barlow and John Tsitouridis. (Refer Appendix 7.2)

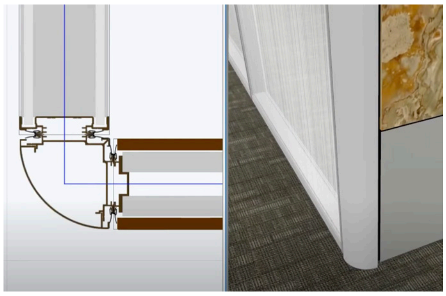
Wall system name	Designer	Year	Wall type Application	Approach to services	Dimension of Parts	Flexibility
Siniat Residential	Siniat	2021	Intertenancy wall	not-serviced	small unit (one person)	Permanent / no flexibility
SpeedPanel	SpeedPanel	2021	Internal partition	not-serviced	mechanical assistance	Whole panel demountable
Smart-wall telescopic	Rondo	2021	Internal partition	Integrated on-site (conduits)	small unit (two people)	designed to be moveable
DIRTT	DIRTT	2021	Internal partition	integrated with serviced floor	small unit (two people)	cladding removeable
Maison Tropicale	Jean Prouve	1951	External wall	not-serviced	small unit (two people)	Whole panel demountable
Katsura Imperial Villa	Hachijo Toshihito	1624	Internal partition	not-serviced	small unit (two people)	designed to be moveable
Dymaxion House	Buckminster Fuller	1944	External wall	Integrated on-site (conduits)	mechanical assistance	Permanent / no flexibility
Packaged House System	Wachsmann & Gropius	1942	External+IT+Partition	not-serviced	small unit (two people)	Whole panel demountable
Schröder House	Gerrit Rietveld	1924	Internal partition	not-serviced	small unit (two people)	fold-away furniture elements
USM	USM Haller	1965	Internal partition	not-serviced	small unit (one person)	cladding removeable
Modscape	Modscape	2021	External+IT+Partition	Integrated off-site	small unit (two people)	Permanent / no flexibility
SIPS	SPA	1996	External wall	Integrated on-site (conduits)	mechanical assistance	Permanent / no flexibility
Dincel	Dincel	1989	External+IT+Partition	Integrated on-site (conduits)	small unit (two people)	Permanent / no flexibility
Royal Academy of Arts	Gilles Restin	2019	Experimental design	not-serviced	small unit (one person)	Whole panel demountable
Wikihouse	Open source	2011	External+IT+Partition	Integrated on-site (conduits)	small unit (two people)	Permanent / no flexibility
Full Fill Homes	Anupama Kundoo	2015	External wall	not-serviced	small unit (two people)	Whole panel demountable
School Pod	Gollifer Langston	2008	Experimental design	Integrated on-site (conduits)	mechanical assistance	Whole panel demountable

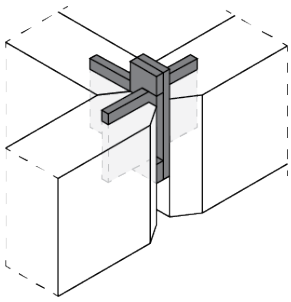
Example of categorisation and analysis of componentised wall system allowing a searchable database.

4.2 Themes emerging from exemplars and alternatives

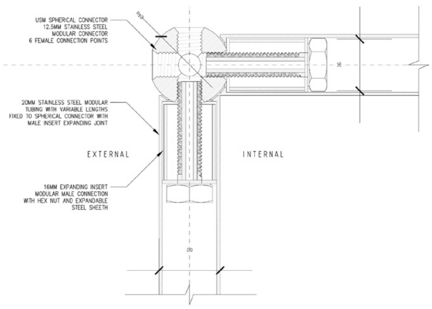


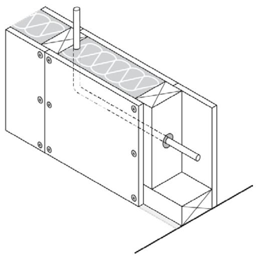
- Digital integration of supply chain from design to manufacture and delivery.
- An example is the ICE platform which enables designers to work with standard components and details through a BIM platform with real-time calculation of bill of materials and delivery schedules.



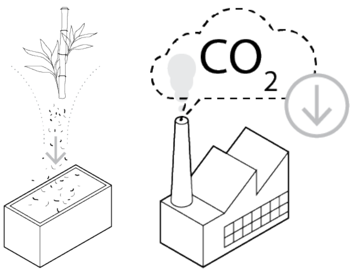


- Smart junctions at joints, floor and ceiling, which provide a prefab integrated solution to weak points in performance.
- An example is the enduring USM Haller furniture system which provides a universal joint for all points on the frame into which panelised surfaces clip.

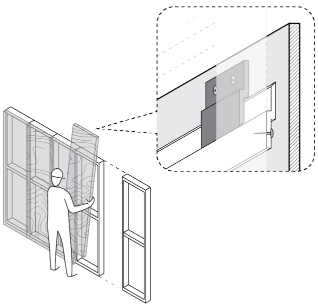




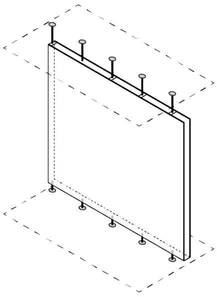
- Pre-integration of services enabled by digital integration between design and factory, and services consultants.
- An example is the DIRTT pre-assembled steel stud partition system which comes to site pre-serviced and ready to plug and play.



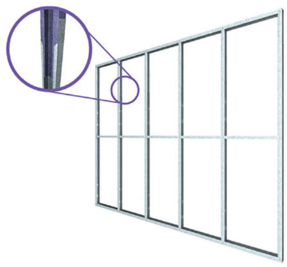
- New bio-materials offer potential to reduce CO_2 and improve performance.
- An example is Ortech's Durra Panel product, manufactured locally in Bendigo from compressed straw which provides negative carbon impacts and improves fire, thermal and sound insulation.

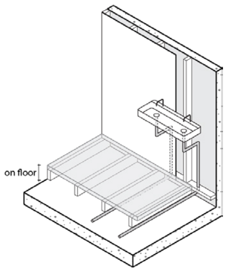


- Replaceable surface panels allow for repair and upgrade over time.
- An example is the FastMount removable wall system designed for commercial applications which allows surface panels to be repaired and upgraded or even swapped out with technology enabled smart panels.

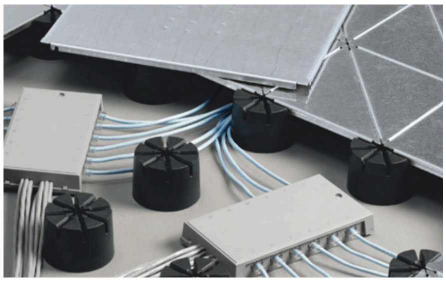


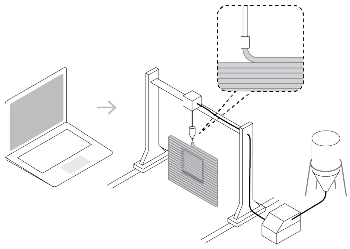
- Adjustable wall systems that deal with tolerance issues on site.
- An example is the Rondo Smartwall Telescopic which allows steel stud systems to be height variable to deal with site conditions.



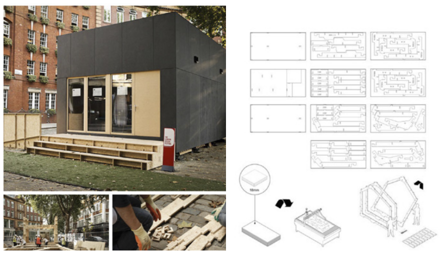


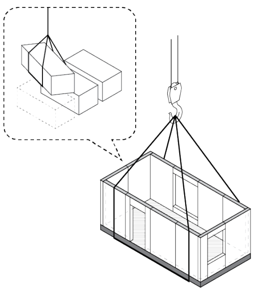
- Wall integrated with floor and ceiling systems including for services.
- An example is DIRTT Power, a modular grid system of raised tiles that allows services to run below the floor, enabling flexibility and adaptability of walls.



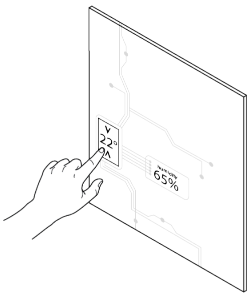


- Advanced manufacturing allows new possibilities in componentised walls.
- An example is the Wikihouse - an open source kit of parts. Every component in the house can be produced through a digital file input to a CNC machine.

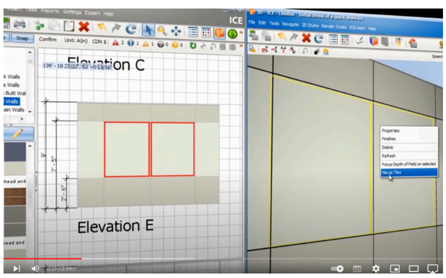




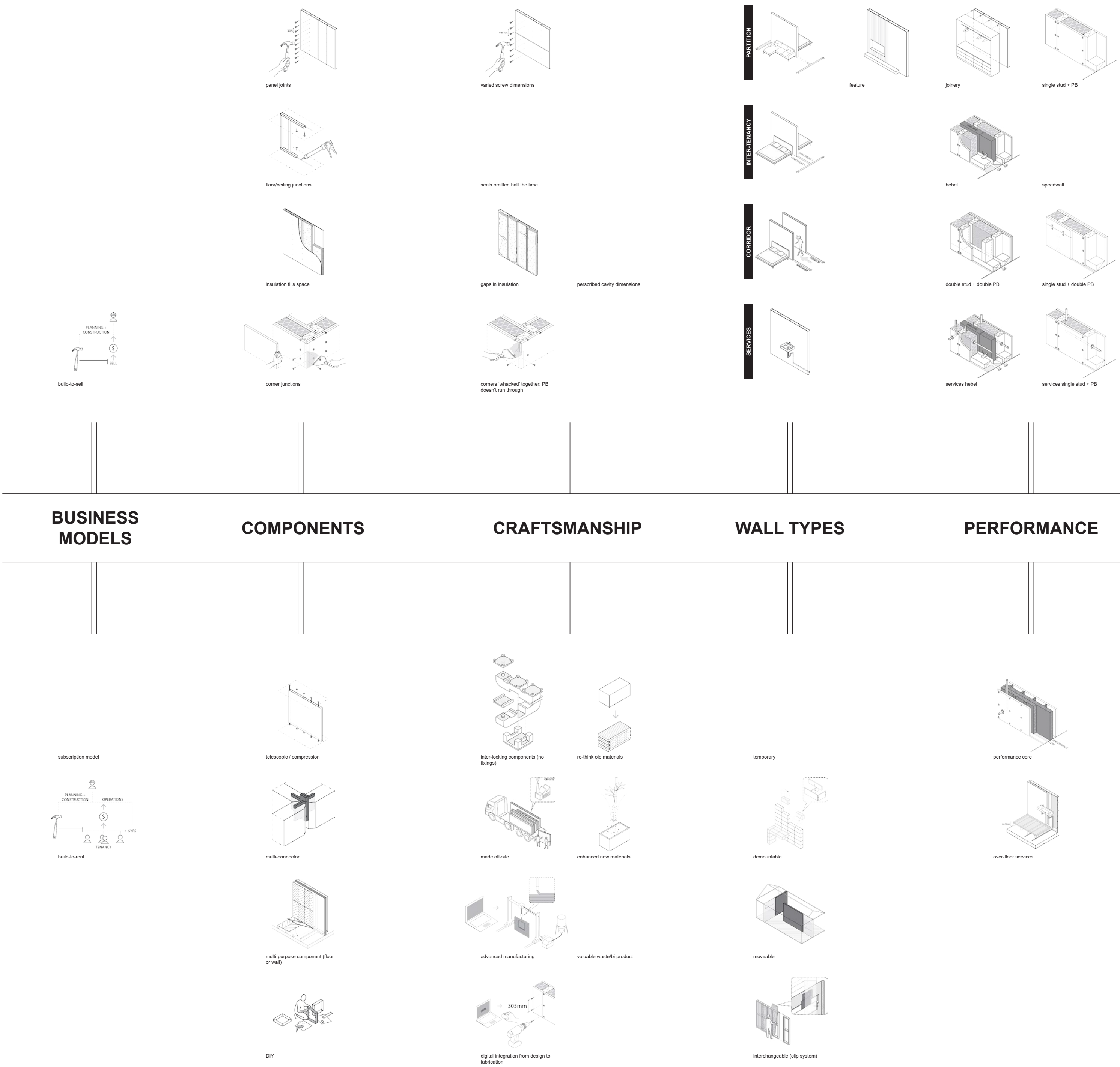
- Pod technology enabling sections of interiors to be fully prefabricated and serviced.
- An example is the Schiavello Modular fully serviced bathroom pod, which can be inserted into floor plates.



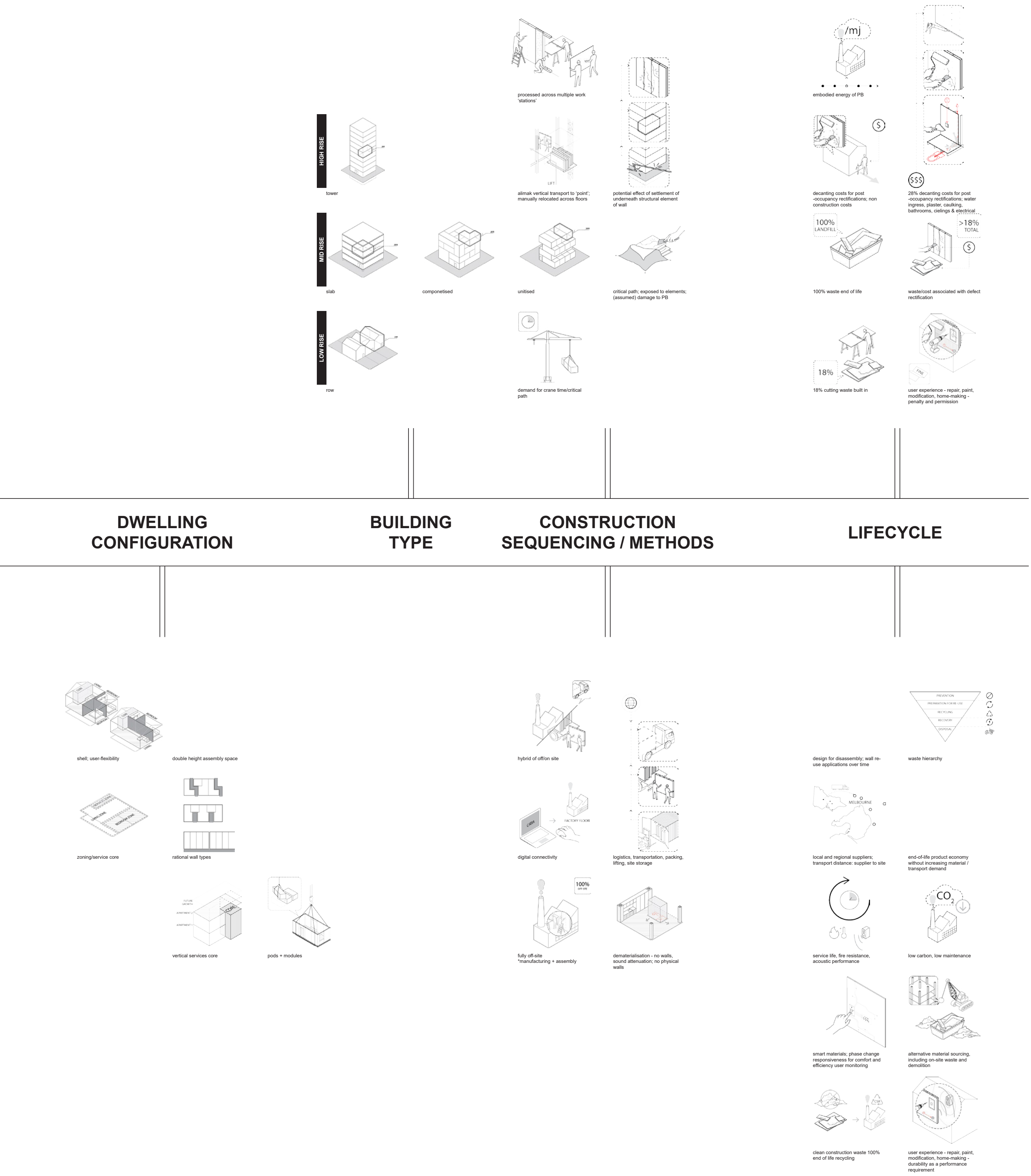
- Smart panels with Integrated tech which activates surfaces for electricity, heating and cooling technologies.
- An example is the 3D printed electrics pioneered for aviation wall panels by Airbus to apply smart technology to thin surfaces.



4.2 Multi-scalar mapping of alternatives (below) compared with BAU (above)



This diagram maps alternatives compared to BAU, across multiple areas raised by this research project. Each individual drawing can also be found at a larger scale elsewhere in this report.


HIGH RISE
MID RISE
LOW RISE
tower
slab
componetised
unitised
row
processed across multiple work 'stations'
alimak vertical transport to 'point'; manually relocated across floors
potential effect of settlement of underneath structural element of wall
critical path; exposed to elements; (assumed) damage to PB
demand for crane time/critical path
/mj
embodied energy of PB
decanting costs for post -occupancy rectifications; non construction costs
28% decanting costs for post -occupancy rectifications; water ingress, plaster, caulking, bathrooms, ceilings & electrical
100% LANDFILL
100% waste end of life
>18% TOTAL
waste/cost associated with defect rectification
18%
18% cutting waste built in
user experience - repair, paint, modification, home-making - penalty and permission
DWELLING CONFIGURATION
BUILDING TYPE
CONSTRUCTION SEQUENCING / METHODS
LIFECYCLE
shell; user-flexibility
double height assembly space
zoning/service core
rational wall types
vertical services core
pods + modules
hybrid of off/on site
digital connectivity
FACTORY FLOOR
logistics, transportation, packing, lifting, site storage
100%
fully off-site *manufacturing + assembly
dematerialisation - no walls, sound attenuation; no physical walls
design for disassembly; wall re-use applications over time
waste hierarchy
MELBOURNE
local and regional suppliers; transport distance: supplier to site
end-of-life product economy without increasing material / transport demand
service life, fire resistance, acoustic performance
CO2
low carbon, low maintenance
smart materials; phase change responsiveness for comfort and efficiency user monitoring
alternative material sourcing, including on-site waste and demolition
clean construction waste 100% end of life recycling
user experience - repair, paint, modification, home-making - durability as a performance requirement

5. PROVOCATIONS

We tested barriers and opportunities through a set of four provocations - speculative wall designs that addressed issues identified in the problem definition, and attended to emerging themes and opportunities developed through a study of exemplars. The provocations proved useful in discussing potential improvements offered by different approaches to componentised walls, revealing real and contextual issues to their adoption, and identifying areas where more research is required. In this report we use them to frame the potential advantages as well as barriers to the adoption of componentised walls.

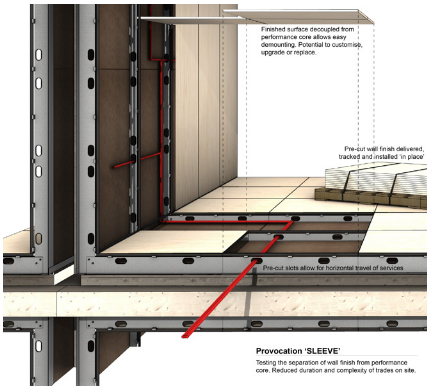
5.1 Methodology

Design research uses an applied methodology to test outcomes against real-world conditions. With these provocations, our aim was to propose actual wall systems that could be assessed, tested and considered against the issues and opportunities of componentised walls. Each provocation draws on specific issues identified through the problem definition and proposes methods to address them. They also draw on the opportunities and themes identified through the study of exemplars as a means to find solutions to address particular issues. By drawing and detailing these provocations, we could test them against performance requirements, building layouts, costs and build-ability.

An example is provocation 2 – performance sleeve. This provocation specifically sets out to solve the issue of defects associated with services penetrations in BAU approaches to internal walls. In BAU approaches, performance relies on the exact installation of layers, seals, insulation and fixings to achieve desired fire and sound separation. Services penetrations through and within these elements create performance failures and rely on conscientious craftsmanship to ensure separation is not compromised. The concept of the performance sleeve is to provide independence to performance requirements. An inner wall layer, or 'performance core', achieves all separation requirements whilst never interrupted by services. The finishing surface 'sleeve' is not critical to performance needs, and services can dictate penetrations.

To test whether the performance sleeve idea was viable, we designed a wall build up based on existing materials and systems and drew up details to show how layers would be constructed on site. Engineers from the University of Melbourne then tested and assessed these details for performance requirements, as well as lifecycle costing so that we could compare our proposed wall system with BAU. We could also estimate costs for each material. This applied testing enabled an assessment of the viability of options, and the kinds of issues associated with the general approach.

The provocations also proved invaluable as discussion points with partners and experts which drew out issues we had not considered. An example is provocation 1 – improved BAU – which proposes simple improvements such as pre-cutting of plasterboard. As we discussed this provocation with the team, it became evident that there was a lack of clarity around when, how and from whom plasterboard was procured – establishing more information about procurement practices became a central recommendation of this report.



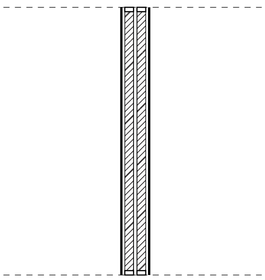
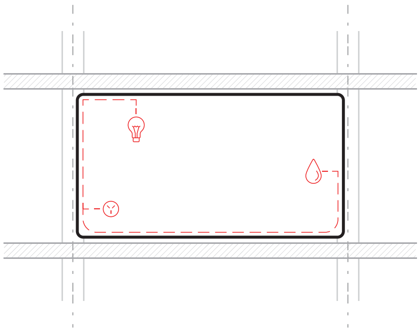
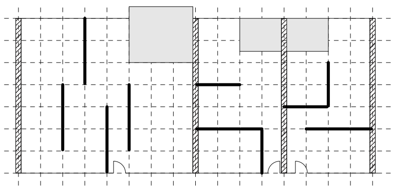
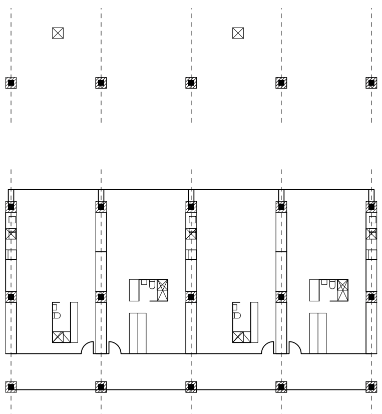
Testing concepts through applied design details allowed real world limitations and issues to be revealed and discussed

Durra Panel S50

Product Name	Durra Panel S50 Plain
Nominal Thickness	50mm
Weight	18.5 kg/m² (nominal)
Width (Standard)	1187mm
Maximum Length	3600mm
Face Colour	Brown (Kraft liner)
* Strength	Point load 5.8kN
Impact Resistance	High
Thermal Conductivity	0.081 W/mK
Thermal Resistance	0.62 m²W/k
Specific Heat Capacity	1050 J/kgK
Embodied Energy	12.6 MJ/m²
VOC Emission rate (ASTM D5116)	<0.05 mg/m²/hr (7 days)
Biscuit Slots	Available

Componentised wall details were tested for performance and cost, with inner wall layers made up of materials with high specification efficiencies such as Durra Panel. Durra Panel Specification source: Ortech Industries, Technical Manual: Durra Panel, Durra Steel Sections, Panelised Building Systems. 03.10.2017, Section 1.3.4.

Matrix of four provocations and their findings

Provocation	Overview	Key Findings
IMPROVED BAU 	To understand barriers to simple improvements initiatives such as off-site cutting of material and pre-assembly of frames.	Lack of clarity as to why available off-site initiatives (such as pre-cutting) are not being adopted. Pre-assembly raises questions about cranage & construction sequencing. Disjuncture between informality of on-site construction and certainty required for pre-cutting. Who bares risk? Lack of digital integration across design, consultants and suppliers a big barrier.
PERFORMANCE SLEEVE 	To explore the separation of performance, services and cladding.	Self-supporting performance materials can reduce wall thickness / eliminate studs. Floor and ceiling junctions are critical 'failure' points. High performance renewable materials exist and are in development. Independent surface cladding can aid future flexibility as well as rectification and maintenance works.
PLUG-N-PLAY 	To liberate internal partitions from services other than power; maximum flexibility & minimal wall thickness.	Is flexibility required or cost effective in residential applications? Build-to-rent applications may shift this equation. Would need to be combined with inter-tenancy wall options. Floor and ceiling junctions are critical for ease of installation and demounting. Depends on modular dimensionality of interiors, not common practice in design.
NO WALLS 	To explore the potential of pods & furniture to fulfill requirements of spatial division (eliminating walls).	Requires integrated building logic / and apartment design to enable pods to replace walls. Issues arising on site from services pods (cranage, sequencing, ceiling junctions) would also apply to furniture pods. Floor and ceiling junction issues remain - these elements would need to be added post pod installation.

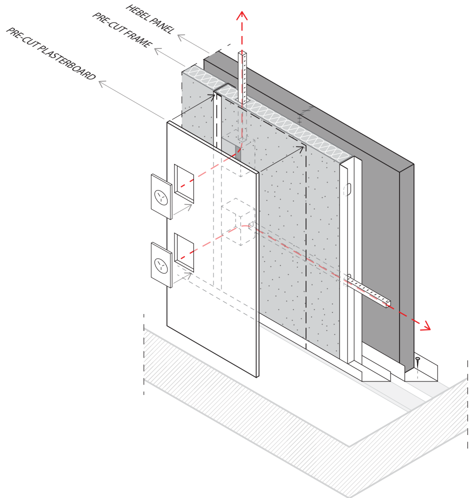
Provocations overview

5.2 Lessons from provocations

Provocation 1 - Improved BAU

This provocation is based on identifying simple initiatives to adjust existing BAU wall systems, shifting elements of the process off site without changing the essential material build up or challenging existing performance methods. Shifts proposed are:

- pre-cutting (by the manufacturer) of standard materials including plasterboard, Hebel and steel studs
- pre-assembly of stud frame including installation of services runs.



Sketch showing simple changes to BAU wall systems; pre-cut plasterboard and pre-cut frame; shifting some parts of the process off site.

Findings

The research identified that simple changes to BAU internal wall systems are currently available and could be implemented immediately. Such initiatives could be beneficial in addressing identified issues, but continue to face barriers.

Opportunities

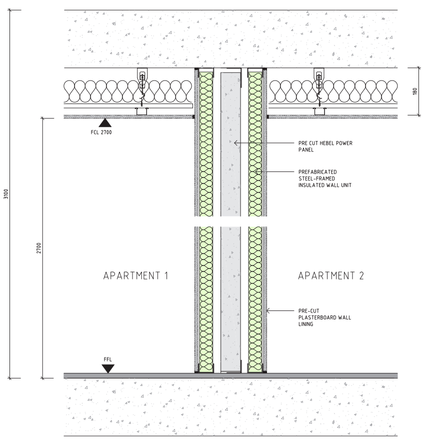
- Reduce waste (and thereby costs) on site. Potential waste savings could equal current over-order (i.e. 12-18%).
- Smaller pre-cut board sizes would reduce OH&S incidents (namely musculo-skeletal disorders) linked directly to handling plasterboard on site.
- Pre-assembly of studs could reduce OH&S incidents on site associated with cutting, and if craned, eliminate incidents relating to handling.
- Pre-assembly of services locations and insulation into studs could reduce defects associated with penetrations.
- Reducing time on site generally may contribute to improved time costs associated with sequencing (refer to Appendix 7.1 for more information).

Barriers

- Current practice builds in large tolerances to account for deviation from documented design due to on site inaccuracies, increasing the risk of pre-cutting and raising the question of who would bear this risk.
- There is a lack of clarity around the internal processes used for procurement within organisations. Why aren’t pre-cut solutions being applied already? What procurement structures make pre-cut solutions difficult to implement?
- BAU internal fitout does not require craning while pre-assembled solutions may, raising the possibility of implications for BAU critical path planning.
- Pre-assembly and/or off-site integration of services would require a location, transport and personnel - i.e. a third party. Who would this be?
- Lack of digital integration with services information, or with suppliers and manufacturers raises questions about industry readiness for off-site solutions.

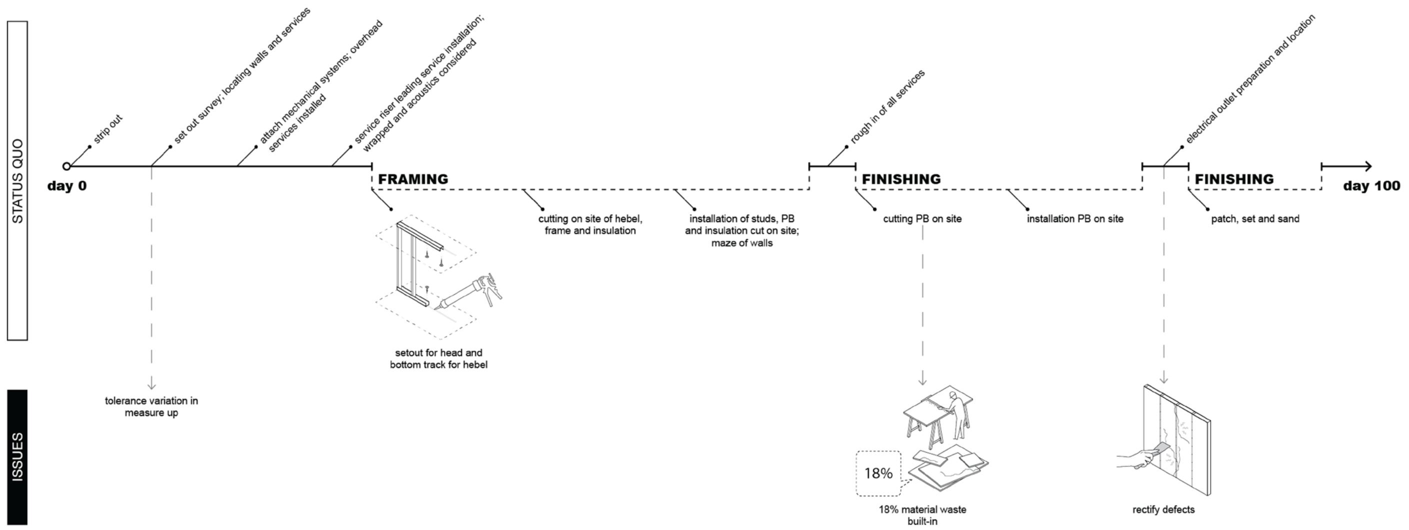
Limitations

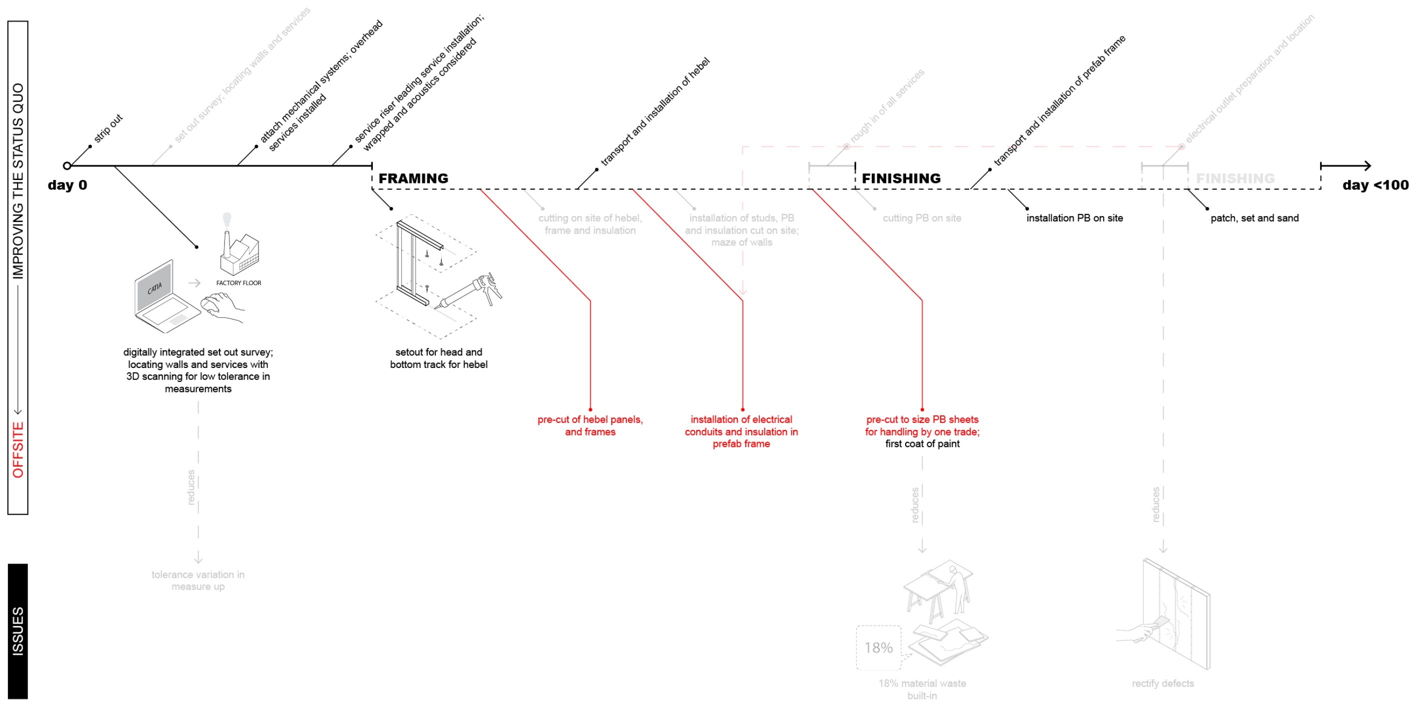
Provocation 1 would not address the issue of serious defects associated with the complexity of achieving performance through BAU approaches to internal walls.



BAU details look the same for *Provocation 1: Improved BAU* but efficiency and handling time is significantly improved through pre-cutting and organisation of services off siite prior to delivery.

Timeline showing sequence of trades to complete fitout in BAU (above) and Improved BAU (below)



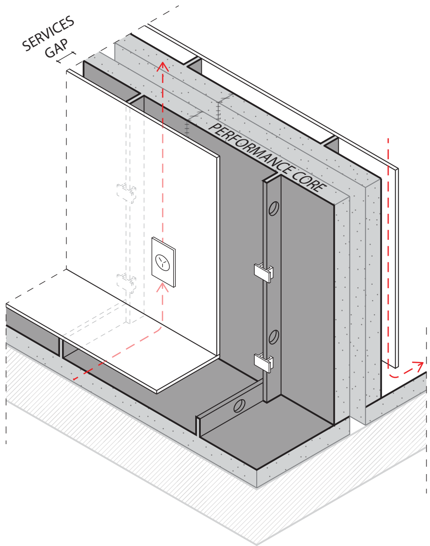


Internal fitout becomes time critical at the end of construction for multi-storey residential buildings, when all other trades are complete - Lendlease referred to this as 'the last 100 days'. Any off site efficiencies to reduce the time for the final floor fitout has potential for significant cost and time benefits. These diagrams demonstrate improvements offered by precutting of materials and off site installation of services.

Provocation 2 - Performance sleeve

This provocation is based on the concept of an inner material layer which achieves all performance requirements and is not penetrated by services. This approach decouples performance from both surface and services cavity, allowing simplification of fitout sequence and reducing trades responsible for achieving performance.

We tested this provocation through the design of a wall build-up using two layers of Ortech Durra Panel - a compressed straw panel which achieved all performance requirements according to University of Melbourne testing (see Appendix 7.2). Over this base wall achieving performance, a cavity created through non-structural steel battens holds services and a surface panel fulfills a finishing role only.



Sketch showing the concept of a performance sleeve, where performance is decoupled from both the services cavity and the finished surface.

Findings

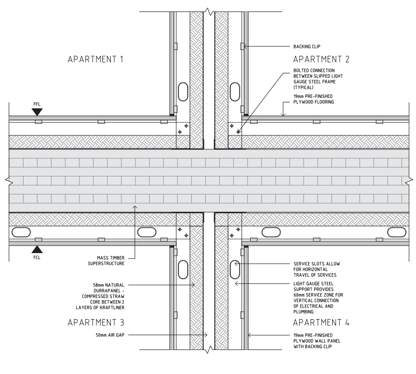
The research noted a performance sleeve could have significant benefits but identified barriers to what would constitute quite a significant shift from BAU approaches.

Opportunities

- A performance sleeve could make significant improvements to reducing serious defects, for example those associated with fire and sound separation.
- Services installation and subsequent finishing could be streamlined by reducing penetrations through performance layers.
- New bio-materials such as strawboard have potential as a performance sleeve due to the way they perform in fire, sound and thermal protection.
- The notion of a sleeve, which continues part or full way across the ceiling and floor, has potential to address flanking issues - particularly relevant in timber or steel structural applications.
- Decoupling performance from the surface layer and services has potential to improve defects rectification, as well as to repair and alter aspects of interiors.

Barriers

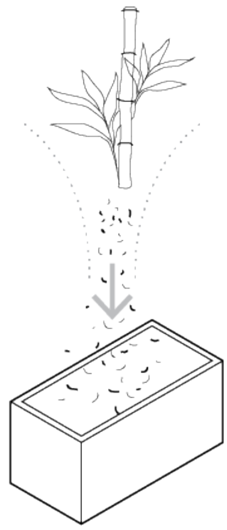
- The sleeve constitutes a significant shift from BAU, raising questions about its viability relating to existing skills and practices within the industry. Potentially this may require a separate installer (as is the practice for Durra Panel).
- The overall thickness of the wall including a performance sleeve would need to approach current wall thickness to avoid losing too much floor area.
- Costs associated with alternative materials such as strawboard would need to be quantified - a method to factor in value from improvements as described above is likely required to make an argument for a significant shift in logic.
- Performance could be achieved with differing levels of off site logic - more study would be required to understand implications for sequencing etc. Cranage may be required depending on weight of panels etc.



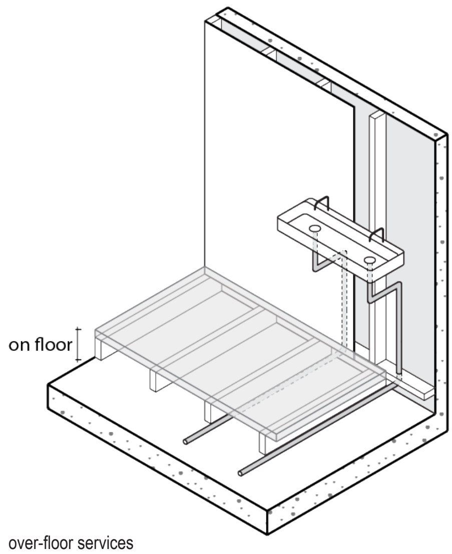
Example detail section of performance build up using two layers of Durra Panel separated with an air gap. The performance layer is shown here continuing along floor and ceiling to deal with flanking issues. Finishing sleeve is composed of plywood sheeting.

Limitations

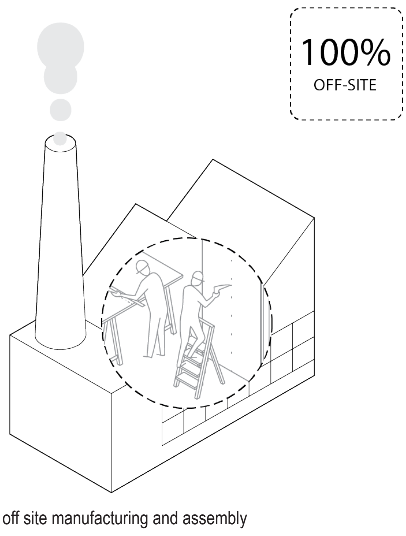
The performance wall system shown here is designed to address issues with inter-tenancy walls only. Further research could relate to partition wall build-ups.



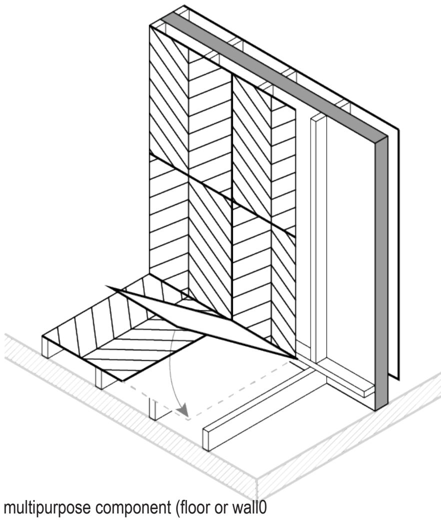
enhanced new materials



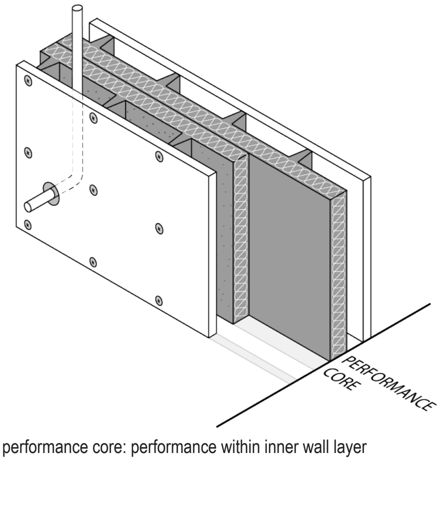
over-floor services



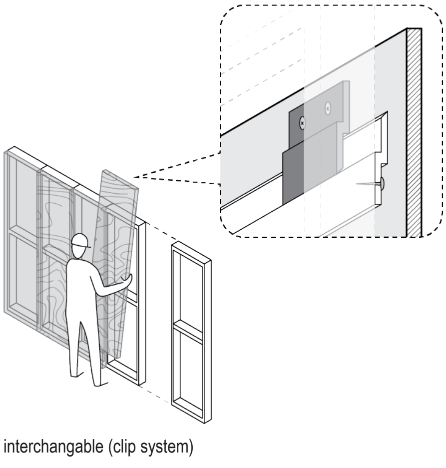
fully off site manufacturing and assembly



multipurpose component (floor or wall0



performance core: performance within inner wall layer

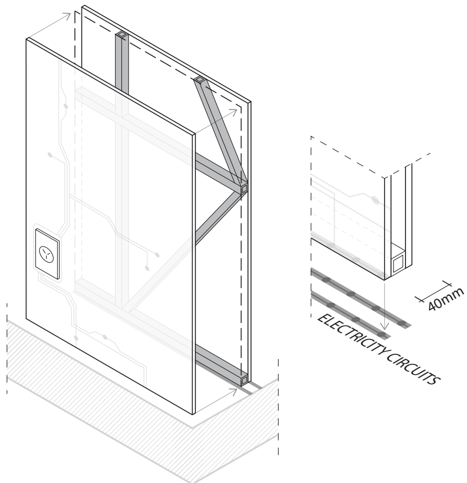


interchangable (clip system)

Key principles for the performance sleeve provocation: fire, thermal and acoustic comfort are achieved by wrapping the inner wall or ‘performance core’ with a finishing ‘sleeve’; services penetrations cut holes into finishing surfaces only.

Provocation 3 - Plug and play

Provocation 3 recognises that not all internal walls are equal - intra-tenancy walls are free of many of the performance and property requirements that inter-tenancy walls must achieve. The plug and play option exploits the potential freedom of partitions from services with the exception of electrical and pushes these partitions to be as thin, light and flexible as possible. We tested this provocation through the design of a hollow steel framed partition with low current electric circuits installed on the inner face of the metal panel infill.



Sketch showing how a 'plug and play; wall could be achieved through a steel frame and clad solution.

Findings

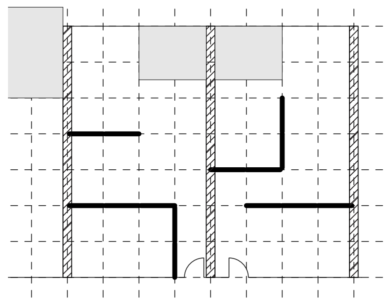
The research found this option could deal with issues of waste by proposing a product that retains residual value over time because it can be reused, repaired and adapted rather than demolished and constructed anew. This product could be particularly focused towards build-to-rent options where longevity is valued, and walls may be reconfigured to suit changing households over time.

Opportunities

- This option reduces waste on site, and over time by implementing a product style system that retains value. This may be particularly suited to scenarios where longevity is valued such as a build-to-rent situation.
- It increased flexibility of interiors over time, allowing for layouts to be re-configured.
- Like fixtures, this design can be easily removed, upgraded, replaced or changed.

Barriers

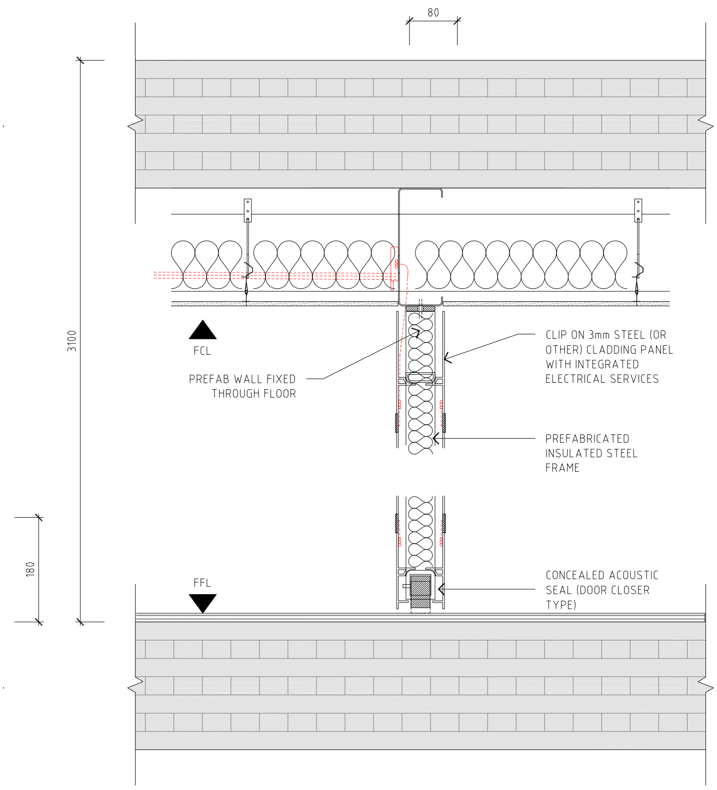
- While flexible and upgradeable solutions are feasible in commercial situations, given the reasonably static nature of residential interiors, does a flexible system make sense?
- Products based on longevity need a corresponding business model to make sense - build-to-rent may provide that context.
- A plug and play solution to electric services would require integration with a ceiling or floor.
- Questions were raised around who would make, own, service and install these specialised products. Do products exist which fulfill similar requirements and could these be tested for residential applications?
- Questions of sound insulation in intra-tenancy walls remain.
- Issues arise between a modular system and a non-modular building design. Would this type of system only work within a modular building or could it be adaptable to site conditions?

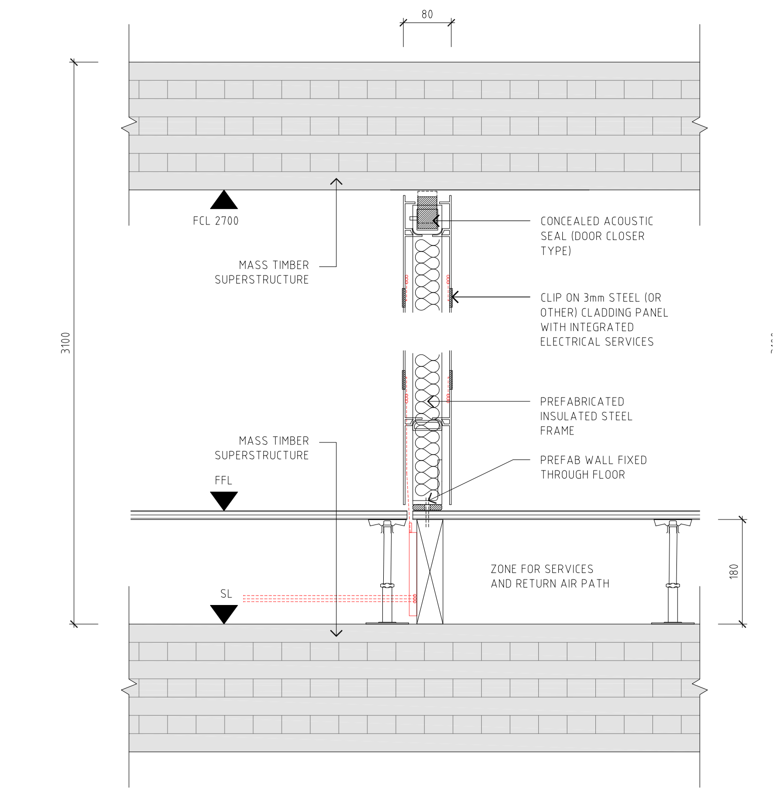


A modular plug and play solution would require apartment layout to be designed to accommodate.

Limitations

Provocation 3 deals only with internal partitions. It demonstrates a product based approach to walls as a provocation to consider how questions of longevity may impact how we consider internal walls. However, such a solution requires a dedicated fabricator / third party. Existing solutions could be identified or adapted from other industries such as commercial fitouts.

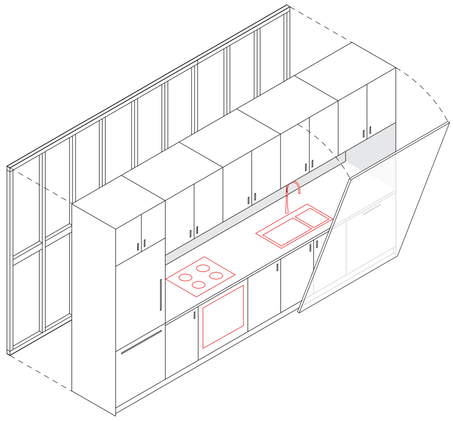




Electrical runs along floor or ceiling can give freedom to wall locations and options for future adaptation.

Provocation 4 - No walls

This provocation is based on leveraging existing pod technology to consider how to eliminate internal walls altogether. Extensive research and development has been given to the topic of services pods, including within the Building 4.0 CRC team. Pods are being utilised in construction across different sectors. This provocation suggests that apartments could be divided by performance enabled pods along party walls, and divided internally by furniture and services pods. We tested examples provided by Lendlease. Some of these were able to be adopted to pod designs.



Could all requirements for internal walls be achieved through pods?

Findings

The research found that division within apartments could be achieved entirely through furniture and services pods - but only within some apartment footprints. Pods for division of interiors would also face similar challenges to bathroom pod installation.

Opportunities

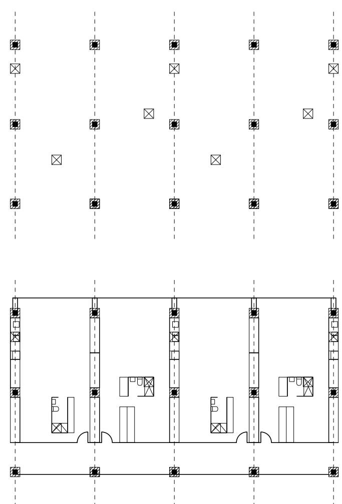
- The completion of interiors entirely through the insertion of serviced and finished pods poses that same potential as bathroom pods - to eliminate a series of difficult and time consuming trades and activities from site.
- As with any completely off-site solution to internal walls, benefits would be gained through reduction of OH&S incidents and waste.
- Serviced pods, if designed to achieve inter-tenancy performance requirements, could address issues associated with on-site performance quality.

Barriers

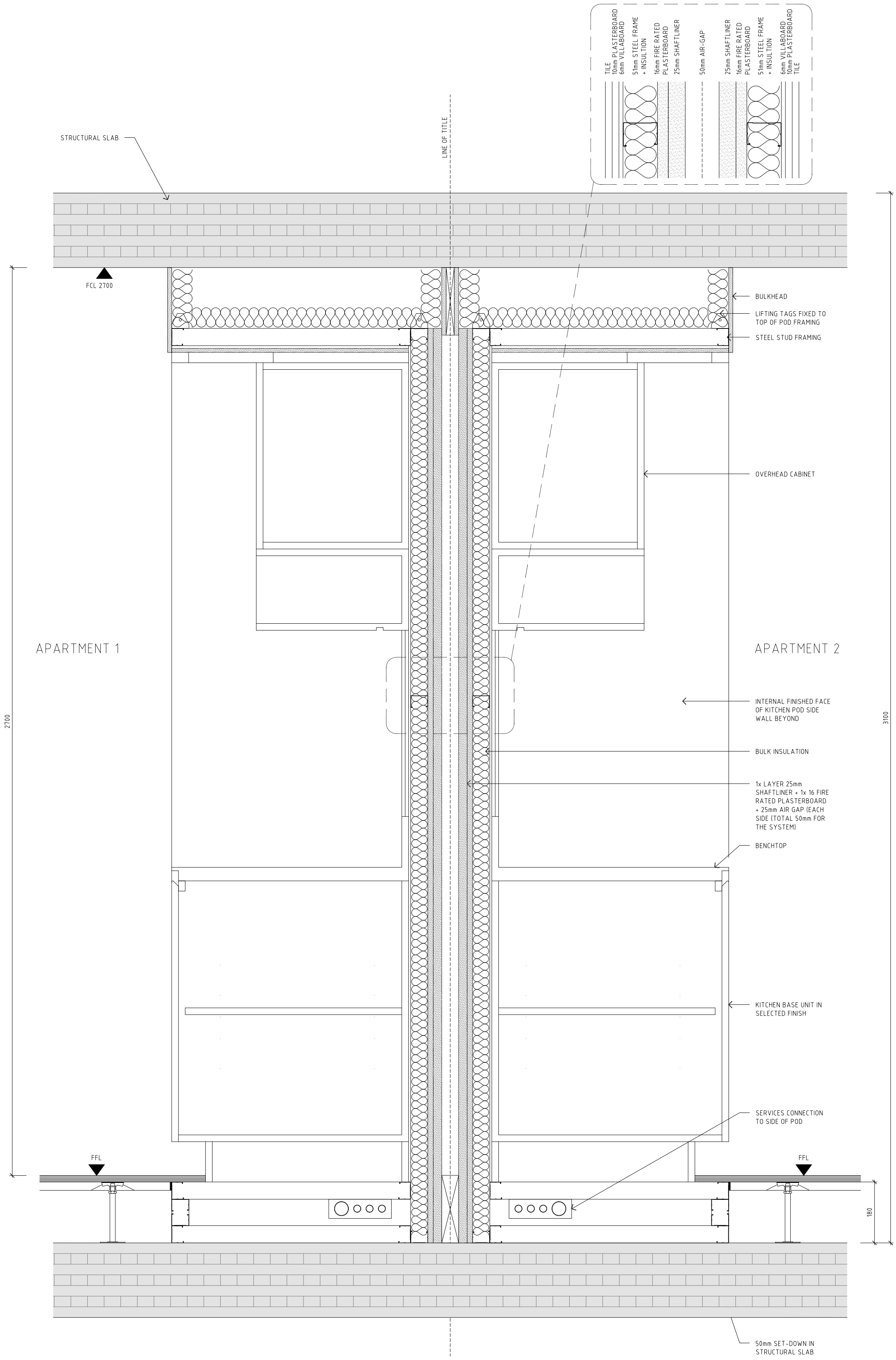
- Significant issues have been identified in the installation of bathroom pods which have prevented successful adoption of this technology across the industry. Project #31 explored these in more detail.
- How compliance is achieved in off-site systems remains unclear. Does compliance still rely on the finishing of junctions to ceiling and floor, and ultimately remain an on-site issue?
- Using pods as a division for apartments only works for some apartment layouts. Apartment design and layout would need to be considered with pods in mind from the beginning of the design phase.

Limitations

No walls deals with multiple issues of internal walls by removing them and replacing them with pods. Like provocation 3, such a solution requires a dedicated fabricator / third party to be viable.



The use of furniture pods would also require apartment design to be adapted to suit.



Back to back kitchen pods can be detailed to provide required performance along inter-tenancy walls, including consideration of raised floors to accomodate services.

6. RECOMMENDATIONS

The findings from section 5 lead to a series of recommendations for future research. A key recommendation is on improving data collection and analysis to provide more targeted and meaningful evidence to support potential improvements to issues such as OH&S and defects. A case based approach to future research would assist in developing such data.

Digital integration across supply chains and with consultants is noted as a key issue for any innovation in componentised wall. The report recommends attention to this aspect in future research.

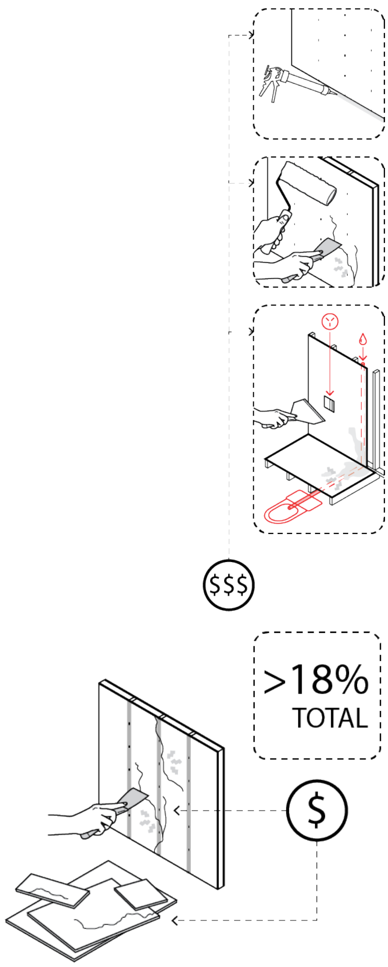
Noting the integrated issues across the supply chain for realising even the most simple of off-site improvements, the report recommends future research include suppliers, manufacturers and organisations 'in the middle' of the supply chain to find meaningful responses to identified barriers.

6.1 Improved collection, categorisation and analysis of data

At the outset of project #28, the plan was to analyse real project data and visit case studies on site to understand issues around defects, OH&S and other factors. This proved difficult, in large part due to COVID restrictions, but also due to the timeframes required to set up such consultations processes with large partner organisations. Literature reviews on identified issues were useful to support in broad terms the issues raised by partner organisations. More meaningful findings though, would be created through analysis of project and/or organisation data.

A key recommendation is to establish a case study approach to future research in which project data from partner organisations can be analysed across the lifespan from design through to construction. Specific data around the costs of current issues will support the argument for a shift to componentised walls, and provide the inputs to develop a costing model which is able to factor in the long-term and ongoing costs of particular approaches to internal walls. Such an approach should be supported by a framework to provide consistent metrics and a database to provide industry wide access. Specific data which would assist includes:

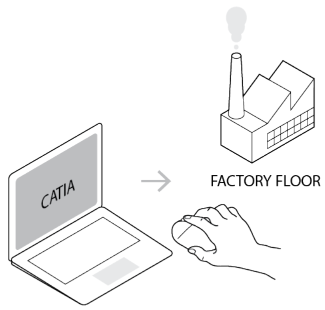
- OH&S incidents catergorised by activity. This can assist in comparing on-site and off-site potentials for OH&S improvements.
- Defects catergorised by type, location and impact from defects rectification period, as well as over the lifespan of the building warranty. This can assist in isolating the number and seriousness of defects associated with internal wall construction.
- Project mapping of procurement decision making - who, when and how are decisions about material supply made. This type of information may be best understood by following a 'live' project in the procurement phase.
- Mapping of critical path planning to understand the relationship of activities associated with internal walls and when they are, or are not on the critical path in construction. Attention is also required on crane time to understand implications for larger pre-assembled components to be lifted.



6.2 Attention to digital processes

A repeating issue arising from the provocations was the need for digital integration for the implementation of any form of off-site construction. An important recommendation therefore is a survey of partner organisations to understand Building Information Management (BIM) currently in place, and to what extent consultants and suppliers are connected to these platforms. Key questions in relation to this survey include:

- When are BIM platforms used by partner organisations in the construction process, i.e. is it part of the design, documentation and ordering process and how it is connected, if at all, to costing models and procurement of building elements?
- Who is connected to BIM platforms? Does it extend from designers to consultants, construction managers, suppliers and manufacturers?
- What exemplars exist for digital integration across the supply chain and what can we learn from these examples?

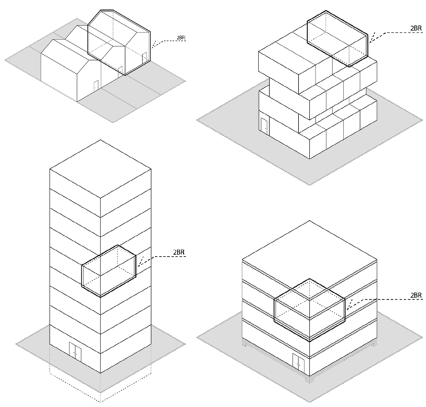


More research is required to understand existing and possible innovations with digital integration.

6.3 Expanded design research and prototype testing

Design research allowed the testing of example componentised walls at the level of the system and detail. An expanded approach would build on this basis including:

- Test componentised systems within existing / proposed (real examples) building plans in different types of residential buildings to understand implications for layout, dimensionality and detailing.
- Apply specific componentised walls to different structural conditions including concrete, timber and steel frame options
- Work through provocation 1 - improved BAU - with reference to a specific project with attention to when decisions are made regarding supply of materials.
- Establish comparative models for build-to-sell and build-to-rent conditions. How does this shift the requirements and investment in internal walls?
- Explore existing and local componentised wall options against partner projects. How do costs stack up in relation to BAU? What are the issues when componentised systems meet BAU on-site conditions?

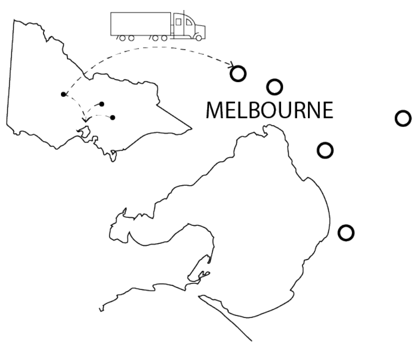


Expanded design research will test different building typologies and structure models.

6.4 Partners across the supply chain

An essential aspect of the research is the recognition that that any initiatives to increase off-site processing of walls or to install componentised systems will rely on others in the supply chain. This may include manufacturers of base components, sub-contractors who assemble systems and components and also suppliers and installers. For this project, key partners may include:

- Plasterboard manufacturers
- Steel stud manufacturers
- Suppliers of wall systems (Rondo, Knauf etc.)
- Manufacturers of associated products including insulation, fire seals, fixings and others who contribute to the overall performance of internal walls.



The interconnected nature of internal wall construction will benefit from expanding partners across the supply chain.

Endnotes

1 Malindu Sandanayake et al., "Residential building defects investigation and mitigation – a comparative review in Victoria, Australia, for understanding the way forward," *Engineering, Construction and Architectural Management*, Vol. 29 No. 9, (2022): 3689-3711. https://doi.org/10.1108/ECAM-03-2021-0232

2 Nicole Johnston and Sacha Reid, *An Examination of Building Defects in Residential Multi-Owned Properties*, (Melbourne: Deakin University, Griffith University, 2019).

3 OH&S issues associated with plasterboard are outlined in: Department of Justice and Attorney-General, Workplace Health and Safety Queensland, *Manual handling plasterboard: Campaign report* (State of Queensland: 2013).

4 Safe work Australia, *Work Health and Safety Perceptions: Construction Industry* (Canberra: 2015).

5 Plasterboard waste is estimated vary in research but have been estimated to between 10 and 18%. Ana Jiménez-Rivero, Ana De Guzmán-Báez and Justo García-Navarro, "Enhanced On-Site Waste Management of Plasterboard in Construction Works: A Case Study in Spain," *Sustainability* Vol.9, Issue 3 (2017): 450, https://doi.org/10.3390/su9030450

6 Rayan H. Assaad et al., "Quantification of the State of Practice of Offsite Construction and Related Technologies: Current Trends and Future Prospects," *Journal of Construction Engineering and Management*. (May 2022): 148, 04022055. 10.1061/(ASCE)CO.1943-7862.0002302.

7 Shane Murray, "Design Research: Translating theory into practice," in *Design Research in Architecture: An overview*, ed. Murray Fraser (Farnham, UK: Ashgate, 2013), 95-116.

8 Anecdotal evidence from industry partners, based on Lendlease project experience. This is supported in research, for example: Sandanayake et al., "Residential building defects investigation and mitigation," 3689-3711.

9 Anthony Mills, Peter Love and Peter Williams, "Defect Costs in Residential Construction," *Journal of Construction Engineering and Management*. 135(1) (January 2009): 12, 16, DOI:10.1061/(ASCE)0733-9364(2009)135:1(12)

10 Sandanayake et al., "Residential building defects investigation and mitigation," 3689-3711.

11 Sandanayake et al., "Residential building defects investigation and mitigation," 3689-3711.

12 Hefferman, M. Victoria won't follow NSW on building defects reform, The Age, January 18, 2022

13 Johnston and Reid, *An Examination of Building Defects*.

14 Johnston and Reid, *An Examination of Building Defects*, 30.

15 Duane Roskoskey, *Drywall Recycling Management Guide*. (Michigan: Michigan Department of Environmental Quality, 2007).

16 Joe Pickin et al., *National Waste Report 2020* (Docklands: Department of Agriculture, Water and the Environment; Blue Environment, 2020). This estimate excludes mining and other industrial wastes for which little data is available. Mining waste is estimated to be around 500Mt, seven times that of Australia's general waste.

17 The waste hierarchy developed from the European Union Waste Framework in the 1970s and has been widely adopted worldwide to establish priorities for waste management. The principles adopted in Australia's National Waste Action Plan 2019 are based on the waste hierarchy.

18 Science and Technology Select Committee, *Off-Site Manufacture for Construction: Building for Change* (London, UK: House of Lords, 2018).

19 "Recycling Modernisation Fund," Department of Climate Change, Energy, the Environment and Water, Australian Government, https://www.environment.gov.au/protection/waste/how-we-manage-waste/recycling-modernisation-fund/state-territory-agreement-announcements

20 Department of Sustainability, Environment, Water, Population and Communities, *National Waste Policy Case Study: CSR Gyprock™ take-back scheme for gypsum board product* (Commonwealth of Australia: 2011).

21 "Cross-industry joint venture to build new plastic recycling facility," Cleanaway, 2021, https://www.cleanaway.com.au/sustainable-future/cross-industry-jv-plastic-recycling-facility/

22 "National Waste Policy Action Plan 2019," Australian Government, state and territory governments and the Australian Local Government Association, 2019, 1–41. https://www.dcceew.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf

23 Safe work Australia, *Work Health and Safety Perceptions*.

24 Department of Justice and Attorney-General, *Manual handling plasterboard*.

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26 Assaad et al., "Quantification of the State of Practice."

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Jiménez-Rivero, Ana, Ana De Guzmán-Báez and Justo García-Navarro, "Enhanced On-Site Waste Management of Plasterboard in Construction Works: A Case Study in Spain," *Sustainability* Vol.9, Issue 3 (2017): 450, https://doi.org/10.3390/su9030450

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Mills, Anthony, Peter Love and Peter Williams. "Defect Costs in Residential Construction." *Journal of Construction Engineering and Management*. 135(1) (January 2009): 12, 16, DOI:10.1061/(ASCE)0733-9364(2009)135:1(12)

Murray, Shane. "Design Research: Translating theory into practice." in *Design Research in Architecture: An overview*. Edited by Murray Fraser, 95-116. Farnham, UK: Ashgate, 2013.

Pickin, Joe, Christine Wardle, Kyle O'Farrell, Piya Nyunt, Sally Donovan. *National Waste Report 2020*. Docklands: Department of Agriculture, Water and the Environment; Blue Environment, 2020. http://www.environment.gov.au/protection/waste/national-waste-reports/2020.

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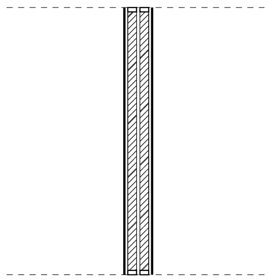
7. APPENDIX

The appendix collects significant bodies of work in relation to key research activities including the detailed drawings and testing of the provocations; the full review of exemplars; performance testing, life cycle evaluation and material costs undertaken by University of Melbourne; the summary of the literature review and a record of interviews and workshops undertaken.

7.1 Provocations: design and assessment

7.1 Provocations: design and assessment

PROVOCATION 1: IMPROVED BAU



Overview

To understand barriers to simple improvements initiatives such as off-site cutting of material.

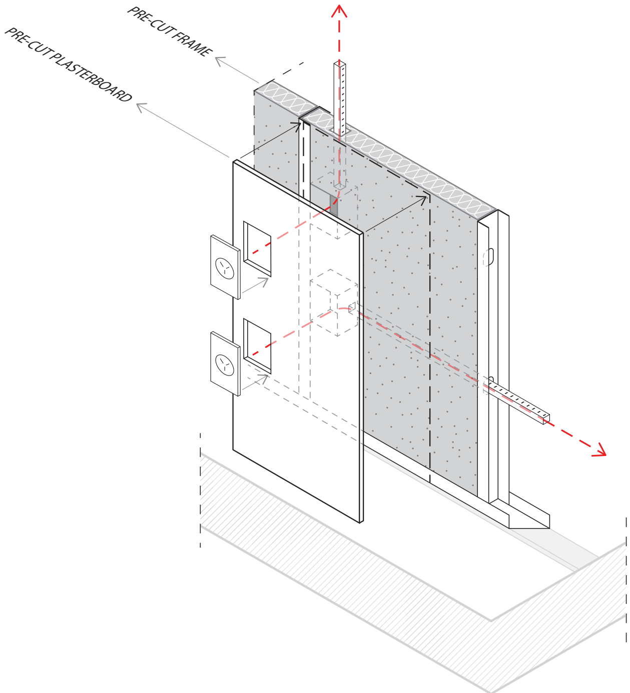
Key Findings

BAU can be improved but there are limits.

Lack of clarity as to why off-site initiatives can't be adopted.

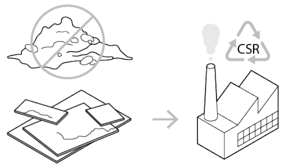
Significant costs exist around decanting, defects and built-in waste but more data is needed.

Partition Wall Type

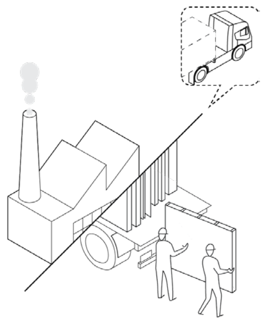


Key Principles

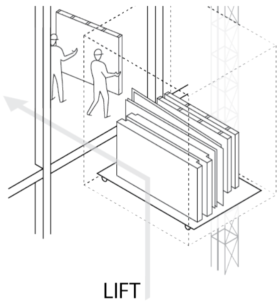
100% plasterboard waste recycled



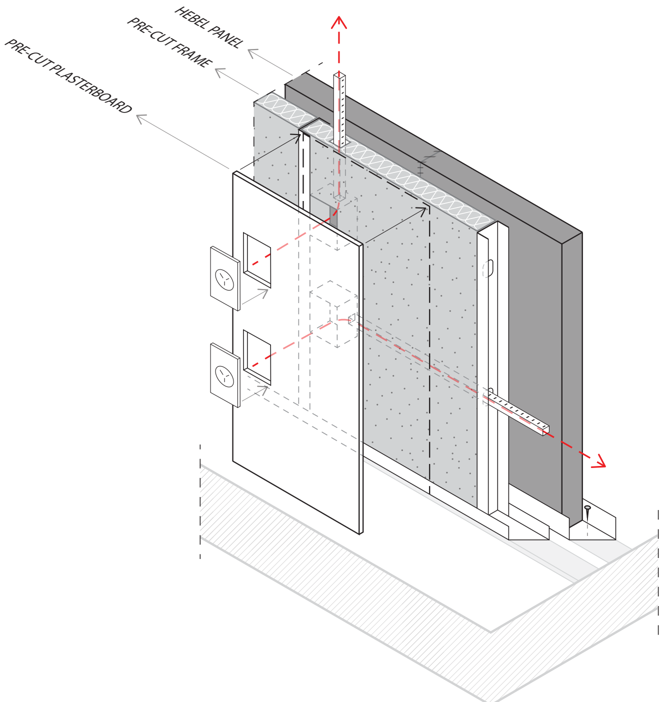
Combination off-site and on-site construction



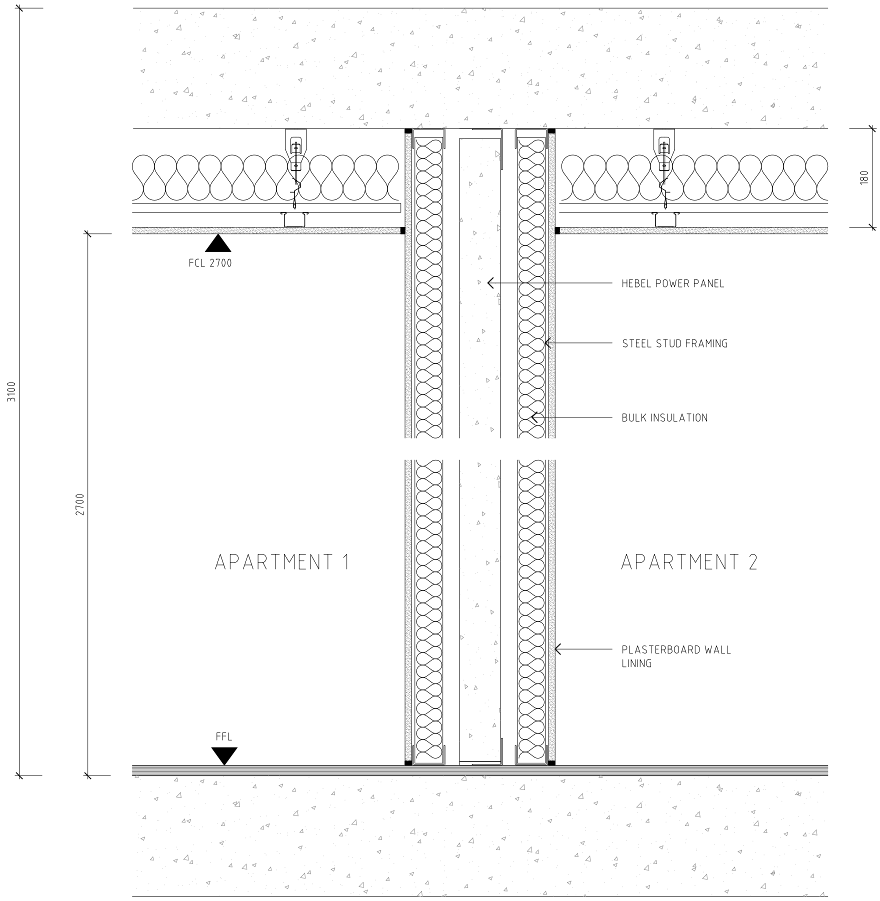
Less manual lifting handling - improved OH&S



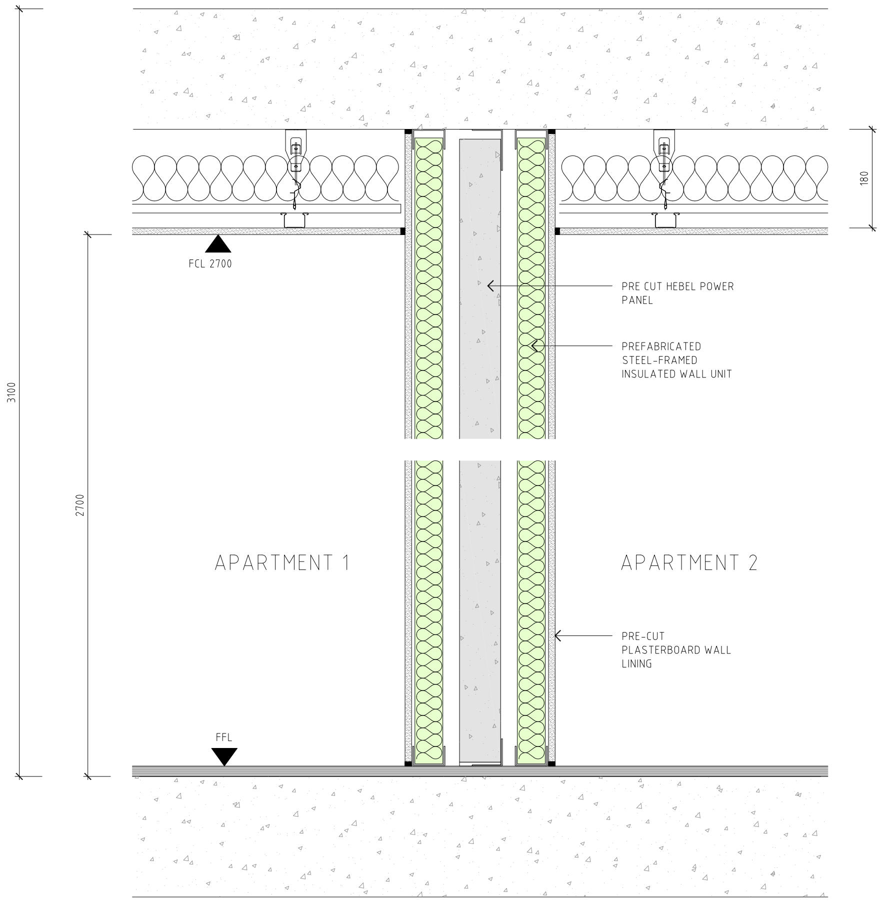
Inter-tenancy Wall Type



Status Quo



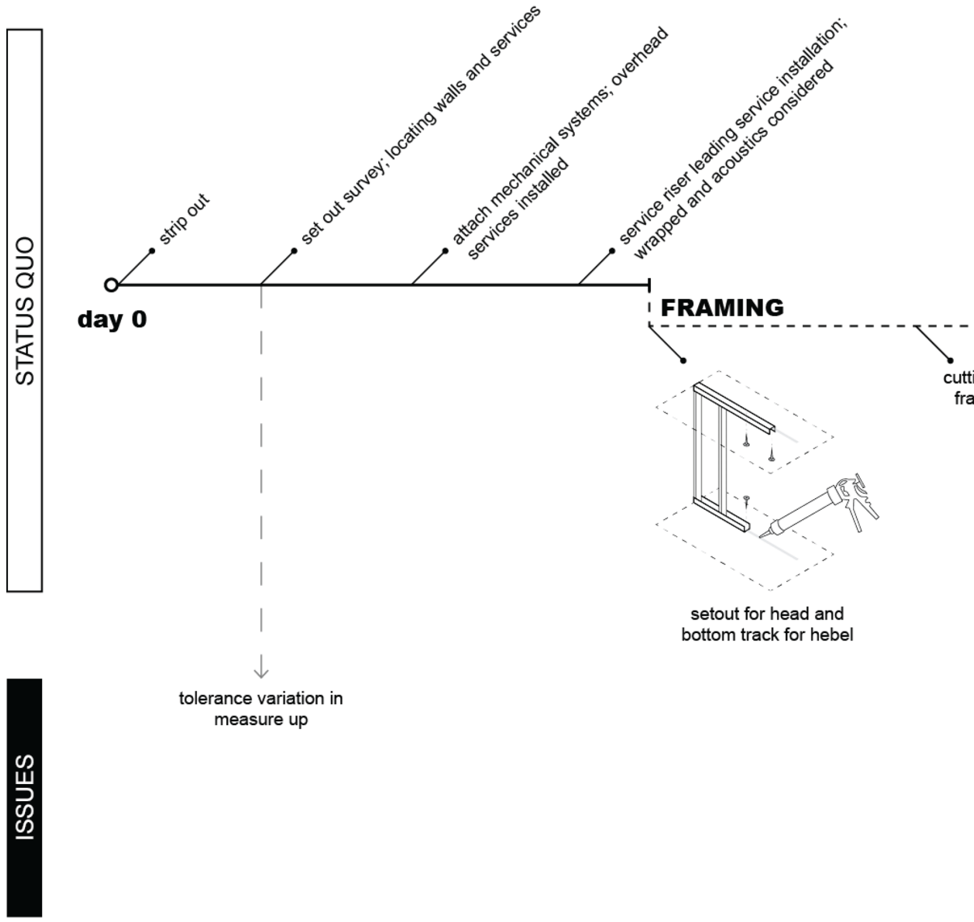
Improved Status Quo



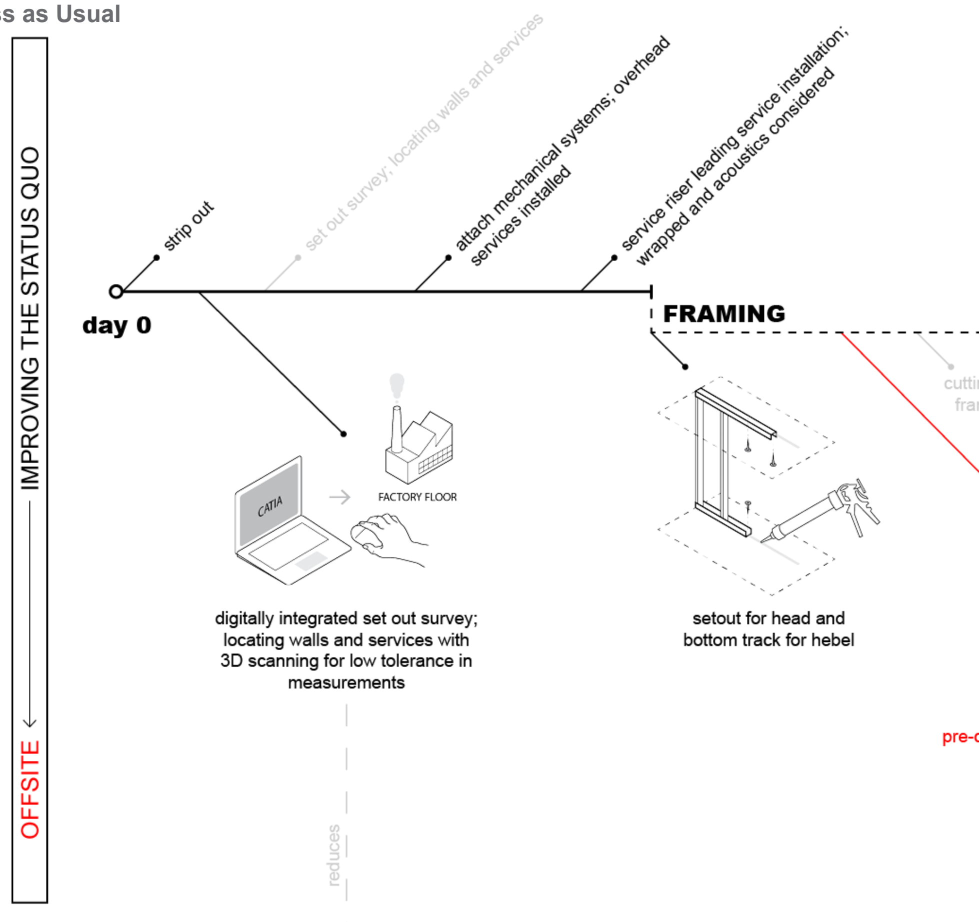
7.1 Provocations: design and assessment

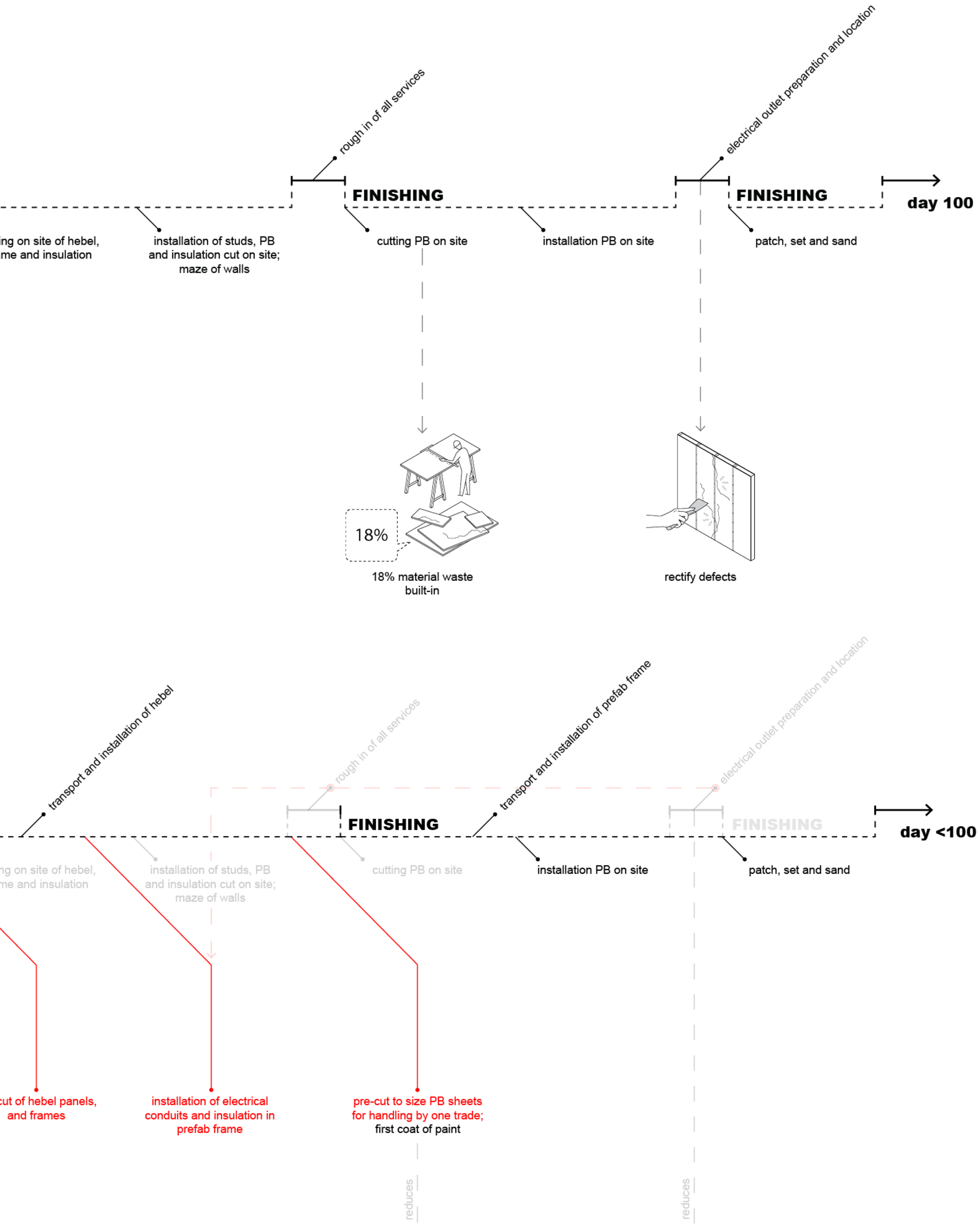
PROVOCATION 1: IMPROVED BAU

Construction Sequencing: Business as usual



Construction Sequencing: Improved Business as Usual

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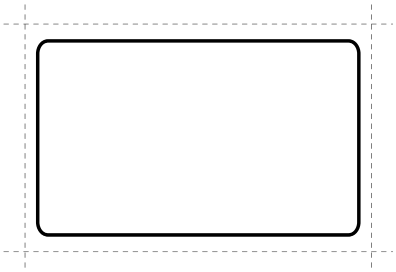
ing on site of hebel,
me and insulation
installation of studs, PB
and insulation cut on site;
maze of walls
cutting PB on site
installation PB on site
patch, set and sand
18%
18% material waste
built-in
rectify defects
transport and installation of hebel
rough in of all services
transport and installation of prefab frame
electrical outlet preparation and location
FINISHING
FINISHING
day <100
ng on site of hebel,
me and insulation
installation of studs, PB
and insulation cut on site;
maze of walls
cutting PB on site
installation PB on site
patch, set and sand
cut of hebel panels,
and frames
installation of electrical
conduits and insulation in
prefab frame
pre-cut to size PB sheets
for handling by one trade;
first coat of paint
reduces
reduces

7.1 Provocations: design and assessment

PROVOCATION 2: PERFORMANCE CORE



Overview

To explore the separation of performance from cladding

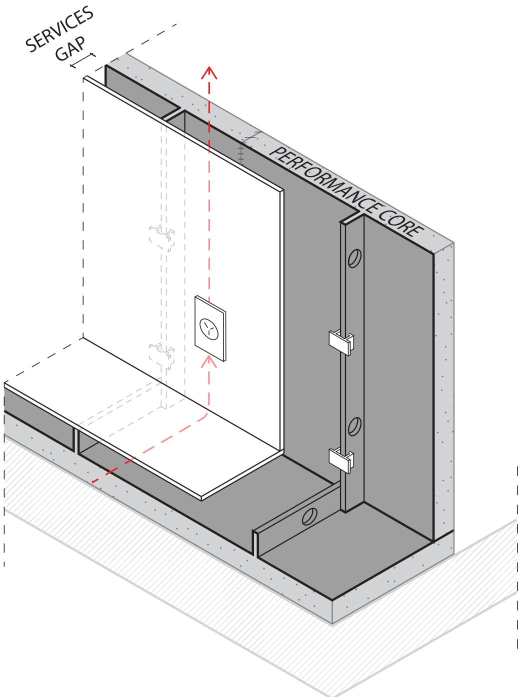
Key Findings

Self-supporting performance materials can reduce wall thickness / eliminate studs

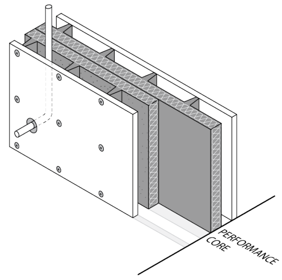
Floor and ceiling junctions are critical ‘failure’ points.

High performance renewable materials exist and are in development.

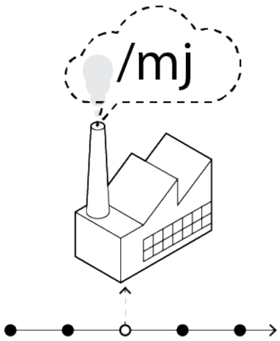
Inter-tenancy Wall Type



Key Principles

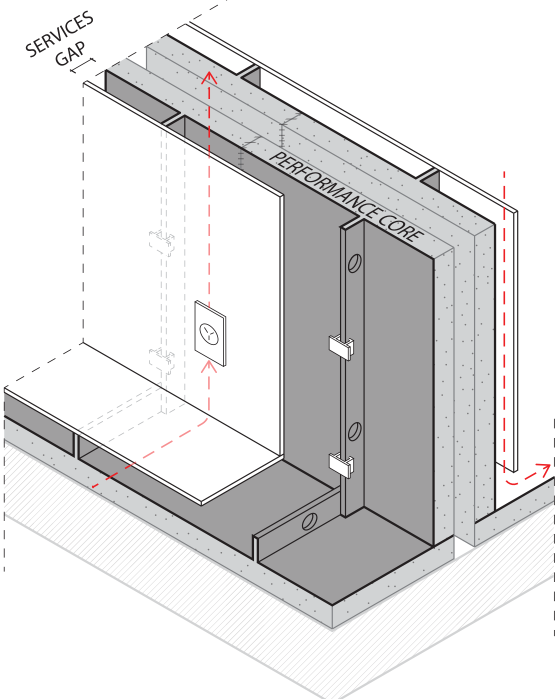


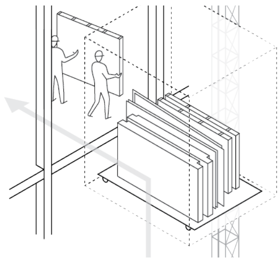
Performance core



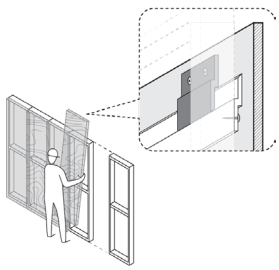
Improved carbon footprint

Inter-tenancy Wall Type



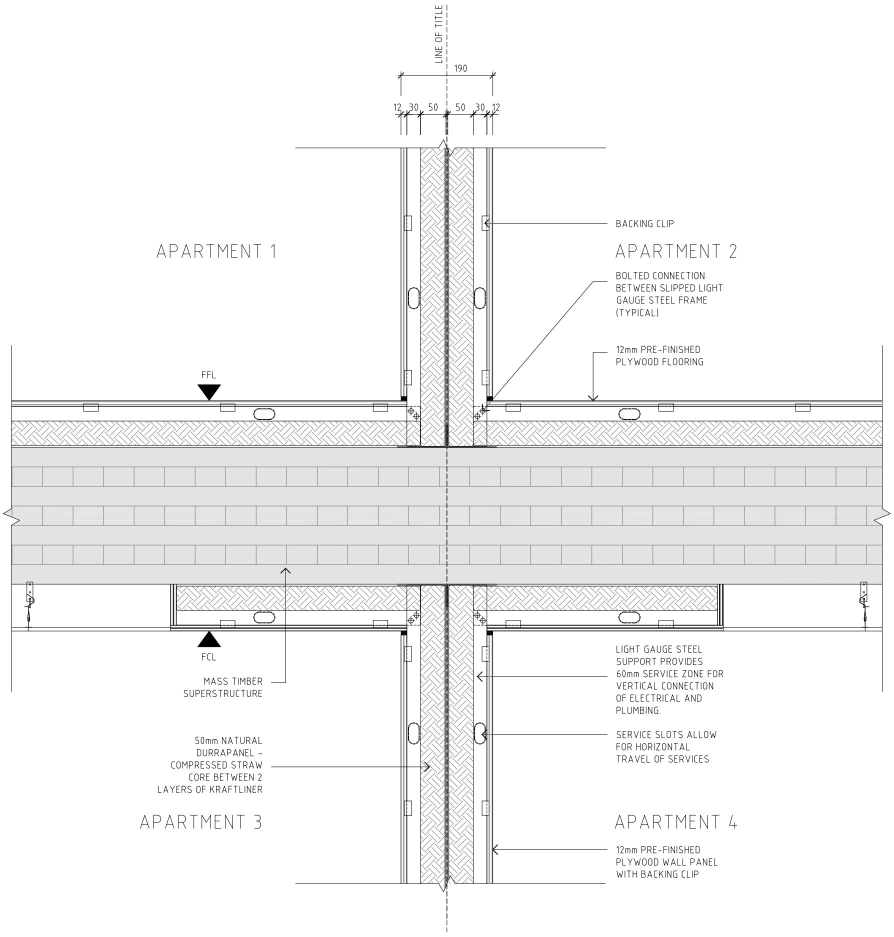


Less manual lifting handling - improved OH&S

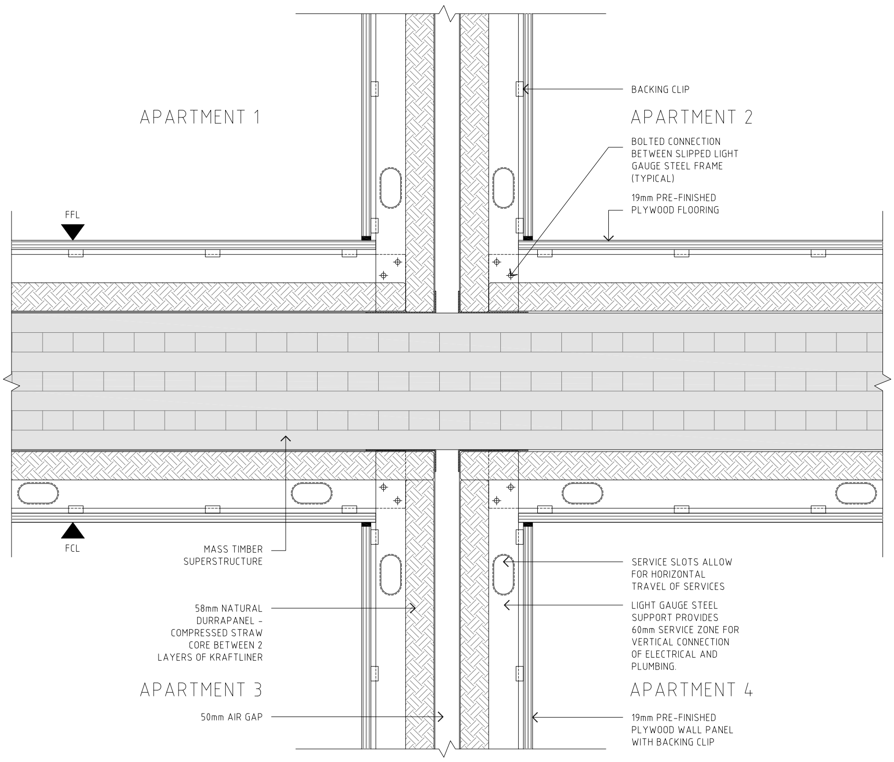


Removable wall panels

Continuous Sleeve Unit with Durra Panel



Continuous Sleeve Unit with Durra Panel



Durra Panel S50

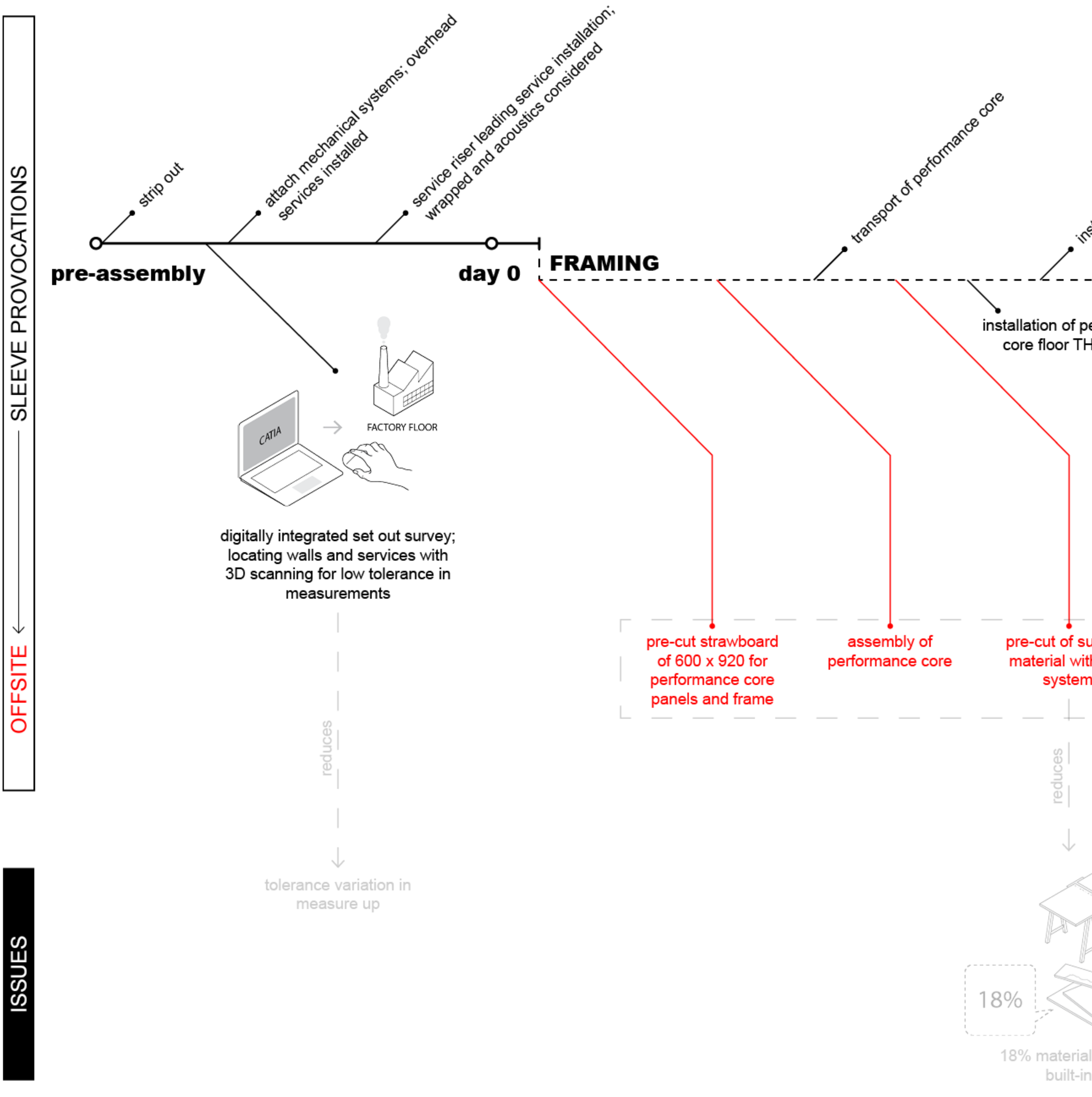
Product Name	Durra Panel S50 Plain
Nominal Thickness	50mm
Weight	18.5 kg/m² (nominal)
Width (Standard)	1187mm
Maximum Length	3600mm
Face Colour	Brown (Kraft liner)
* Strength	Point load 5.8kN
Impact Resistance	High
Thermal Conductivity	0.081 W/mK
Thermal Resistance	0.62 m²W/k
Specific Heat Capacity	1050 J/kgK
Embodied Energy	12.6 MJ/m²
VOC Emission rate (ASTM D5116)	<0.05 mg/m²/hr (7 days)
Biscuit Slots	Available

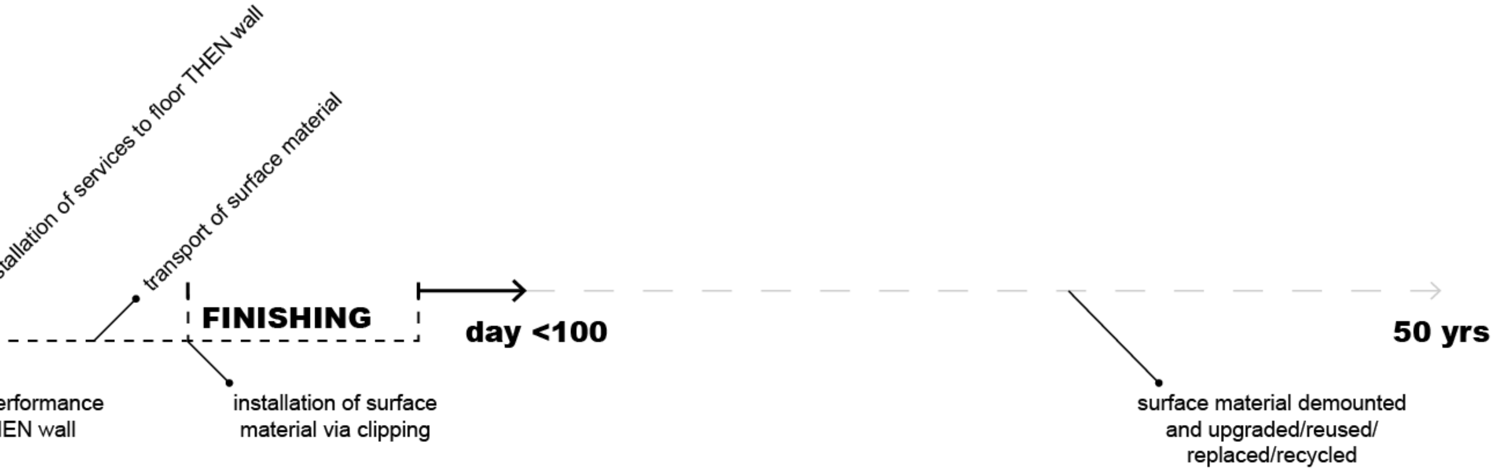
- Provides 60 minutes FR

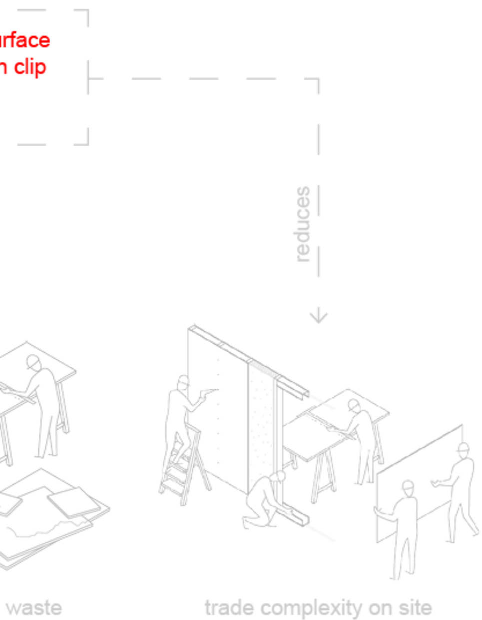
7.1 Provocations: design and assessment

PROVOCATION 2: PERFORMANCE CORE

Construction Sequencing

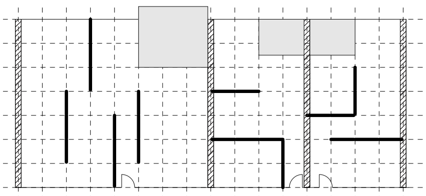



stallation of services to floor THEN wall
transport of surface material
FINISHING
day <100
50 yrs
erformance
IEN wall
installation of surface
material via clipping
surface material demounted
and upgraded/reused/
replaced/recycled

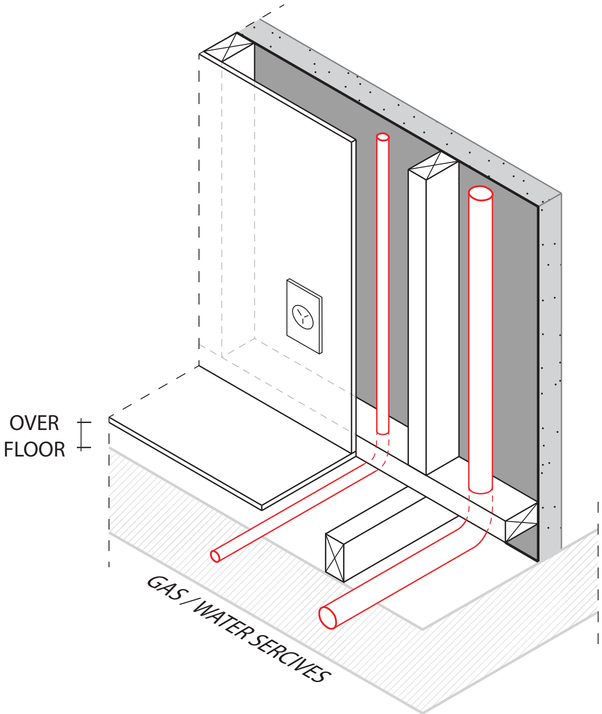

rface
n clip
reduces
waste
trade complexity on site

7.1 Provocations: design and assessment

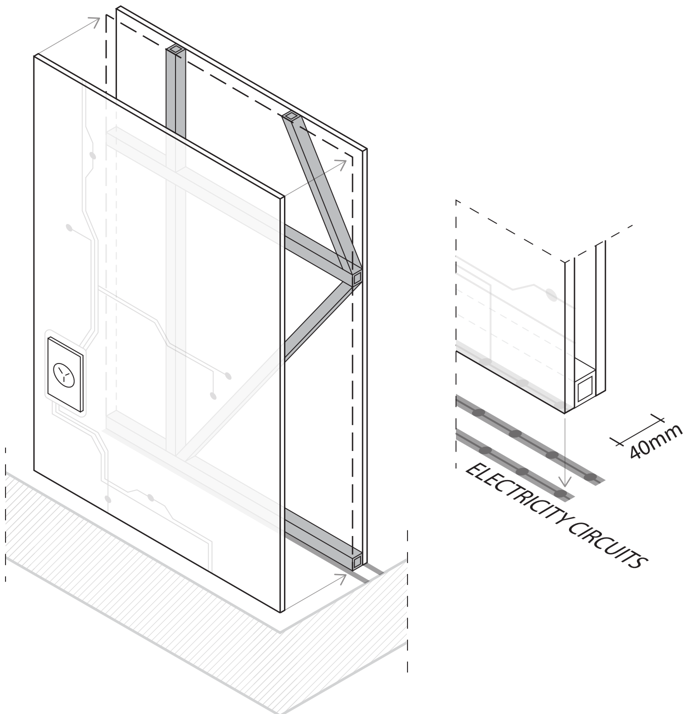
PROVOCATION 3: PLUG-N-PLAY

	Overview	Key Findings
	To liberate internal partitions from wet services, maximum flexibility & minimal wall thickness	Appetite for commercial application. However, would need to be combined with inter-tenancy wall options. Leverages innovations in electrical supply / servicing / monitoring / interfaces. Floor and ceiling junctions are critical for ease of installation and demounting.

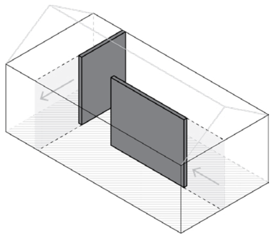
Partition Wall Type



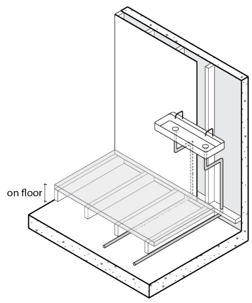
Inter-tenancy Wall Type



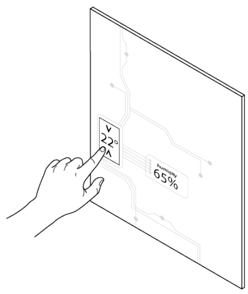
Key Principles



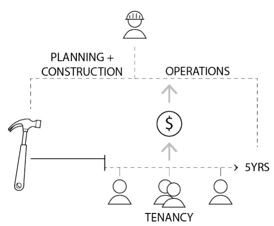
Flexible internal walls



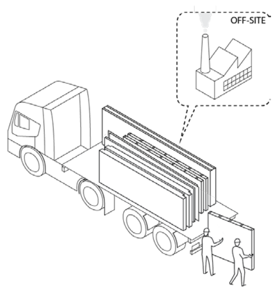
Over-floor services



Tech enabled materials

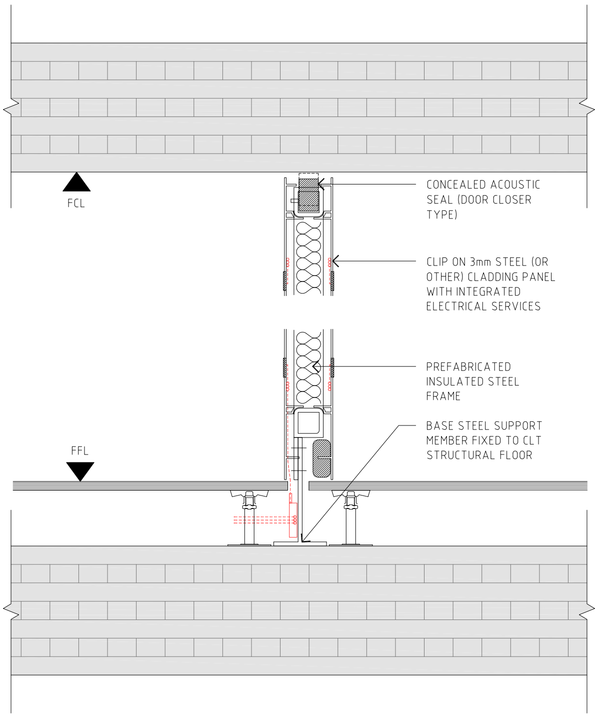


Build to rent models

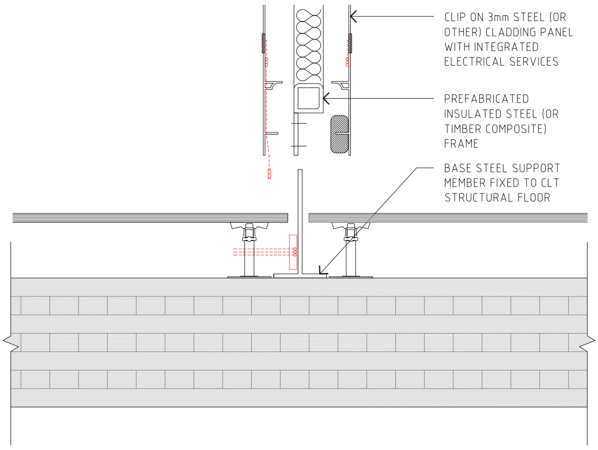


Fully off-site

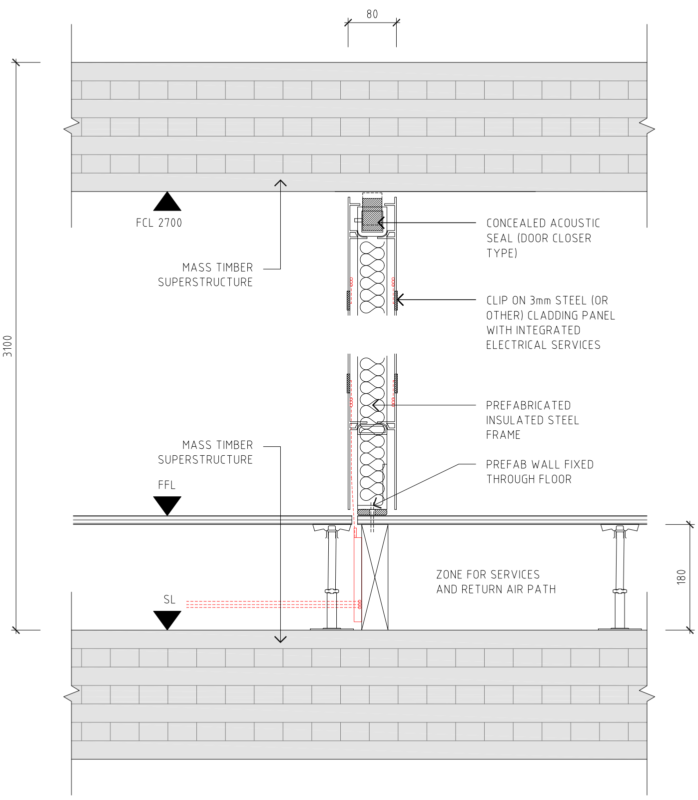
Plug-n-play



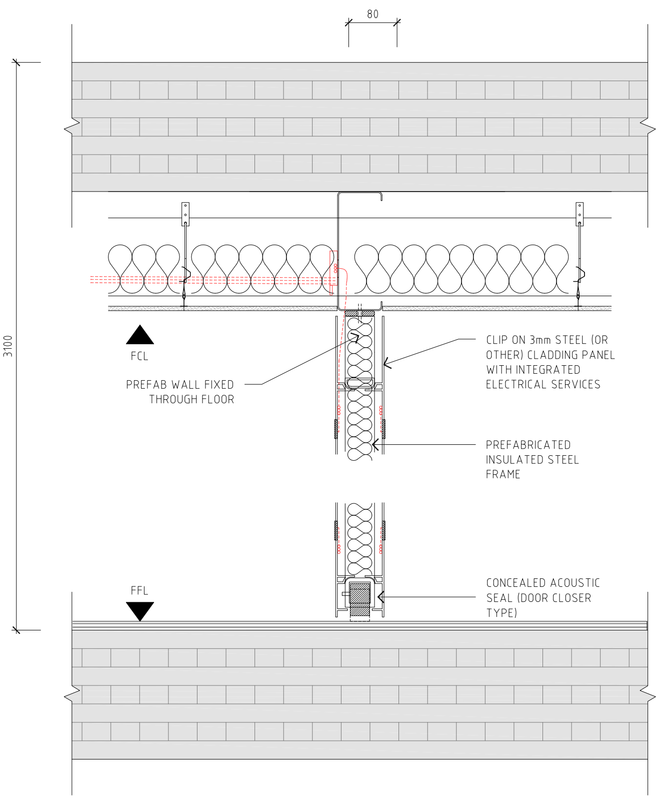
Plug-n-play Exploded View



Plug-n-play Raised Floor



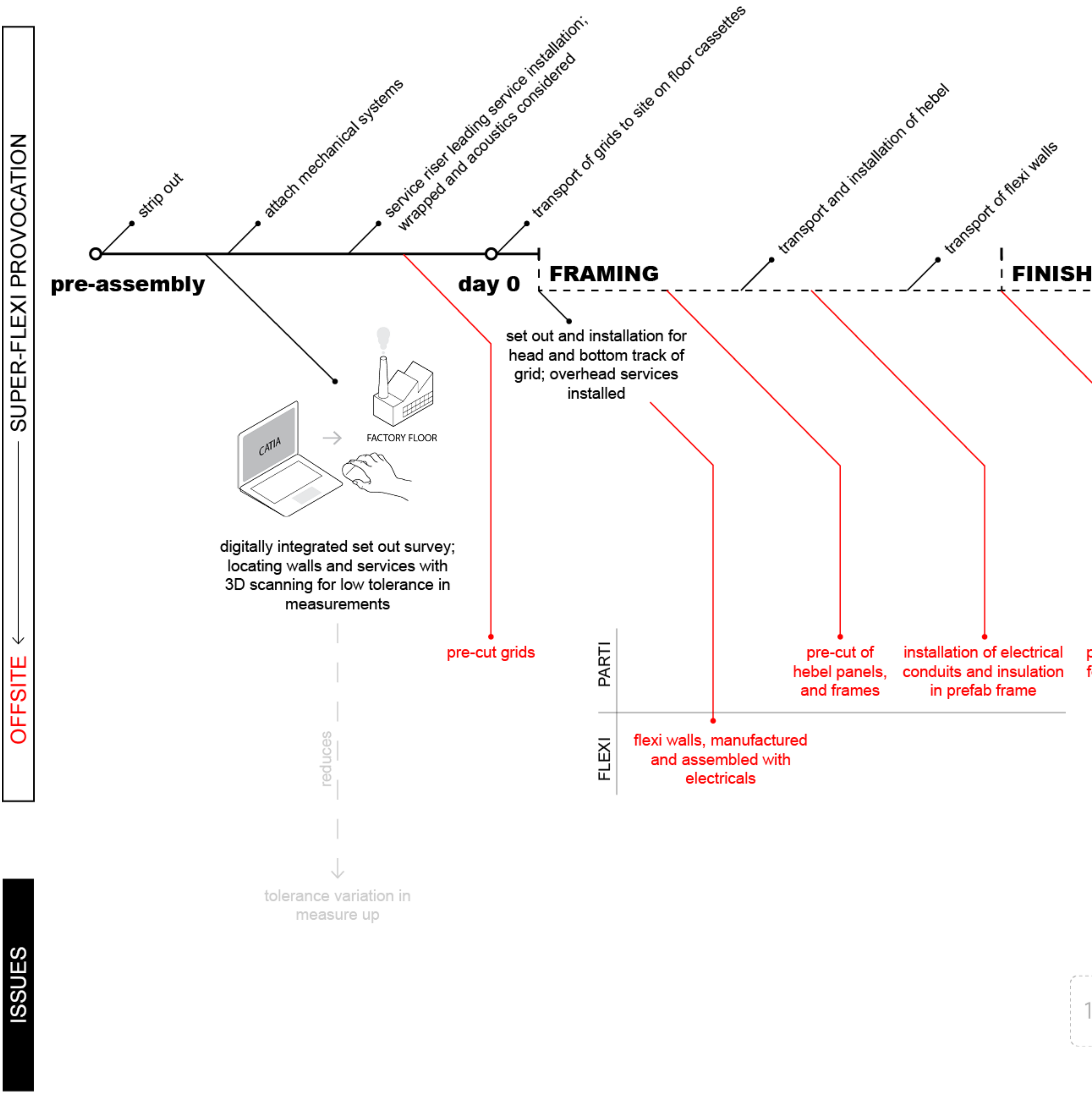
Plug-n-play Suspended Ceiling

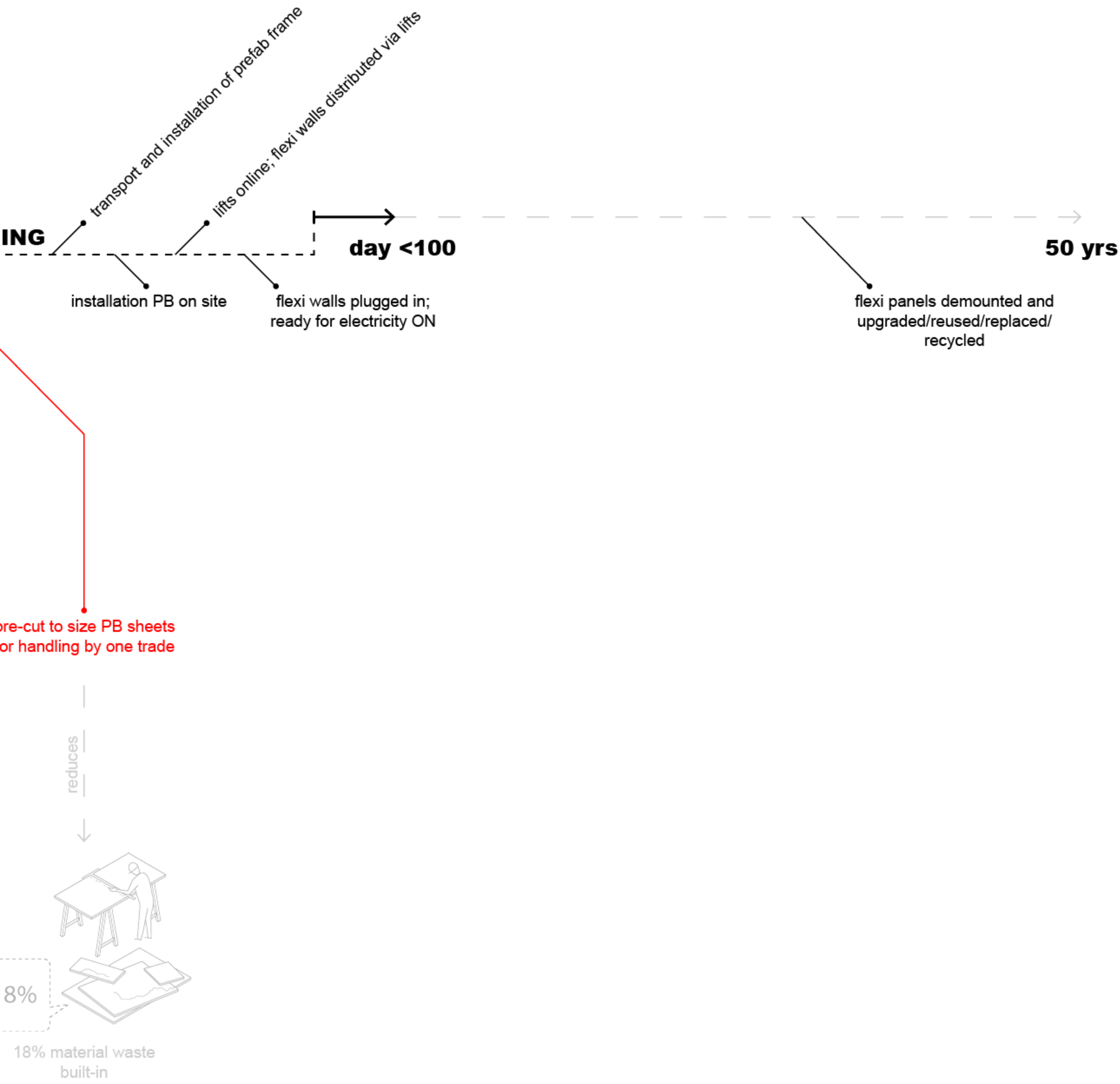


7.1 Provocations: design and assessment

PROVOCATION 3: PLUG-N-PLAY

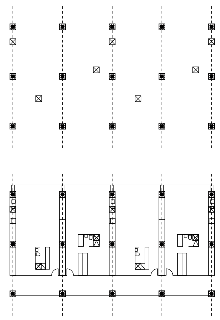
Construction Sequencing: Plug-n-play



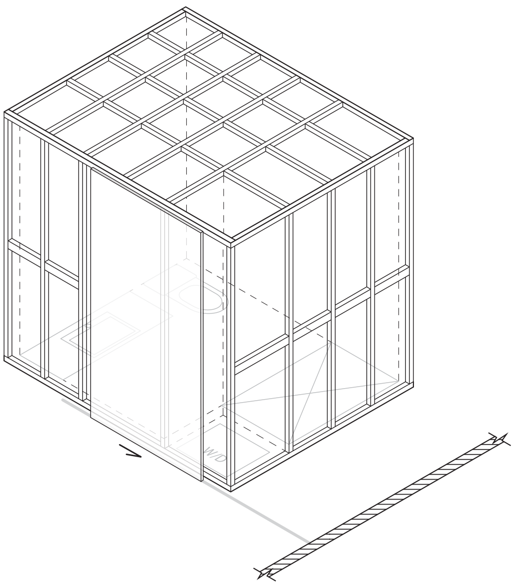

ING
transport and installation of prefab frame
lifts online; flexi walls distributed via lifts
day <100
50 yrs
installation PB on site
flexi walls plugged in;
ready for electricity ON
flexi panels demounted and
upgraded/reused/replaced/
recycled
ore-cut to size PB sheets
or handling by one trade
reduces
8%
18% material waste
built-in

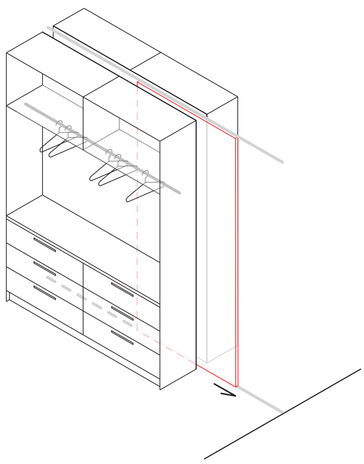
7.1 Provocations: design and assessment

PROVOCATION 4: NO WALLS

	Overview	Key Findings
	To explore the potential of pods & furniture to fulfill requirements of spatial division (eliminating walls)	Eliminating walls by using pods as spatial divisions appears feasible. Pods challenge existing logic of building sequencing. This would need to be resolved to make 'no walls' viable.

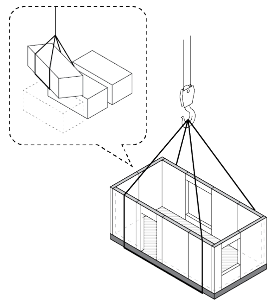
Partition Wall Type



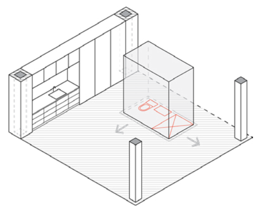


Key Principles

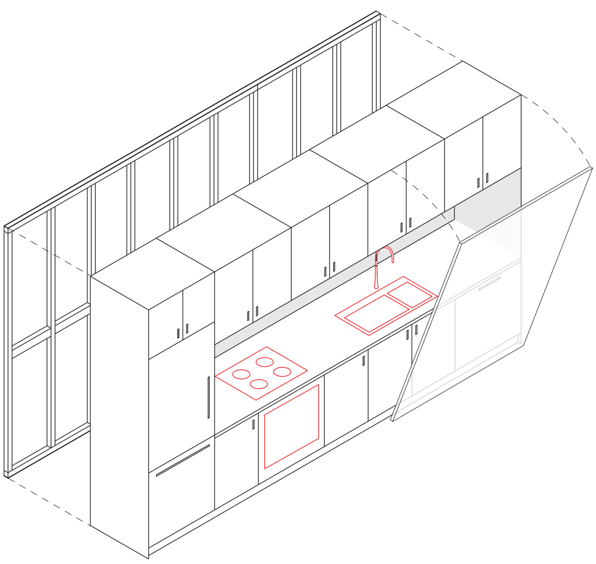
Pod technology

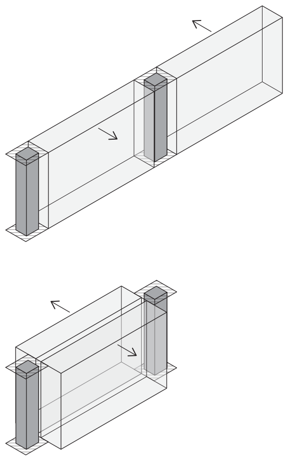


No walls

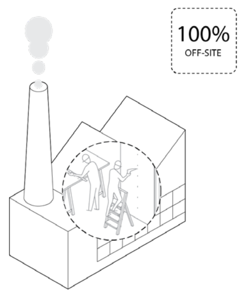


Inter-tenancy Wall Type





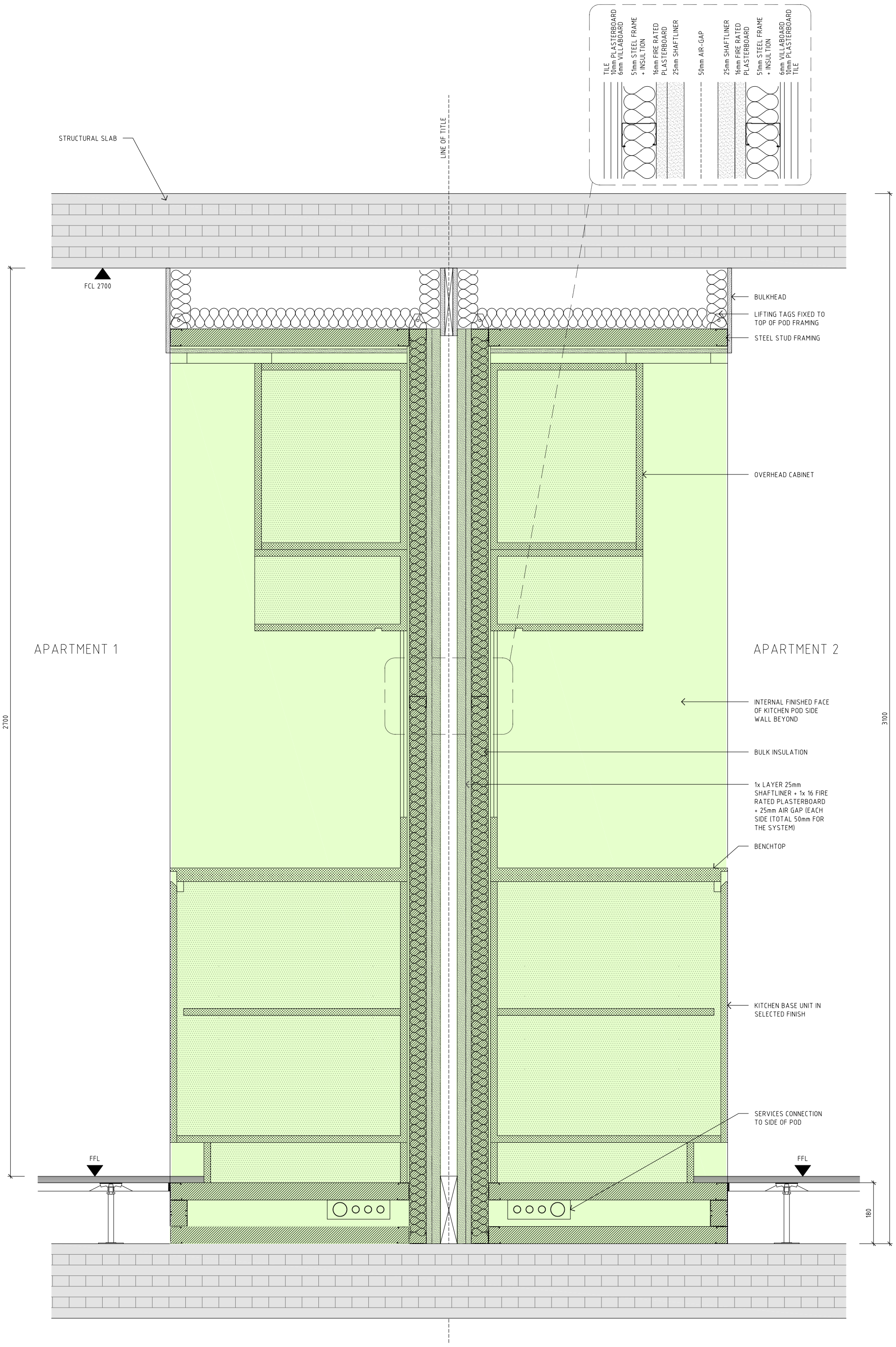
Fully off-site



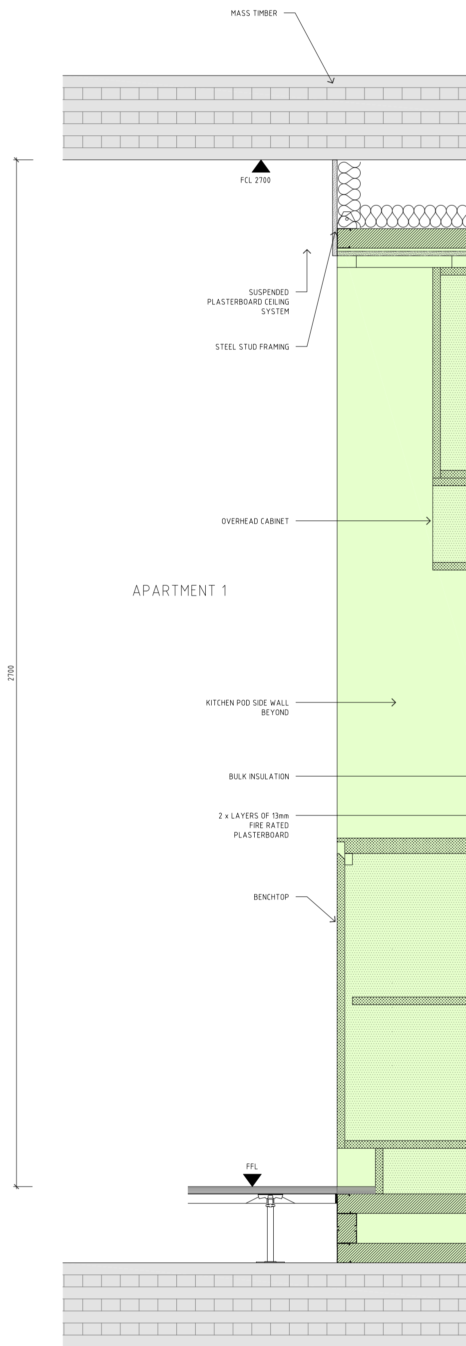
7.1 Provocations: design and assessment

PROVOCATION 4: NO WALLS

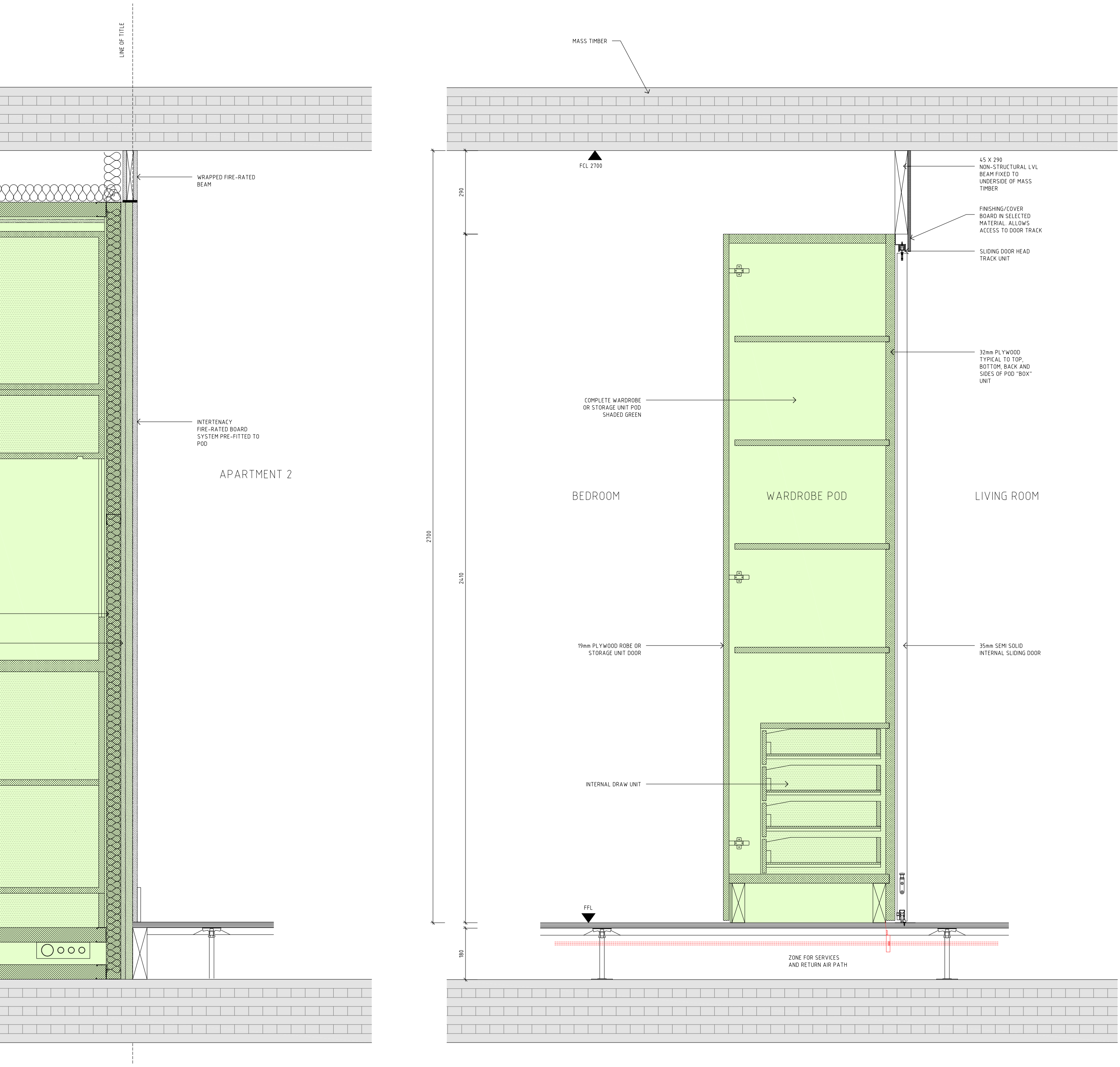
No Walls Back-to-Back Kitchen Pod



No Walls In-Line Kitchen Pod



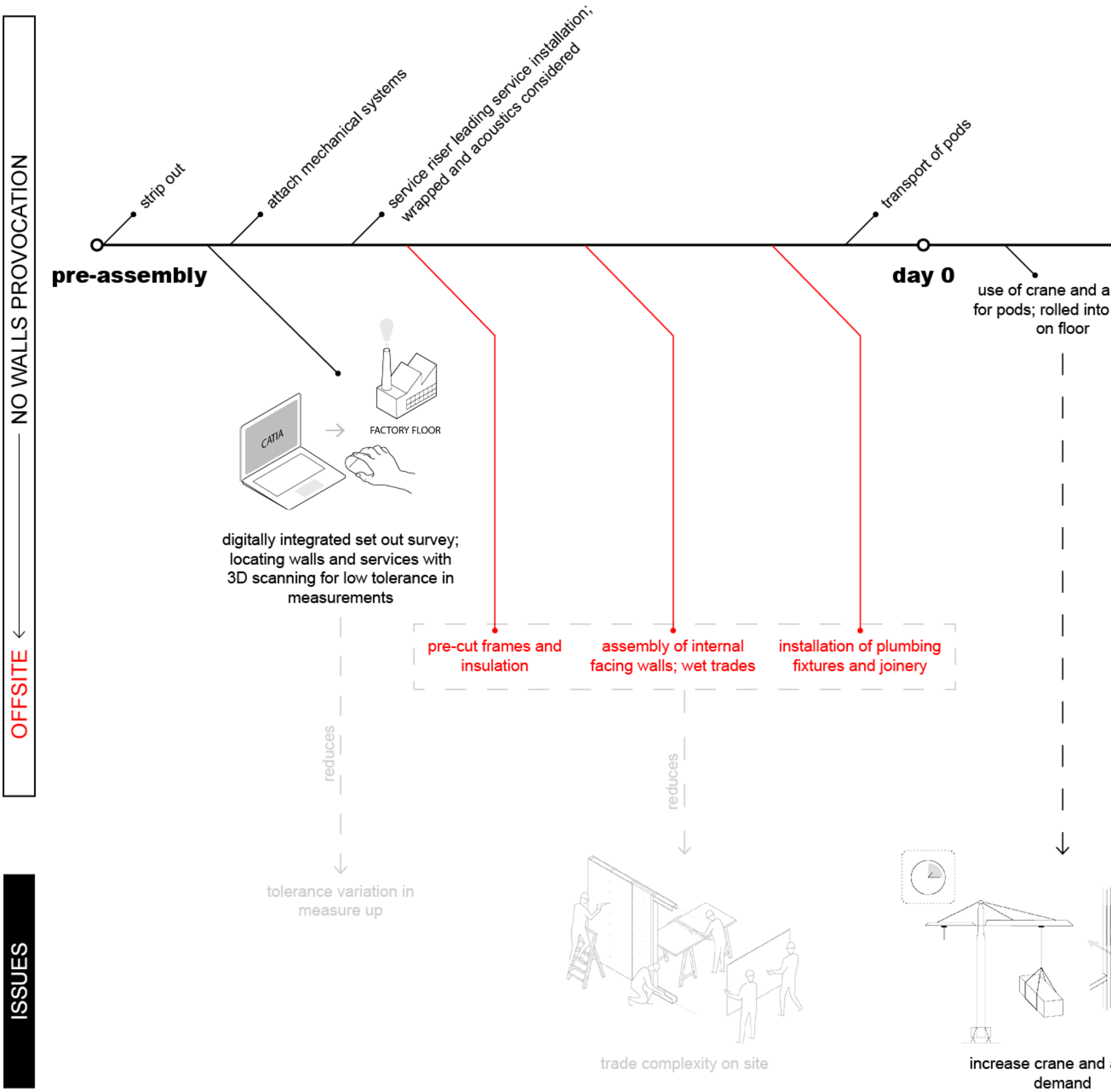
No Walls Robe Storage with Sliding Door

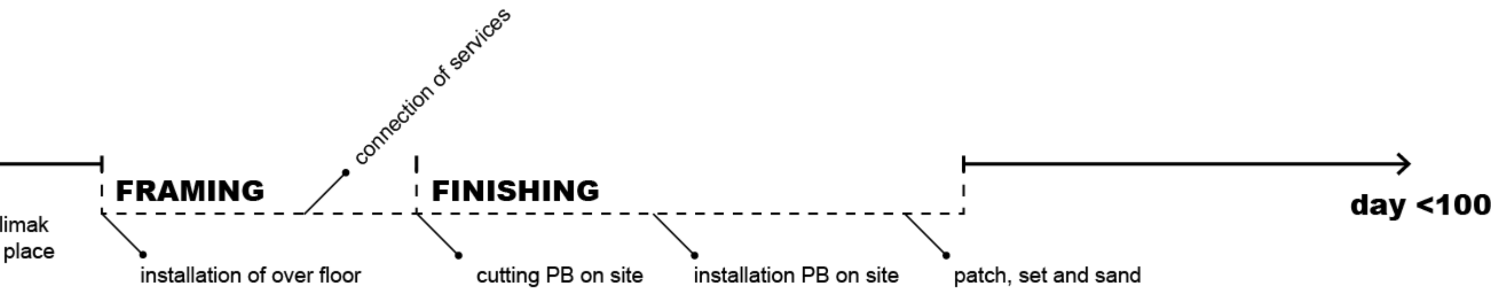


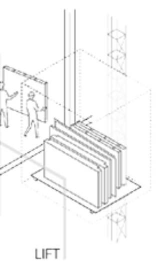
7.1 Provocations: design and assessment

PROVOCATION 4: NO WALLS

Construction Sequencing: No Walls




connection of services
FRAMING
FINISHING
day <100
limak
place
installation of over floor
cutting PB on site
installation PB on site
patch, set and sand


LIFT

alimak

7.2 EXEMPLARS AND ALTERNATIVES

This appendix details each of the exemplars studied through drawings and images.

EXEMPLARS AND ALTERNAVIVES

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

EXPERT PANEL 1

MONASH University | THE UNIVERSITY OF MELBOURNE | building 4.0 crc | MONASH ART DESIGN & ARCHITECTURE

DESIGN-LED RESEARCH

architecture studies unit
architecture masters design studio

[illegible]

[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
7	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
	28 SEP		MID SEMESTER BREAK - NO CLASS
10	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]		[illegible]
14	MON 1 NOV		FOLIOS DUE MONDAY NOV 1

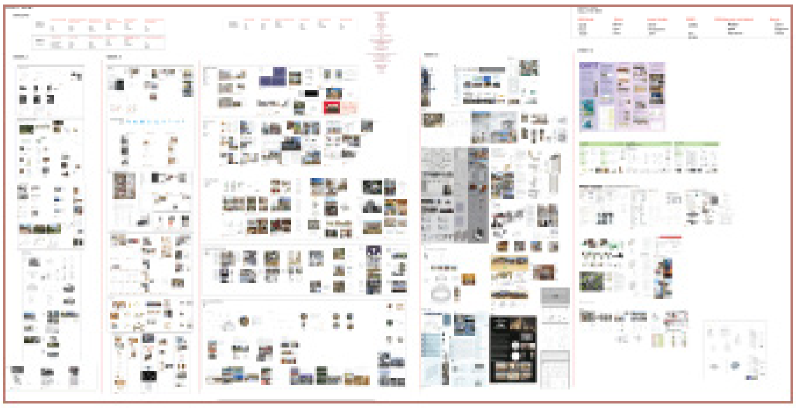
[illegible]

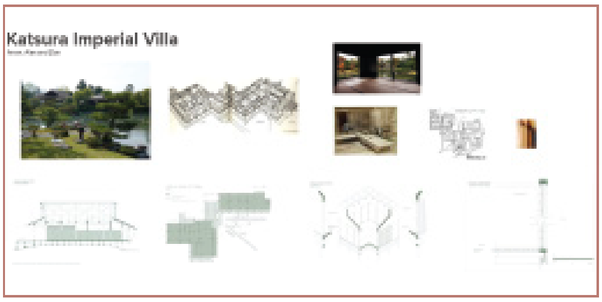
CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

3

DESIGN-LED RESEARCH

architecture studies unit
architecture masters design studio



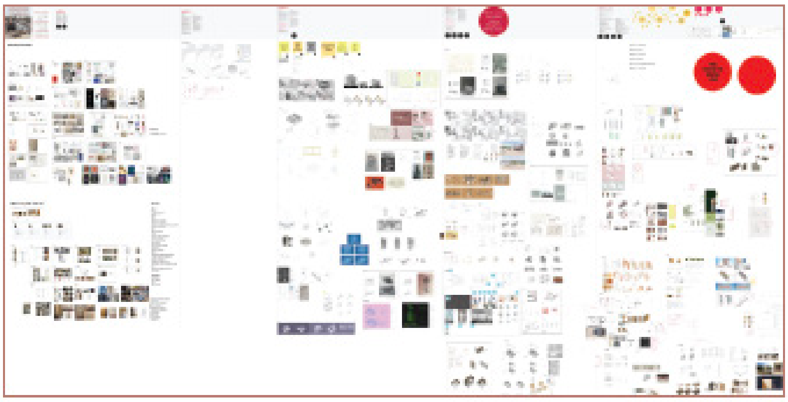


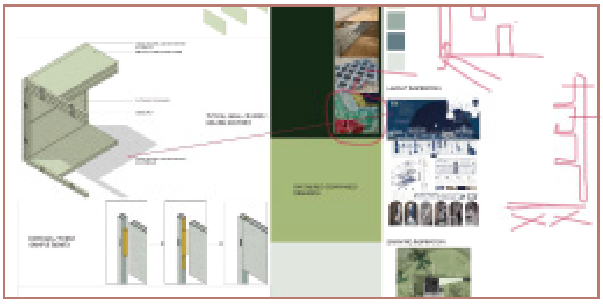
CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

4

DESIGN-LED RESEARCH

architecture studies unit
architecture masters design studio





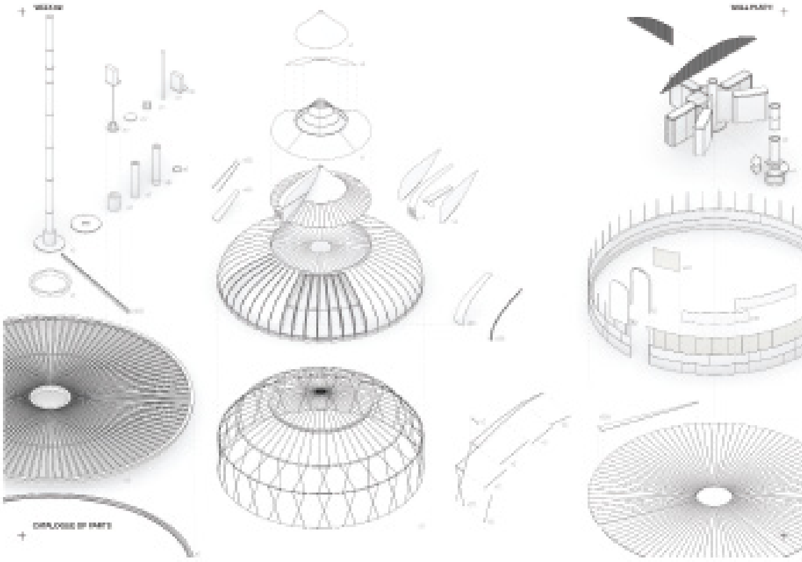
CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

PIONEERS OF PREFABRICATION

early experimental design
building techniques
prototypes

PIONEERS OF PREFABRICATION

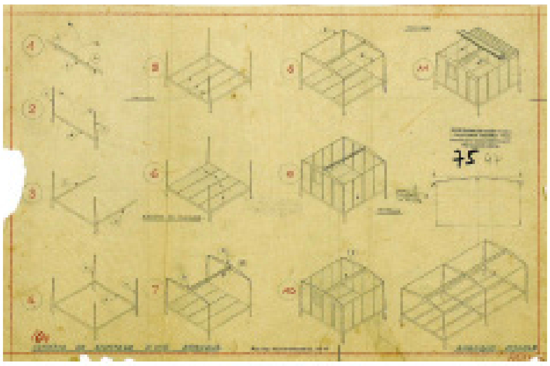
early experimental design
building techniques
prototypes



[illegible]
[illegible]
[illegible]
[illegible]

PIONEERS OF PREFABRICATION

early experimental design
building techniques
prototypes



[illegible]
[illegible]
[illegible]
[illegible]

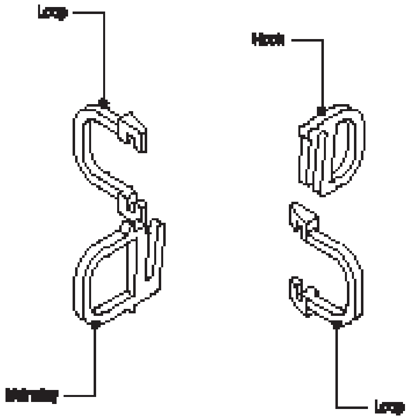
PIONEERS OF PREFABRICATION

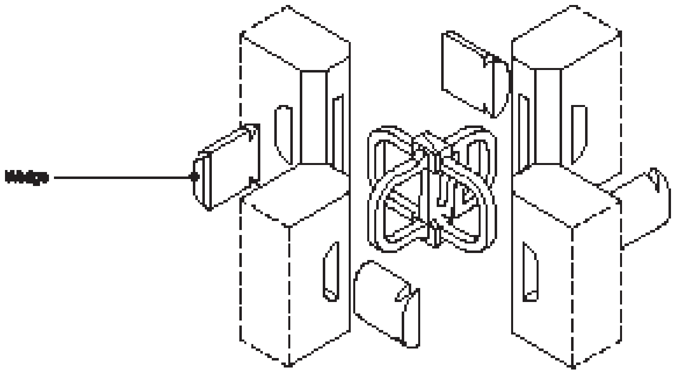
early experimental design
building techniques
prototypes

[illegible]
[illegible]
[illegible]
[illegible]

PIONEERS OF PREFABRICATION

early experimental design
building techniques
prototypes





The Packaged House
1942
Konrad Wachsmann and Walter Gropius
[illegible]
[illegible]
[illegible]

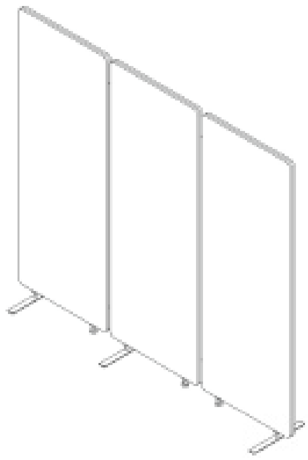
COMMERCIAL MODULAR SYSTEMS

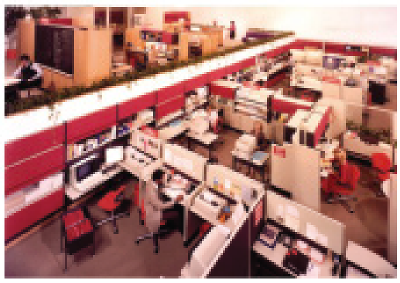
modular office fitout
furniture
demountable buildings
flexible wall systems
local modular

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

COMMERCIAL MODULAR SYSTEMS

modular office fitout
furniture
demountable buildings
panelized wall systems
local modular buildings

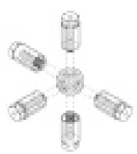


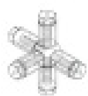


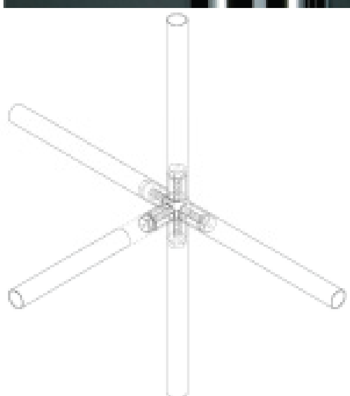
[illegible]

COMMERCIAL MODULAR SYSTEMS

modular office fitout
furniture
demountable buildings
panelized wall systems
local modular buildings





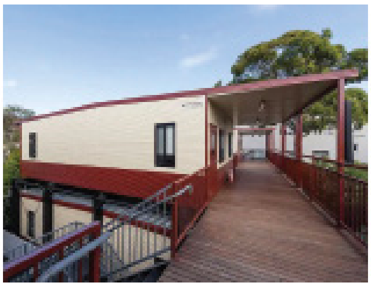


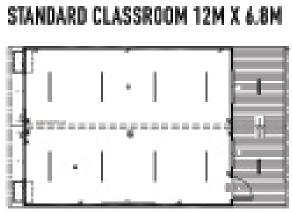
[illegible]

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

COMMERCIAL MODULAR SYSTEMS

- modular office fitout
- furniture
- demountable buildings
- panelised wall systems
- local modular buildings

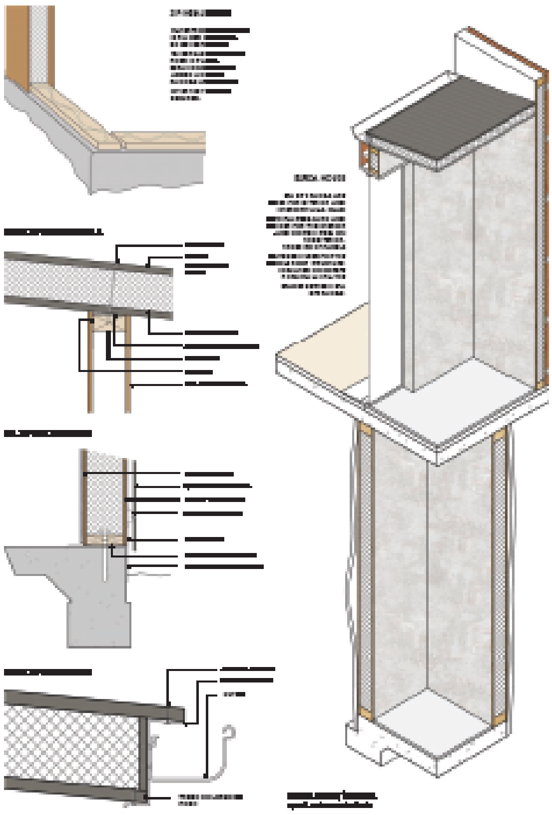




[illegible]

COMMERCIAL MODULAR SYSTEMS

- modular office fitout
- furniture
- demountable buildings
- panelised wall systems
- local modular buildings



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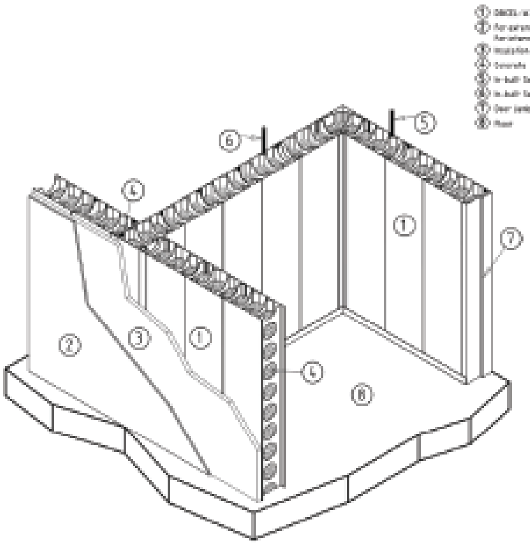
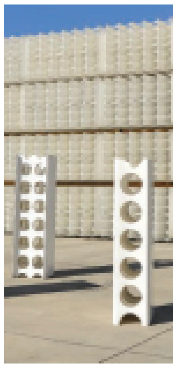
COMMERCIAL MODULAR SYSTEMS

modular office fitout
furniture
demountable buildings
panelised wall systems
local modular buildings





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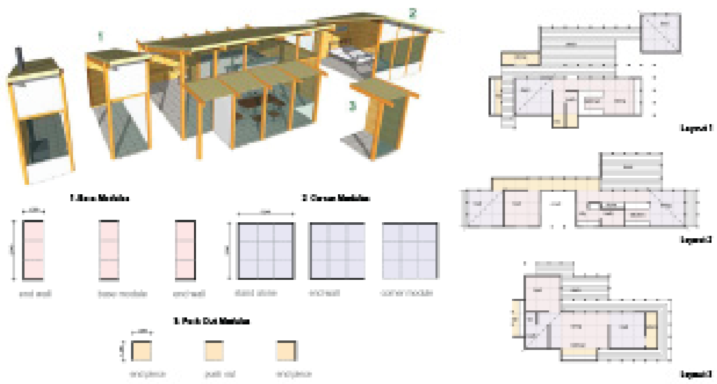

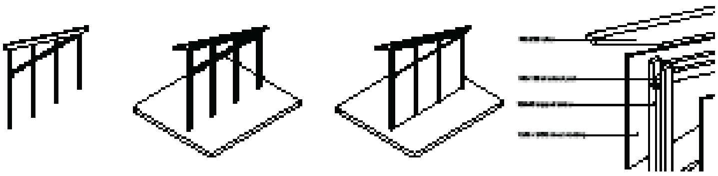

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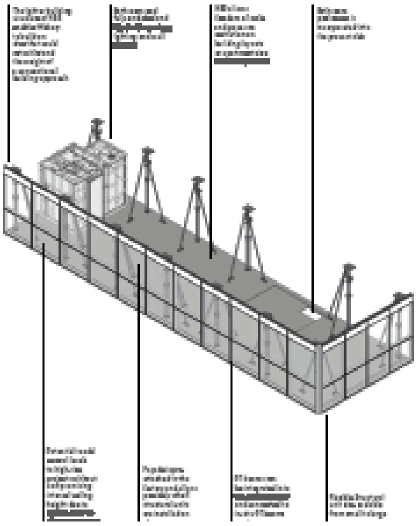

CONTEMPORARY EXPERIMENTAL SYSTEMS

advanced manufacturing / cnc
architecturally designed one-off
services integration
digital twin
relief housing
pods

CONTEMPORARY EXPERIMENTAL SYSTEMS

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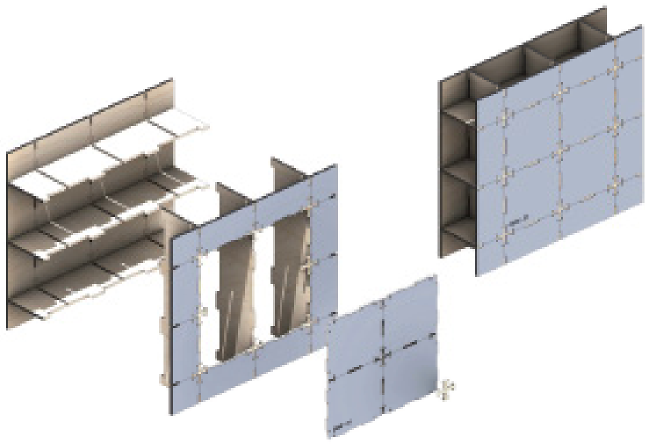

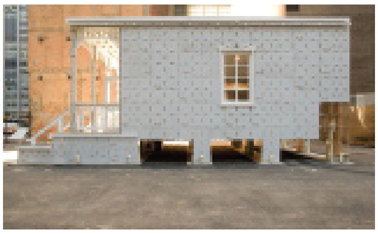

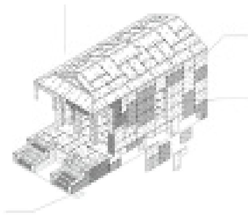

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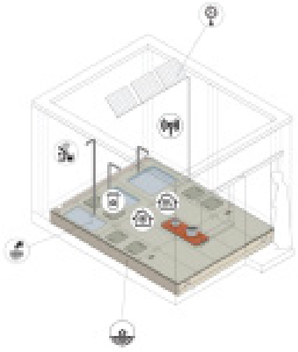

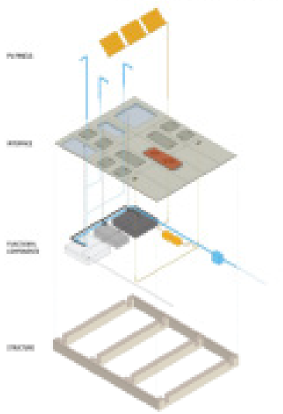

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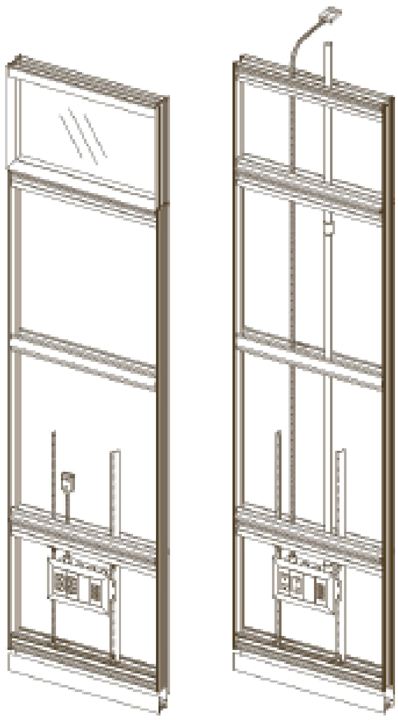

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

CONTEMPORARY EXPERIMENTAL SYSTEMS

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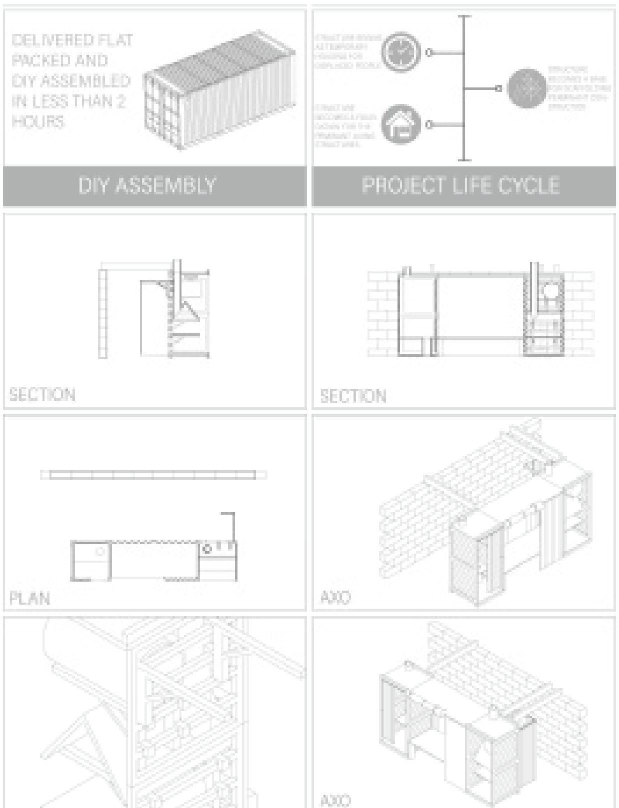

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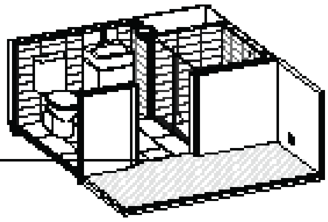


[illegible]

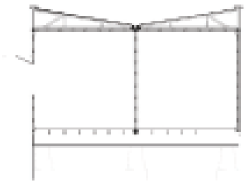
COMPONENTS

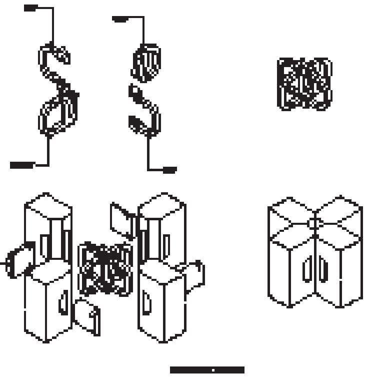
connectors
interlocking units
frames

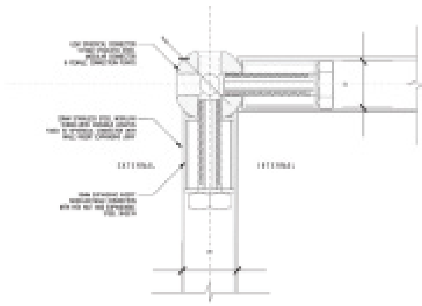
CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

COMPONENTS

connectors
interlocking units
frames







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COMPONENTS

connectors
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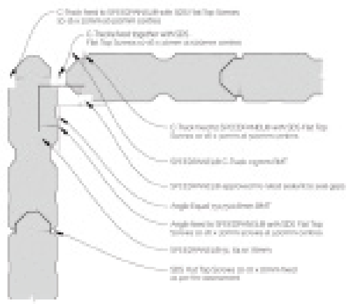

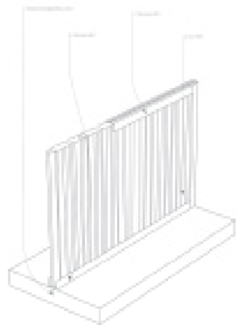

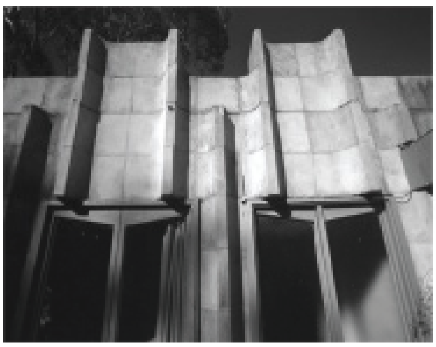

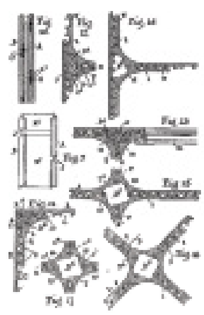

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COMPONENTS

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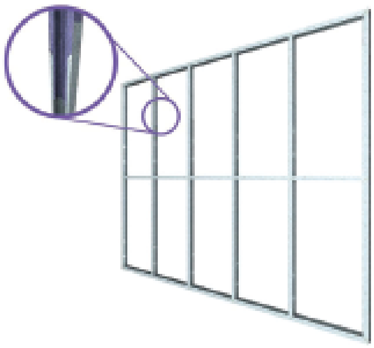

IMAGE	PART NUMBER	CAD FILE	DESCRIPTION
	6451		64mm [w] x 41mm [h] Prefab C Steel Stud with Lip BMT: 0.55 Available Lengths: Made to Order
	6452		64mm [w] x 39mm [h] Prefab 'R' Steel Stud with Lip BMT: 0.55 Available Lengths: Made to Order
	6453		64mm [w] x 41mm [h] Prefab C Steel Track with Lip BMT: 0.55 Available Lengths: Made to Order
	6454		64mm [w] x 40mm [h] Prefab 'U' Steel Track BMT: 0.55 Available Lengths: Made to Order
	6455		64mm [w] x 41mm [h] Prefab 'C' Steel Nogging with Lip BMT: 0.55 Available Lengths: Made to Order
	6456		64mm [w] x 44mm [h] Prefab 'U' Steel Nogging BMT: 0.55 Available Lengths: Made to Order

WALL TYPES

categories
performance core
multi-component modularity
services over-floor
removable/temporary
compression system

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

WALL TYPES

- categories
- performance core
- multi-component modularity
- services over-floor
- moveable/temporary
- compression system

Wall system name	Designer	Year	Wall type: Application	Approach to services	Dimension of Parts	Flexibility
[illegible] Residential	[illegible]	2021	Inter-tenancy wall	not serviced	small unit (one person)	Permanent / not flexible
SpeedPanel	SpeedPanel	2021	Internal partition	not serviced	mechanical assistance	Whole panel demountable
Smart wall [illegible]	[illegible]	2021	Internal partition	Integrated on site (conduits)	small unit (two people)	designed to be movable
DIRTT	DIRTT	2021	Internal partition	Integrated with raised floor	small unit (two people)	cladding removable
Maison Tropicale	Jean Prouvé	1951	External wall	not serviced	small unit (two people)	Whole panel demountable
Katsura Imperial Villa	Hachijo Toshihito	1624	Internal partition	not serviced	small unit (two people)	designed to be movable
Dymaxion House	Buckminster Fuller	1944	External wall	Integrated on site (conduits)	mechanical assistance	Permanent / not flexible
Packaged House System	Wachsmann & Gropius	1942	External + Partition	not serviced	small unit (two people)	Whole panel demountable
Schröder House	Gerrit Rietveld	1924	Internal partition	not serviced	small unit (two people)	Sliding / furniture element
USM	USM Haller	1965	Internal partition	not serviced	small unit (one person)	cladding removable
Modscape	Modscape	2021	External + Partition	Integrated off site	small unit (two people)	Permanent / not flexible
SIPS	SIPA	1988	External wall	Integrated on site (conduits)	mechanical assistance	Permanent / not flexible
Dincel	Dincel	1989	External + Partition	Integrated on site (conduits)	small unit (two people)	Permanent / not flexible
Royal Academy of Arts	Gilles Retsin	2019	Experimental design	not serviced	small unit (one person)	Whole panel demountable
WikiHouse	Open source	2011	External + Partition	Integrated on site (conduits)	small unit (two people)	Permanent / not flexible
Full Fill Home	Anupama Kundoo	2015	External wall	not serviced	small unit (two people)	Whole panel demountable
School Pod	Gollifer Langston	2008	Experimental design	Integrated on site (conduits)	mechanical assistance	Whole panel demountable
Yurts	Vernacular type	[illegible] BC	External wall	not serviced	small unit (one person)	Whole panel demountable
Paper Partition System	Shigeru Ban	2018	Internal partition	not serviced	small unit (one person)	Whole panel demountable
Hex House	Architects for Society	2021	External wall	Integrated with raised floor	small unit (two people)	Permanent / not flexible

[illegible] to identify categories for research.

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

WALL TYPES

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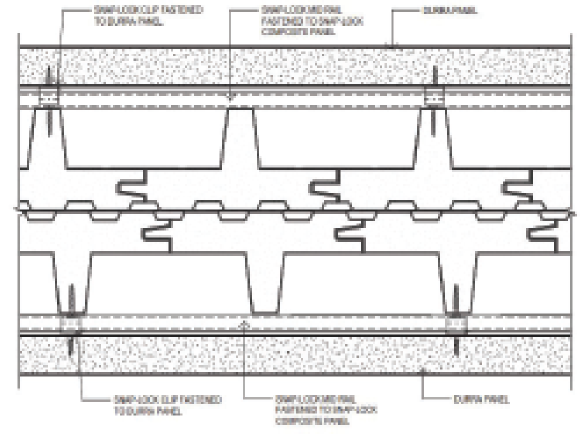

3 A01 PARTY WALL DETAIL
Scale 1:5

[illegible]

CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

WALL TYPES

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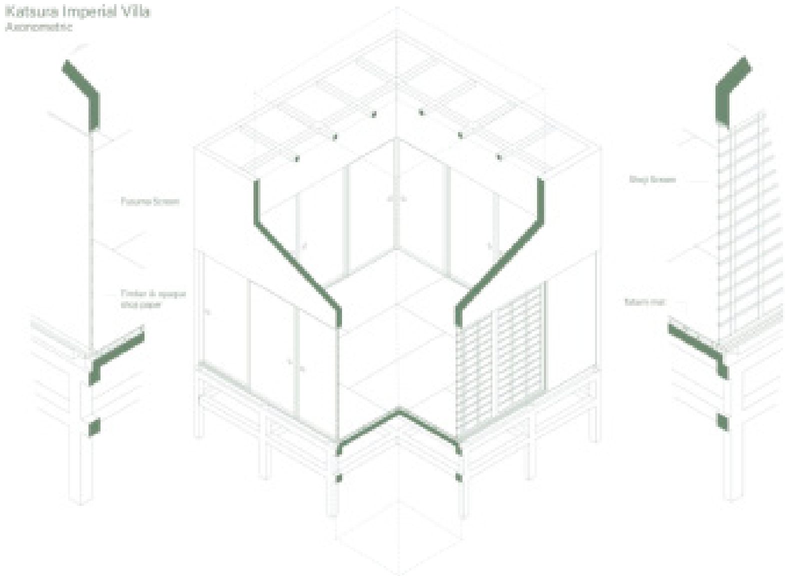

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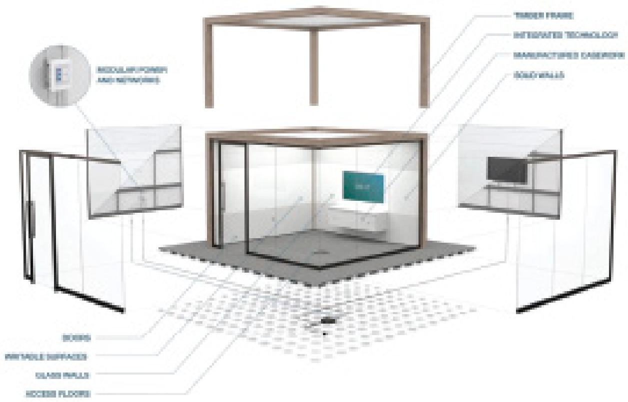

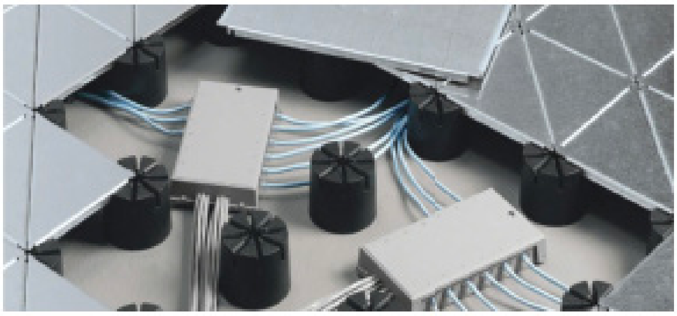

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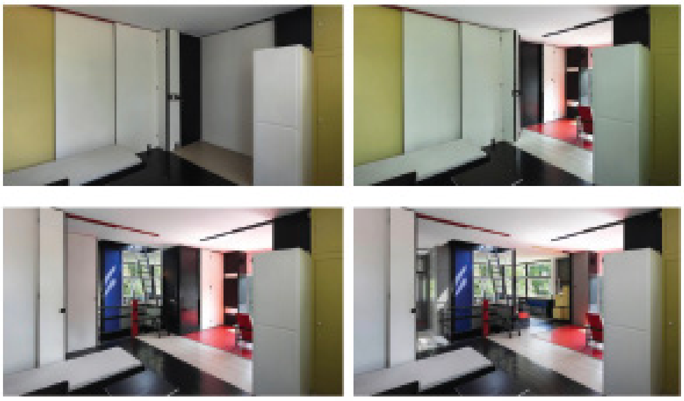

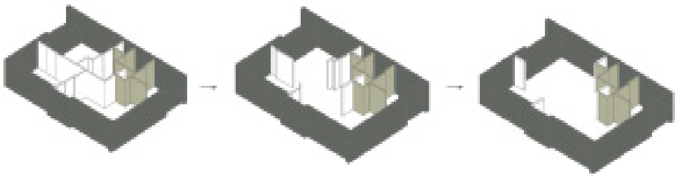

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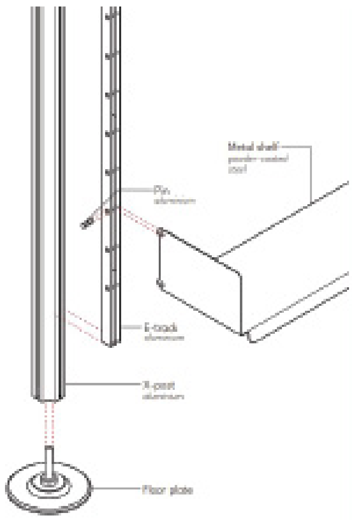

[illegible]

CRAFTMANSHIP AND PERFORMANCE

advanced manufacturing
new materials and recycling
clip systems – interchangeable
joints
performance – fire, acoustic, thermal, odour

CRAFTMANSHIP AND PERFORMANCE

advanced manufacturing
new materials and recycling
clip systems – interchangable
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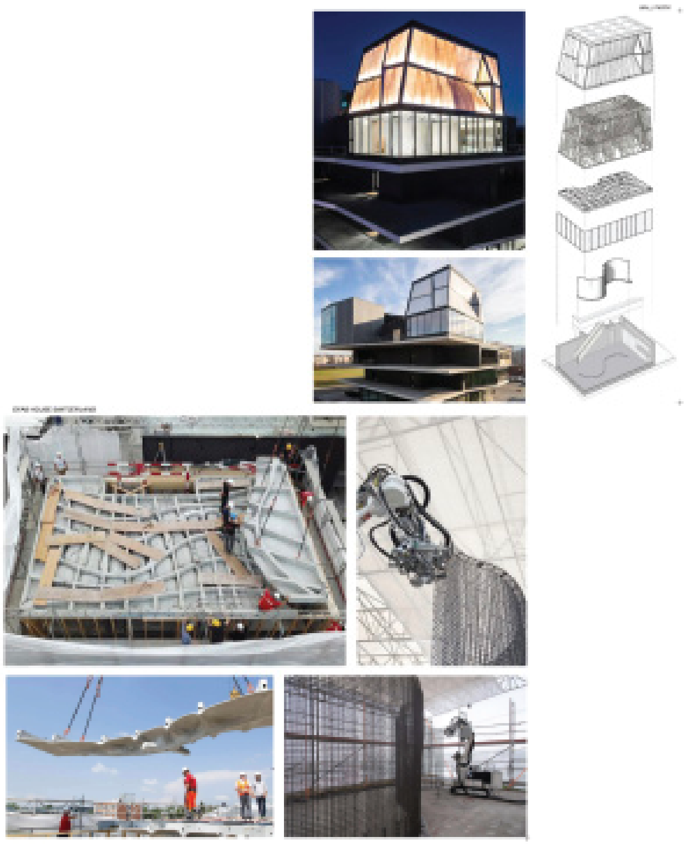
performance – fire, acoustic, thermal, odour



DFAB House
National Centre of Competence in Research (NCCR), Switzerland
[illegible]

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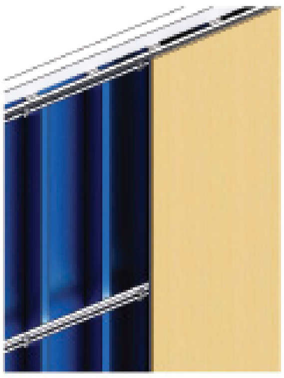

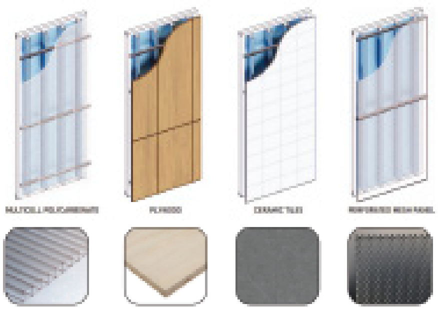

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CONSTRUCTION LOGIC

on-site
off-site
typology of building
sequencing
digital connectivity

CONSTRUCTION LOGIC

on-site
off-site
sequencing
digital connectivity

CONSTRUCTION LOGIC

- on-site
- off-site
- sequencing
- digital connectivity

CONSTRUCTION LOGIC

- on-site
- off-site
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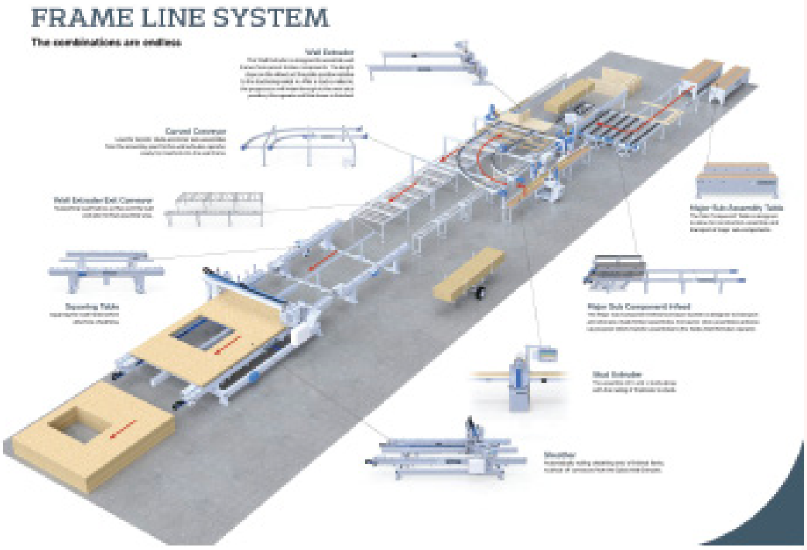
CRC#28 COMPONENTISED INTERNAL WALL SYSTEMS FOR MULTI-RESIDENTIAL APPLICATIONS

CONSTRUCTION LOGIC

on-site
off-site
sequencing
digital connectivity



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CONSTRUCTION LOGIC

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off-site
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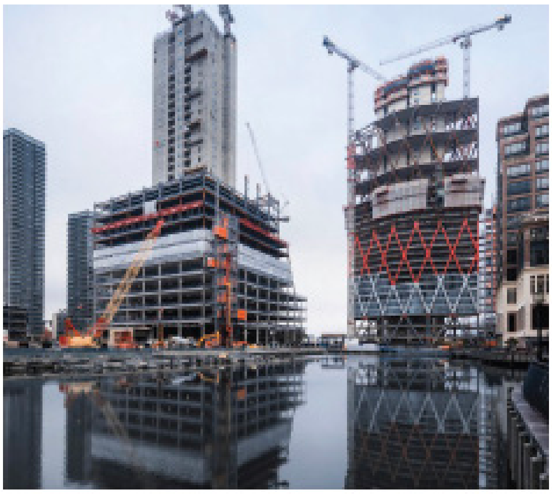

[illegible]

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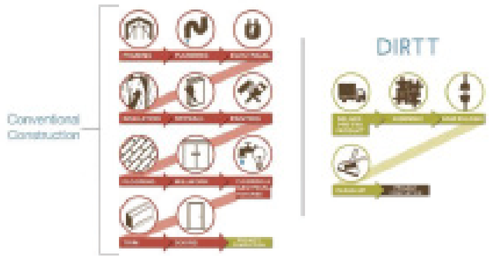


7.3 PERFORMANCE AND LIFE-CYCLE

This appendix contains an analysis of the performance requirements for internal walls.

Project #28 - Componentised Internal Wall Systems for multi-residential Applications.

(1) Performance Criteria of Componentised Internal Wall Systems for multi-residential Applications

1

Overview of performance criteria of Internal Walls

(1) Acoustic separation

- The National Construction Code of Australia specifies requirements, including sound insulation requirements, for building partitions (walls and floors), depending on the classification of the building and the nature of the air spaces being separated by the partition in question. Additional sound insulation requirements may also be specified by other authorities.
- The acoustic privacy required by various spaces is dependent upon:
  - the noise level generated within the source room
  - the degree to which legibility is acceptable within the receiving room or sp
- For information, the following outlines the subjective acoustic privacy that would be achieved from various levels of noise reduction or RW ratings between spaces.
- Note: These Wall System Ratings must be considered in conjunction with Background Noise Levels. For example, if the Background Noise Level source is a highway with heavy traffic or a noisy street with a Sound Pressure Level of 70 dB, a wall with RW 50 would take care of loud hi-fi. However, in a quiet residential neighbourhood, the RW 50 wall would not block out average conversation.

2

Overview of performance criteria of Internal Walls

(2) Fire resistance

- Fire performance of internal walls is commonly expressed in terms of the Fire Resistance Level (FRL), determined with respect to the structural adequacy, insulation, and integrity performance criteria.
- In non-load bearing walls, the latter two criteria govern the fire performance, as the studs are usually capable of withstanding the self-weight of the wall system.
- Factors causing Fire Resistance Level (FRL) improvement:
  - Gap clearance and emissivity
  - Reduction of plasterboard degradation
  - Confinement of plasterboard moisture
- References for Fire Testing:
  - Standards Australia, AS 1530. 4 - Methods for Fire Tests on Building Materials, Components and Structures - Part 4: Fire-resistance Test of Elements of Construction, Sydney, Australia (2005)
  - ASTM International - Standard Test Methods for Fire Tests of Building Construction and Materials, E119 - 18a, United States (2008)

3

Overview of performance criteria of Internal Walls

(3) Thermal comfort

- The energy required to heat and cool residential buildings, and the very way we define the "comfortable" thermal conditions we are trying to maintain, play significant roles in environmental impact.
- The use of energy for heating, ventilating and air conditioning (HVAC) of the indoor environment is already the largest sector in energy consumption in most of the developed world (Griffiths et al 1998).
- The higher the star rating, the less energy needed to heat and cool the home to keep it comfortable.
- In residential spaces, an average Nationwide House Energy Rating Scheme (NatHERS) rating of 7 Stars or greater.

4

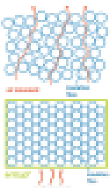
Overview of performance criteria of Internal Walls

(4) Air tightness (transfer of smells).

- An airtight building is one that has been designed and constructed to minimise the uncontrolled movement of air through the walls, roof, floor and joinery.
- Airtightness can be measured. This provides an indication of the quality and likely future performance of the building.
- Benefits:

(1) Energy Efficiency
  - Reduced air infiltration saves energy and therefore less heating/cooling appliances are needed
  - Keeps your home warm in winter and cool in summer

(2) Healthy Indoor Air
  - Eliminates contamination of the indoor air
  - Prevents mould and mildew in the construction from internally driven moisture
  - Enables controlled ventilation



5

Performance Requirements for Non-Load Bearing Internal Walls in NCC2019

1. Acoustic Separation
2. Fire Resistance
3. Thermal comfort
4. Air tightness (transfer of smells)

6

Building Classification (NCC 2019)

- Class 2 buildings
  - Class 2 buildings are apartment buildings. They are typically multi-unit residential buildings where people live above and below each other. The NCC describes the space which would be considered the apartment as a sole-occupancy unit (SOU).
  - Class 2 buildings may also be single storey attached dwellings where there is a common space below. For example, two dwellings above a common basement or carpark.

7

(1) Acoustic Separation - NCC 2019 Requirement

- FP5.1 Sound transmission through walls for Class 2 and 3 buildings.
  - Walls separating sole-occupancy units or a sole-occupancy unit from a plant room, lift shaft, stairway, public corridor, public lobby, or the like, or parts of a different classification, must provide insulation against the transmission of—

    (a) airborne sound; and

    (b) impact generated sound, if the wall is separating a bathroom, sanitary compartment, laundry or kitchen in one sole-occupancy unit from a habitable room (other than a kitchen) in an adjoining unit, sufficient to prevent illness or loss of amenity to the occupants.

8

(1) Acoustic Separation - NCC 2019 Requirement

- FP5.3 Sound transmission through floor and wall penetrations and door assemblies
  - FP5.3 supports the requirements of FP5.1 and FP5.2 in that the performance of building elements in Class 2 and Class 3 buildings are not to be compromised because of services that penetrate the elements.
  - Sounds prohibited under FP5.3 include those from a service pipe in the form of:
- pump vibration;
- water hammer; or
- sewerage or sullage discharging in soil or waste pipes.

9

Acoustic Separation – Verification Method

- Compliance with FP5.2(a) and FP5.3 to avoid the transmission of airborne sound through walls is verified when it is measured in-situ that—

(a) a wall separating sole-occupancy units has a weighted standardised level difference with spectrum adaptation term ($D_{nT,w}+C_{tr}$) not less than 45 when determined under AS/NZS ISO 717.1; or

(b) a wall separating a sole-occupancy unit from a plant room, lift shaft, stairway, public corridor, public lobby, or the like, or parts of a different classification, has a weighted standardised level difference ($D_{nT,w}$) not less than 45 when determined under AS/NZS ISO 717.1; or

(c) any door assembly located in a wall that separates a sole-occupancy unit from a stairway, public corridor, public lobby, or the like, has a weighted standardised level difference ($D_{nT,w}$) not less than 25 when determined under AS/NZS ISO 717.1.

10

Acoustic Separation – Verification Method

- What does R_w mean?
  - The Weighted Sound Reduction Index (R_w) is a number used to rate the effectiveness of a soundproofing system or material. Increasing the R_w by one translates to a reduction of approximately 1db in noise level. Therefore, the higher the R_w number, the better a sound insulator it will be.
- What does R_w+C_{tr} mean?
  - C_{tr} is an adjustment factor which is used to account for low frequency noise - typically the biggest problem with sound insulation. C_{tr} is always a negative number, so the R_w+C_{tr} will always be less than the R_w value. Many sound insulation types will represent how effective they are by displaying the R_w/R_w+C_{tr} values together.

11

(2) Fire Resistance - NCC 2019 Requirement

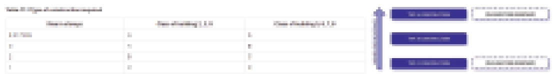
- C1.1 Type of construction required

(a) The minimum Type of fire-resisting construction of a building must be determined in accordance with Table C1.1, except as allowed for—

(i) certain Class 2, 3 or 9c buildings in C1.5; and

(ii) a Class 4 part of a building located on the top storey in C1.3(b); and

(iii) open spectator stands and indoor sports stadiums in C1.7.



12

(2) Fire Resistance - NCC 2019 Requirement

- In a building required to be of Type A construction—

(a) each building element listed in Table 3 and any beam or column incorporated in it, must have an FRL not less than that listed in the Table for the particular Class of building concerned; and

(b) * * * * *

(c) any internal wall required to have an FRL with respect to integrity and insulation must extend to—

(i) the underside of the floor next above; or

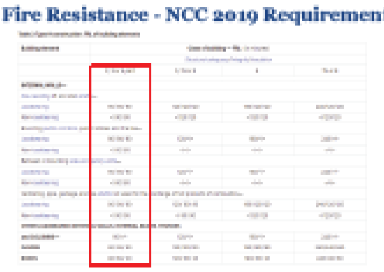
(ii) the underside of a roof complying with Table 3; or

(iii) if under Clause 3.5 the roof is not required to comply with Table 3, the underside of the non-combustible roof covering and, except for roof battens with dimensions of 75 mm x 50 mm or less or sarking-type material, must not be crossed by timber or other combustible building elements; or

(iv) a ceiling that is immediately below the roof and has a resistance to the incipient spread of fire to the roof space between the ceiling and the roof of not less than 60 minutes.

13

(2) Fire Resistance - NCC 2019 Requirement



14

(3) Thermal Comfort- NCC 2019 Requirement

- A building, including its services, must have features that facilitate the efficient use of energy appropriate to—

(a) the function and use of the building; and

(b) the level of human comfort required for the building use; and

(c) solar radiation being—

(i) utilised for heating; and

(ii) controlled to minimise energy for cooling; and

(d) the energy source of the services; and

(e) the sealing of the building envelope against air leakage; and

(f) for a conditioned space, achieving an hourly regulated energy consumption, averaged over the annual hours of operation, of not more than—

(i) for a Class 6 building, 80 kJ/m2.hr; and

(ii) for a Class 5, 7b, 8 or 9a building other than a ward area, or a Class 9b school, 43 kJ/m2.hr; and

(iii) for all other building classifications, other than a sole-occupancy unit of a Class 2 building or a Class 4 part of a building, 15 kJ/m2.hr.

15

(3) Thermal Comfort- Verification Methods

- JV1 - NABERS Energy for Offices
- JV2 - Green Star
- JV3 - Verification using a reference building

16

(3) Thermal Comfort - Verification Methods

- The most common option used to meet the relevant energy efficiency Performance Requirement for units in a Class 2 apartment building, is to obtain an energy rating of at least 5 stars for each unit and an average of 6 stars across all units in the building using a software tool accredited under Nationwide House Energy Rating Scheme (NatHERS).
- The following software tools in regulation mode have been accredited under NatHERS:
  - AccuRate Sustainability v2.4.0 (3.21)
  - FirstRate5 v5.3.1a (3.21)
  - BERS Pro v4.4.0.6 (3.21)
  - HERO v1.2-beta (3.21)
- These tools are suitable for demonstrating compliance with the thermal performance provisions in the National Construction Code (NCC) via the Deemed-to-Satisfy pathway (i.e. clause 3.12.0.1 of NCC Volume Two; and clause J0.2 of NCC Volume One).

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(4) Air Tightness - NCC 2019 Requirement

- A building, including its services, must have features that facilitate the efficient use of energy appropriate to the sealing of the building envelope against air leakage.
- Envelope, for the purposes of Section J in Volume One, means the parts of a building's fabric that separate a conditioned space or habitable room from—
  - the exterior of the building; or
  - a non-conditioned space including—
  - the floor of a rooftop plant room, lift-machine room or the like; and
  - the floor above a carpark or warehouse; and
  - the common wall with a carpark, warehouse or the like.

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(4) Air Tightness - Verification Methods

- Building sealing is essential for facilitating the energy efficiency of a building. JV 4 provides a method of demonstrating compliance with the building sealing requirements in JP1(e). This provides an alternative compliance option to the prescriptive building sealing requirements in Part J3.
- JV4 quantifies the level of sealing (expressed as an air permeability rate) appropriate for different building classifications and climate zones. The method for testing the sealing level is through a blower door test carried out in accordance with Method 1 of AS/NZS ISO 9972.

19

(4) Air Tightness - Verification Methods

- JV4 Building envelope sealing
- Compliance with JP1(e) is verified when the envelope is sealed at an air permeability rate, tested in accordance with Method 1 of AS/NZS ISO 9972, of not more than—

  (a) for a Class 2 building or a Class 4 part of a building, 10 m3/hr.m2 at 50 Pa reference pressure; or

(4) Air Tightness - Verification Methods

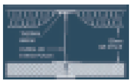
- JV4 Building envelope sealing
- Compliance with JP1(e) is verified when the envelope is sealed at an air permeability rate, tested in accordance with Method 1 of AS/NZS ISO 9972, of not more than—

  (a) for a Class 2 building or a Class 4 part of a building, 10 m3/hr.m2 at 50 Pa reference pressure; or

21

Market Products Performance Assessment

- Durra Panels - manufactured from compressed wheat and rice straw, which is a natural and annually renewable resource.
  - **Acoustic Performance** - Able to create a wide range of high performance acoustic systems
  - **Fire Performance** – Achieves a one hour fire rating
  - **Thermal Comfort** – Achieves an R-value of 4.21.
  - **Cost** - Basic 50mm thick panels cost $21.75 per square metre. Top-of-the-range "Sound Sorb", at 75mm thick, is $75.25 per square metre.



22

Market Products Performance Assessment

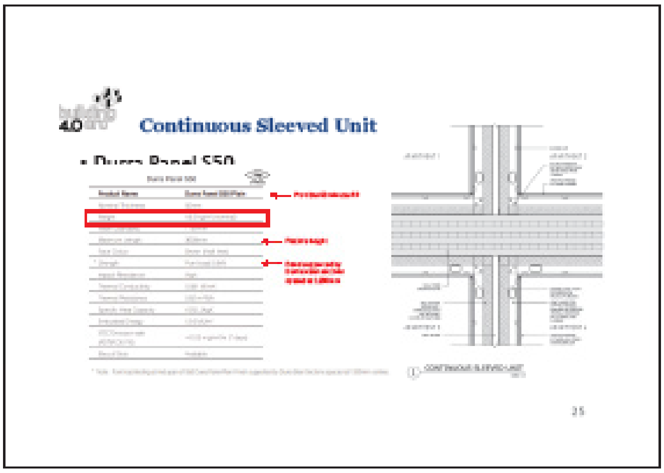
- HEMPCRETE Panels - manufactured from a mixture of lime, hemp hurd and water that will petrify into a bio-composite building material.
  - **Acoustic Performance** - good acoustic damping properties
  - **Fire Performance** – FRL 60/60/60
  - **Thermal Comfort** – R value is 2.75 with plaster and surface resistances taken into account.
  - **Cost** - approximately $135 per square metre based on a 300 mm thick wall
    - Installation Cost - between $230 and $265 per square metre

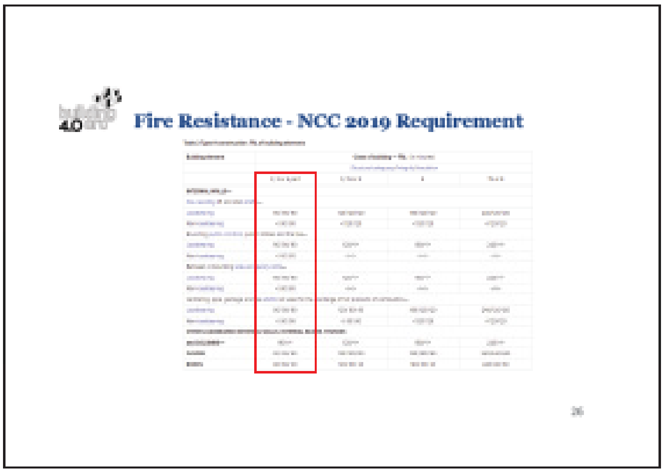
23

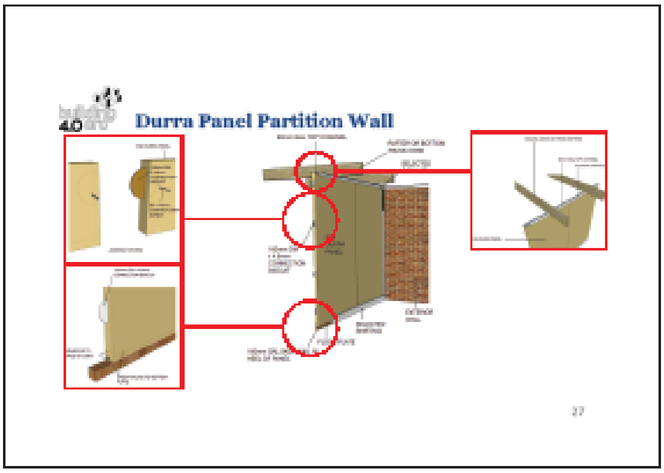
Market Products Performance Assessment

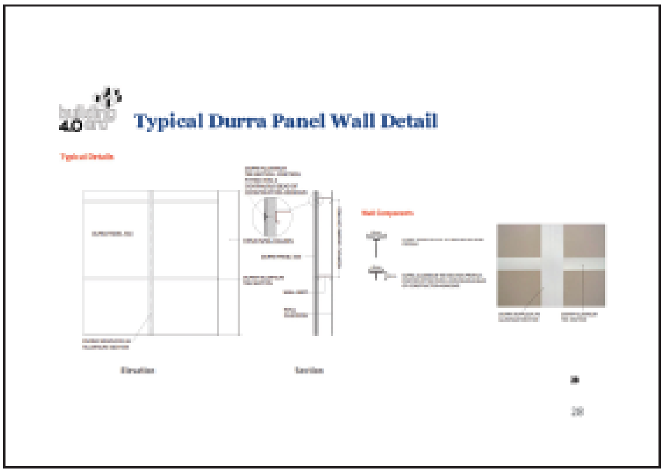
- Rondo QUIET Stud Acoustic Wall System – Composed of 92mm Rondo Quiet Stud, 2x13mm fire-rated plasterboard on both sides and TAC100 Insulation.
  - **Acoustic Performance** – Achieves the requirement for NCC 2019 for Class 2 Building.
  - **Fire Performance** – FRL 60/60/60
  - **Thermal Comfort** – R value is 2.75 with plaster and surface resistances taken into account.
  - **Cost** – Rondo Quiet Stud price is approximately $20.62/m + $9.5/m2 for Fire-rated Plasterboard (each side) + $6.2/m2 for 100mm Insulation infill = $45.82/m2

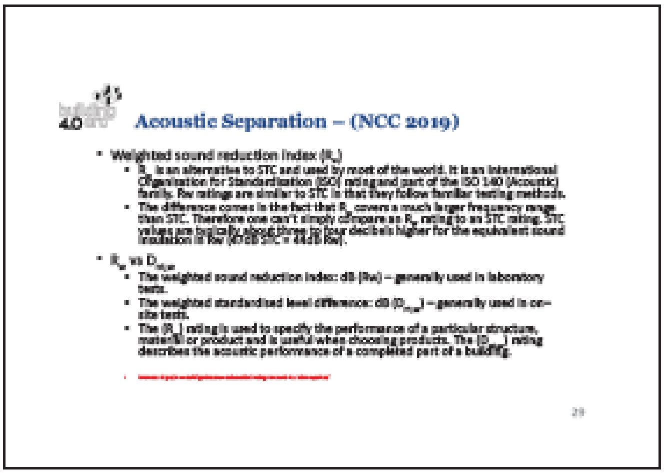
24

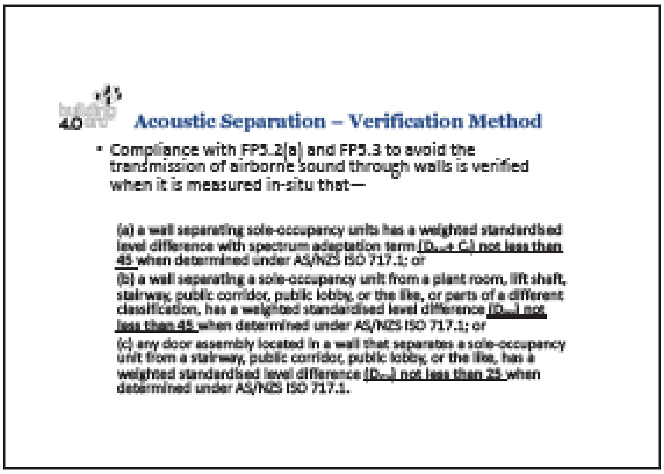

Continuous Sleeved Unit
• Durra Panel 550
25

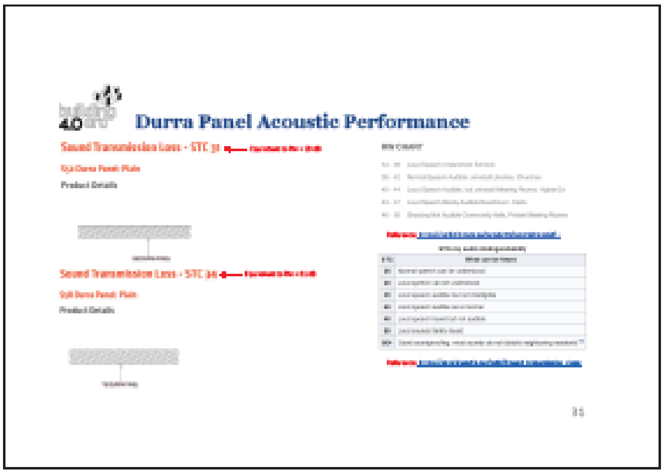

Fire Resistance - NCC 2019 Requirement
26

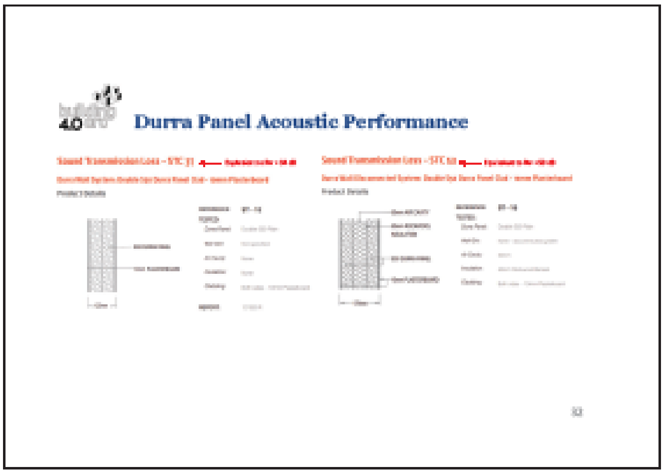

Durra Panel Partition Wall
27


Typical Durra Panel Wall Detail
Typical Details
Elevation
Section
28


Acoustic Separation – (NCC 2019)
• Weighted sound reduction index (Rw)
• The weighted sound reduction index: dB (Rw) – generally used in laboratory tests.
• The weighted standardised level difference: dB (DnT,w) – generally used in on-site tests.
29

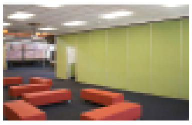

Acoustic Separation – Verification Method
• Compliance with FP5.2(a) and FP5.3 to avoid the transmission of airborne sound through walls is verified when it is measured in-situ that—
(a) a wall separating sole-occupancy units has a weighted standardised level difference with spectrum adaptation term (DnT,w + Ctr) not less than 45 when determined under AS/NZS ISO 717.1; or
(b) a wall separating a sole-occupancy unit from a plant room, lift shaft, stairway, public corridor, public lobby, or the like, or parts of a different classification, has a weighted standardised level difference (DnT,w) not less than 45 when determined under AS/NZS ISO 717.1; or
(c) any door assembly located in a wall that separates a sole-occupancy unit from a stairway, public corridor, public lobby, or the like, has a weighted standardised level difference (DnT,w) not less than 25 when determined under AS/NZS ISO 717.1.

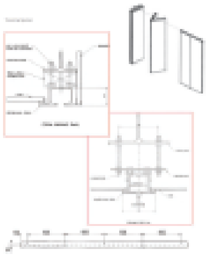

Durra Panel Acoustic Performance
31


Durra Panel Acoustic Performance
32

Interior Partition Wall between Rooms

- Unifold Operable Wall System





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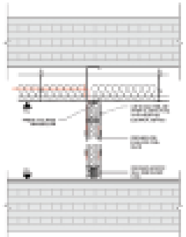
Interior Partition Wall between Rooms

- Super-Flexible Partition
- The acoustic performance will mainly depend on the insulation material.
- For example, operable acoustic wall system provides an NRC (Noise Reduction Coefficient) value of approximately 0.5.
- The NRC value indicates how much sound a material will absorb when sound waves hit it, but is not equivalent to the perceived noise reduction of an installed product. This will vary on a case by case basis.



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Existing assessment methods used for acoustic flanking in buildings

- Numerical simulation
  - Finite element methods (FEM)
  - Statistical energy analysis (SEA)
- ISO 12354:2017
  - SEA-based model
  - Result of two decades of research into modelling for lightweight structures

35

Existing assessment methods used for acoustic flanking in buildings

- Finite element methods:
  - Converts the geometric model to a large global matrix of small elements with associated material properties and solves for displacements resulting from applied loads
  - For dynamic loads, the model is solved repeatedly for successive time increments
  - Very large models and many repeated solutions are required for modelling frequencies > 250 Hz in full scale structures.
    - Higher frequencies require smaller elements and shorter timesteps.
  - Even for low frequencies, prediction accuracy has not been great despite a significant amount of previous research.
- Statistical energy analysis:
  - Represents the system as a set of coupled subsystems and estimates the energy content of the vibration modes for each and energy flows between them
  - Moderately successful for high frequencies in a limited range of lightweight structures for which empirical measurements are available to use as inputs
  - Inaccurate for low frequencies due to the non-diffuse nature of the sound fields.

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ISO 12354:2017

- Published in 2017
- Result of two decades of focused research
- Simplifies and standardises SEA-based predictions for lightweight structures
- Provides theoretical formulae for timber frame wall and floor elements but not for LGS structures
- Performs best with experimental measurements from individual elements for input–

$$D_{ff} = \frac{R_i}{2} + \frac{R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij,n}} + 10\lg\frac{A_0}{l_{ij,lab}}$$

Flanking sound reduction index for flanking pathway from element i to element j | Direct sound reduction indices for participating wall/floor elements | Additional contributions from floor and ceiling layers | Vibration reduction through junction | Normalisation for element and junction size

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Standards for acoustic ratings, measurement and prediction

- Australian Standards
  - AS/ISO 717: Calculation of single number ratings for airborne and impact sound insulation
  - AS/ISO 140: Field and laboratory measurement of sound transmission in buildings and through building elements
  - National Construction Code (NCC) Specifies minimum sound insulation performance requirements
- ISO Standards
  - ISO 717: Calculation of single number ratings for airborne and impact sound insulation
  - ISO 16283: Field measurement of sound transmission between rooms
  - ISO 10140: Laboratory measurement of direct sound transmission
  - ISO 10848: Laboratory measurement of sound transmission for individual flanking pathways
  - ISO 12354: Prediction of apparent sound transmission
- ASTM Standards
  - ASTM E413: Calculation of single number ratings for airborne and impact sound insulation
  - ASTM E336: Field measurement of sound transmission between rooms
  - ASTM E90: Laboratory measurement of direct sound transmission

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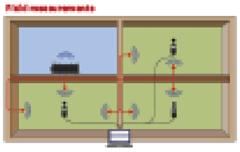
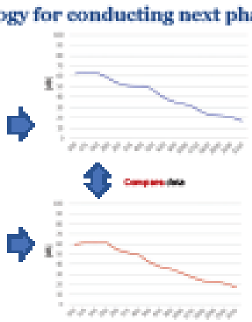
Proposed methodology for conducting next phase ISO 12354 model

Field measurements



ISO 12354 model predictions

$$D_{ff} = \frac{R_i}{2} + \frac{R_j}{2} + \Delta R_i + \Delta R_j + \overline{D_{v,ij,n}} + 10\lg\frac{A_0}{l_{ij,lab}}$$



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(2) Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia

40

Introduction

- Recent study by UoM compared the life-cycle greenhouse gas emissions (LCGHGE) and life-cycle cost (LCC) of CLT and traditional reinforced concrete (RC) residential buildings for three cities in Australia (Melbourne, Sydney and Brisbane).
- Life cycle analyses were conducted within the boundaries of the product and construction, operational and maintenance (O&M), and end of life (EOL) phases.
- The results are compared with a conventional RC building with a similar size, height and layout.

41

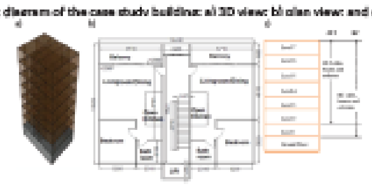
Method

- Assumptions and justifications for the analyses are provided as follows:
  - The discount rate was assumed to be 7% based on Infrastructure Australia (Assessment framework, 2018).
  - The concrete waste was assumed to be sent to landfill as suggested by (Senaratne et al., 2016).
  - The CLT wastes were assumed to be incinerated as they are not suitable for landfill because they contain chemicals for termite protection (Oliveria et al., 2018).
  - The locations of the building were assumed to be in the central business district (CBD) of each city.
  - CLT components were assumed to be supplied from an existing manufacturer located in Wodonga. Therefore, the transportation distances to the Melbourne, Sydney and Brisbane CBD were estimated as 323 km, 560 km and 1398 km, respectively.
  - The transportation distance from the concrete supplier to the construction site was assumed to be 80 km.
  - The construction time of CLT building was taken as 30% less than that of the RC Building (Kremer & Ritche, 2018).

42

Case study building

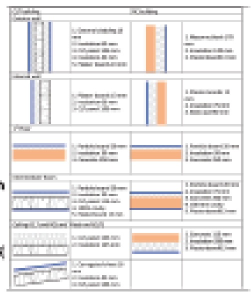
- Two mid-to-high rise eight-storey residential RC and CLT buildings with similar dimensions were selected for LCGHGE and LCC analyses in this investigation (Fig. 1).
- Schematic diagram of the case study building: a) 3D view; b) plan view; and c) elevation view.



43

Case study building

- The area and height of these buildings are 158m2 and 25 m, respectively.
- The ground floor and foundation of both buildings is traditional RC.
- The thickness of the ground floor slab in RC building is 300 mm. The slab thickness of Level 1-7 of the RC building is 250 mm.
- Whilst the CLT building floor is constructed with 115 mm thick Australian Radiata pine CLT panels (i.e. CL3/115). The roof of the CLT building is constructed with 105 mm thick Australian Radiata pine CLT panels (i.e. CL3/105) and corrugated metal cladding.
- Details on the external and internal wall, and wall finishes are provided in Table 1.



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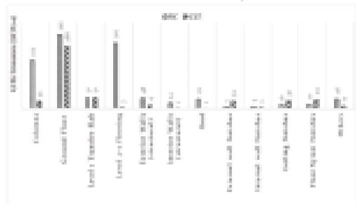
Case study building

- These case study residential buildings were categorized as NCC Class 2 buildings and designed according to the Australian standard AS/NZS 1170; ultimate limit state and serviceability.
- To account for the deemed to satisfy condition in National Construction Code (NCC), the fire resistance level of the CLT wall and floor was considered as 90/90/30 min, respectively for structural resistance/integrity resistance/insulation (Frangi et al., 2009).
- The 278 mm wall thick- ness, which includes the 115 mm thick CLT panel, floor finish and 113 mm ceiling with its cavity, satisfy the NCC acoustic and vibration criteria for floors (Pagnoncelli and Morales, 2016).

45

Results

- Life cycle GHG emissions
- ✓ Breakdown of GHG emissions related to the construction phase of the CLT and RC buildings



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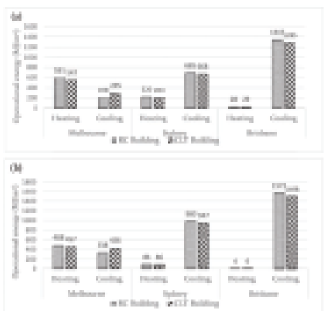
Results

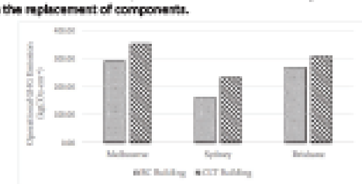
- Life cycle GHG emissions
- ✓ Breakdown of the heating and cooling operational energy for a 50-year life span of the building for the three cities.



47

Results

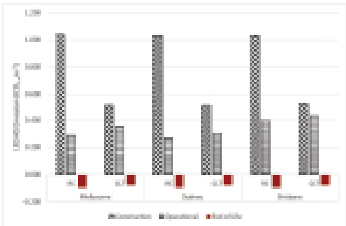
- Life cycle GHG emissions
- ✓ Breakdown of GHG emissions for the operational phase were calculated with the GHG emission factors for electricity in different cities and recurring GHG emissions from the replacement of components.



48

Results

- **Life cycle GHG emissions**
  - ✓ Breakdown of total GHG emissions related to the construction, operation and end of life phases of the RC and CLT building.

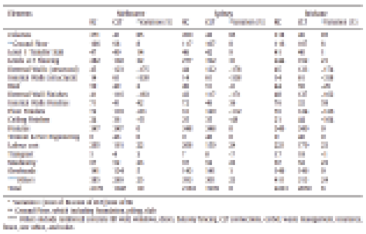


49

Results

- **Life Cycle cost**
  - ✓ Comparison between the initial costs of RC and CLT buildings in Melbourne, Sydney and Brisbane.

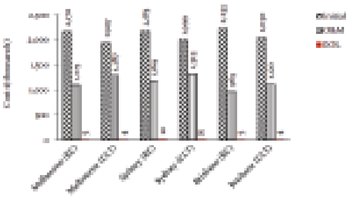
Initial costs($ k) of RC and CLT buildings.



50

Results

- **Life Cycle cost**
  - ✓ Comparison between the total O&MCs of RC and CLT buildings in Melbourne, Sydney and Brisbane.



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Conclusions

- The embodied GHG emissions of the CLT building in the product and construction phase is 50 % lower than that of RC building. This is due to significant reduction of energy intensive material usage in the CLT building.
- The CLT building has slightly lower operational GHG emissions in Sydney and Brisbane, but slightly higher operational GHG emissions in Melbourne.
- The recovery of energy via incineration of CLT components in EOL stage showed significant saving in GHG emissions.
- CLT building has less initial cost than that of RC building, the savings ranging from 8-10%, depending on the city. During the operation phase, the CLT building was found to be 13-16% more expensive than the RC option.
- The lower demolition, transportation and recycling cost of CLT over RC building at the end-of-life phase can be primarily attributed to the lighter weight of CLT.
- The total life cycle cost of CLT building is 0.9–1.3% lower than that of the conventional RC building.

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Future Recommendations

- Based on the life cycle perspective for a period of 50 years, the CLT building has outperformed RC building in the product and construction phase.
- However, optimisation of energy, GHG emissions and cost during the operational phase with new methodologies is required to realise the net benefits of CLT as a sustainable mate- rial.
- Furthermore, more sustainable strategies for timber products at the end of its life span can be used to add value to CLT products.

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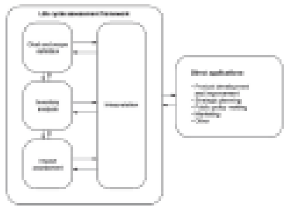
(3) Lifecycle Analysis Framework of Componentised Internal Walls

54

Life Cycle Assessment (LCA) methodology

- LCA is an environmental methodology for evaluating the environmental impacts of a product or process from its origin to its final disposal and follows international standards (ISO 14040 and ISO 14044) based on four stages:
  - ➢ defining the goal and scope,
  - ➢ Life Cycle Inventory (LCI),
  - ➢ Life Cycle Impact Assessment (LCIA) and
  - ➢ Interpretation.



The LCA framework according to ISO 14040.

55

(1) Definition of goal and scope

- The goal of the present project is to evaluate in detail:
  - ➢ the environmental impact of the construction phase of a reference building and compare different combinations of real construction scenarios for internal walls.
  - ➢ the environmental impact (e.g energy saving etc) of the internal wall during the service life (operational lifetime of approximately 50 years).
- The functional unit used in the model of the construction phase has been defined as
  - ➢ the construction of 1 m^2 horizontal living area over the period of 50 years (y), when the reference building is assessed, and
  - ➢ the construction of 1 m^2 vertical area over the period of 50 years (y) for the internal walls assessment, and the evaluation of the waste management scenarios for these walls.

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(1) Definition of goal and scope

- The analysis of the construction phase was divided into the following processes:
  - Fabrication phase involving the production and manufacturing of the material and the energy consumption associated with the extraction.
    - * Method for considering OH&S issues associate with onsite production.
  - The energy consumption by the building machinery and the CO_2 emitted by this machinery.
  - The transport of the raw materials from the factory to the building site.
  - The waste management resulting from the disposal of material and packaging wastes in the working site, and including their transport to the final destination (landfill, incineration or recycling plant).

57

(1) Definition of goal and scope

- The following assumptions will be considered for the transport model:
  - The transport of the materials from their production sites to the material distributors will be included in the data.
  - The transport of the materials to the building site will be evaluated from the materials distributors to the place the building is located. The locations of the building were assumed to be in the central business district (CBD) of each city (Sydney, Melbourne and Brisbane).
  - The transport for the waste management considers the distance (in km) to the waste management plants closest to the building site.

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(1) Definition of goal and scope

- The LC analysis during service life phase will take into account:
  - Assessment of ongoing defects costs and maintenance.
  - Deterioration progress of building material
  - Social and economic factors
  - Factoring in cost of emissions relative to overall carbon zero goals

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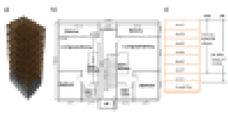
(2) Life Cycle Inventory (LCI)

- In order to calculate the building materials by mass the database PR/PCT 08 was used (ITECa). This database contains reference costs, generic technical documents and environmental information on more than 800 construction products.
- Therefore, two systems scenarios will be evaluated:
  - the reference building and
  - Componentised walls.

60

(2) Life Cycle Inventory (LCI)

- 2.1 - System description for the reference building
- As a reference building we will select a typical block of flats located in main cities in Australia. The block consists of eight floors. Below Figure depicts the layout of the studied building.
- The area and height of the building are 156m² and 25 m, respectively.
- The reference building will be divided into several systems to allow for easier tracking of the building materials: foundation and basement, structural frame, roofing, internal walls, external walls, pavement, flooring, insulation, painting, architectural finishing, carpentry, sanitary plumbing, demolition and other installations.



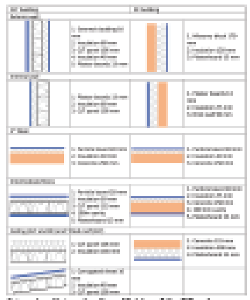
Schematic diagram of the case study building: a) 3D view; b) plan view; and c) elevation view.

61

(2) Life Cycle Inventory (LCI)

2.2 - System description for the internal walls

- The scenarios under study have eight internal walls (vertical interior enclosures (VIE), such as partition walls).
- The detail of the internal wall is as shown in the Figure.



External and internal walls and finishes of the CLT and RC buildings.

62

(2) Life Cycle Inventory (LCI)

2.2 - System description for the internal walls

Densities, embodied energy (EE) intensity and embodied greenhouse gas (EGHG) intensities of construction materials [The Environmental Performance in Construction (EPIC) database]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]

63

(2) Life Cycle Inventory (LCI)

- 2.3 - System description for the waste management scenarios
- The different treatment scenarios for the management of the wastes generated at the building site are described as follows:
- *Landfill*: all the wastes are disposed to landfill.
- *Recycling*: recyclable wastes are sent to a recycling plant, non-recyclable wastes are sent to an incineration plant and non-recyclable or incinerable wastes are sent to landfill.
- *Incineration* covers the plant infrastructure, the incineration process, the electricity generated and the disposal of ashes. Electrical energy recovery (calculated from calorific value data) and the amount of residual ashes (which are disposed by landfill) are also considered.

64

(2) Life Cycle Inventory (LCI)

- 2.3 – System description for the waste management scenarios
- The different treatment scenarios for the management of the wastes generated at the building site are described as follows:
- *Landfill*: all the wastes are disposed to landfill.
- *Recycling*: recyclable wastes are sent to a recycling plant, non-recyclable wastes are sent to an incineration plant and non-recyclable or incinerable wastes are sent to landfill.
- *Incineration* covers the plant infrastructure, the incineration process, the electricity generated and the disposal of ashes. Electrical energy recovery (calculated from calorific value data) and the amount of residual ashes (which are disposed by landfill) are also considered.

65

(3) Life Cycle Impact Assessment (LCIA)

- The *Environmental Performance in Construction (EPIC)* database will be used to obtain the inventory data of the processes involved in the study. These processes were adapted on the Australian system. The quality requirements related to the data used are defined by the following parameters:
- Region of the scenario: Sydney, Melbourne and Brisbane.
- Geographic field: Australian data.
- Technological field: mixed technology.

66

(4) Interpretation

- Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and/or the LCIA.
- The outcome of the interpretation phase is a set of conclusions and recommendations for the study. According to ISO 14040:2006, the interpretation should include the following:
  - *Identification*. Structure the results from the LCI or LCIA phases in order to help determine the significant issues, in accordance with the goal and scope definition and interactively with the evaluation element.
  - *Evaluation*. Establish and enhance confidence in, and the reliability of, the results of the LCA or the LCI study, including the significant issues identified in the first element of the interpretation.
  - *Conclusions, limitations, and recommendations*. Draw conclusions, identify limitations, and make recommendations for the intended audience of the LCA.

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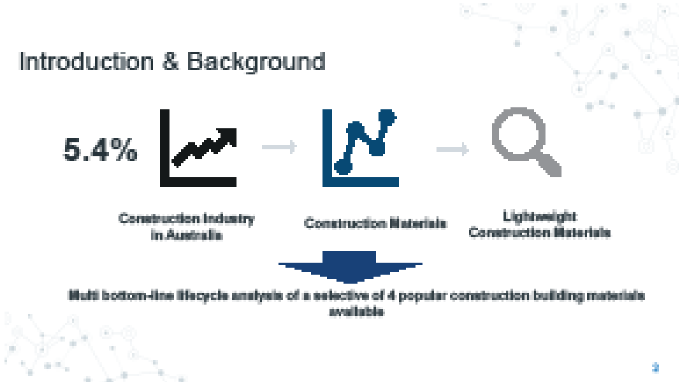
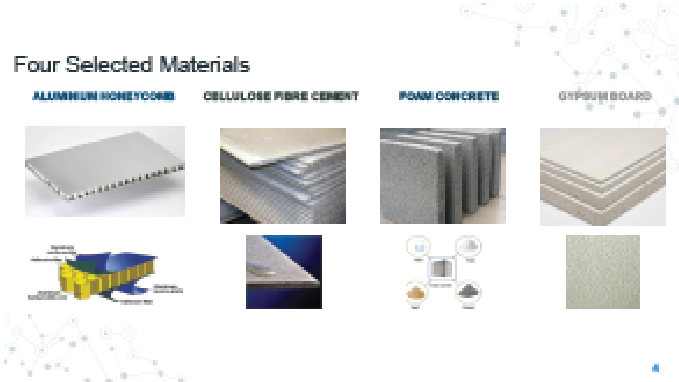
7.3 PERFORMANCE AND LIFE-CYCLE

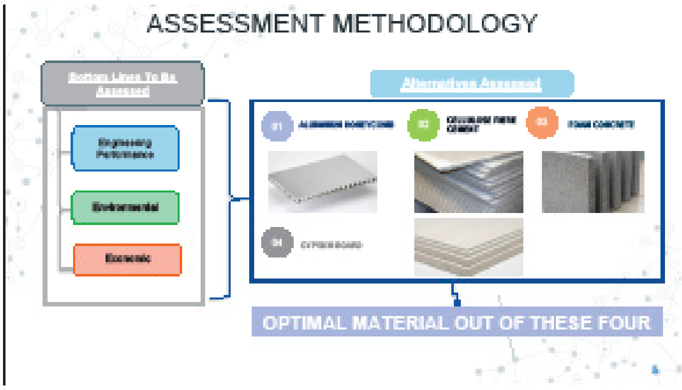
This appendix contains an summary of research undertaken into life-cycle assessment tools.


Lifecycle Analysis on
Selected Locally
Available Lightweight
Construction Materials

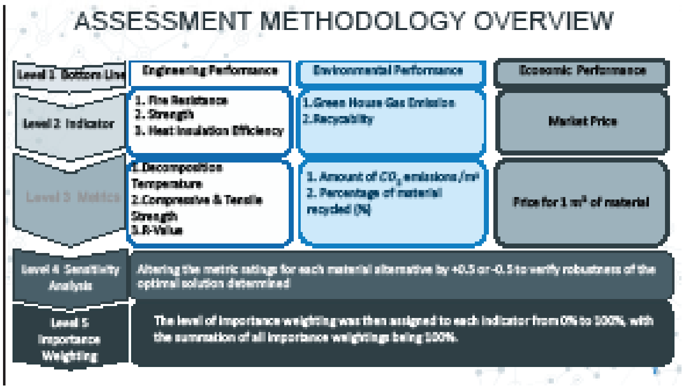

Introduction & Background
5.4%
Construction Industry in Australia
Construction Materials
Lightweight Construction Materials
Multi bottom-line lifecycle analysis of a selective of 4 popular construction building materials available


Project Objectives
1
Provide a comprehensive overview of selected materials across the bottom lines of engineering performances, environmental evaluation and cost evaluation.
2
Find the most desirable material out of the list of 4 construction materials.
3
Identify potential research direction and room for improvement in assessing different types of construction materials.


Four Selected Materials
ALUMINIUM HONEYCOMB
CELLULOSE FIBRE CEMENT
FOAM CONCRETE
GYPSUM BOARD


ASSESSMENT METHODOLOGY
Bottom Lines To Be Assessed
Engineering Performance
Environmental
Economic
Alternatives Assessed
ALUMINIUM HONEYCOMB
CELLULOSE FIBRE CEMENT
FOAM CONCRETE
GYPSUM BOARD
OPTIMAL MATERIAL OUT OF THESE FOUR

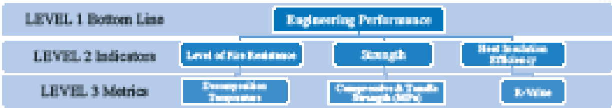

ASSESSMENT METHODOLOGY
System Boundaries
TIME
50 YEARS
SPATIAL
General Residential Zones
FUNCTIONAL UNIT


ASSESSMENT METHODOLOGY OVERVIEW
Level 1 Bottom Line
Engineering Performance
Environmental Performance
Economic Performance
Level 2 Indicator
1. Fire Resistance
2. Strength
3. Heat Insulation Efficiency
1. Green House Gas Emission
2. Recyability
Market Price
Level 3 Metrics
1. Decomposition Temperature
2. Compressive & Tensile Strength
3. R-Value
1. Amount of CO_2 emissions /m^2
2. Percentage of material recycled (%)
Price for 1 m^2 of material
Level 4 Sensitivity Analysis
Altering the metric ratings for each material alternative by +0.5 or -0.5 to verify robustness of the optimal solution determined
Level 5 Importance Weighting
The level of importance weighting was then assigned to each indicator from 0% to 100%, with the summation of all importance weightings being 100%.


Engineering Bottom line

ASSESSMENT METHODOLOGY

Engineering Bottom Line Overview :



ENGINEERING PERFORMANCE

Specifics

Indicator and Metrics		
Main Indicator	Metrics	Direction
Level of fire resistance	Decomposition temperature (°C) BAL 29 Fire Withstand Time (Mins)	More is better
Strength	Compressive and tensile strength (MPa)	More is better
Heat insulation efficiency	$R-Value = \frac{Thickness}{thermal\ conductivity}$	More is better

Engineering Performance Criteria				
	Decomposition temperature °C	Compressive (MPa)	Tensile strength (MPa)	R-Value
Score 5 Performance	[illegible] °C RFP: 60 min	15 MPa	1.50 MPa	0.60
Score 0 Performance	[illegible] °C Cannot hold shape in BAL 29 fire	1MPa	0.5 MPa	0.00

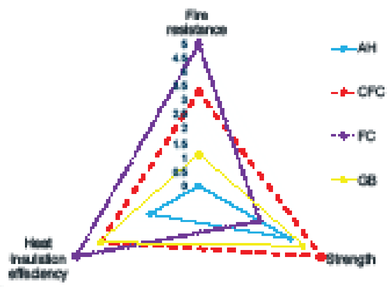
ENGINEERING PERFORMANCE

Results

	Level of fire resistance	Strength		R-Value Thickness assumed to be 22 mm, as it is a typical internal partition wall
		Comp.	Tensile	
Aluminium Honeycomb	Deformation Temperature 415°C	3.8 MPa	125 MPa	R Value = 0.055
Cellulose fibre cement	Deformation Temperature 800°C	20 MPa	7 MPa	R Value = 0.406
Foam Concrete	Deformation Temperature 850°C	4-19 MPa Typically 4 MPa	0.8-1.6 MPa	R Value = 0.747
Gypsum Board	Deformation Temperature 300°C	4.8 – 6.7 Mpa Typically 5.3MPa	1.5-2.4 MPa Typically 1.9 MPa	R Value = 0.52

ENGINEERING PERFORMANCE

Visualised Results



Environmental Bottom line

ASSESSMENT METHODOLOGY

Environmental Bottom Line Overview :

ENVIRONMENTAL PERFORMANCE

Specifics

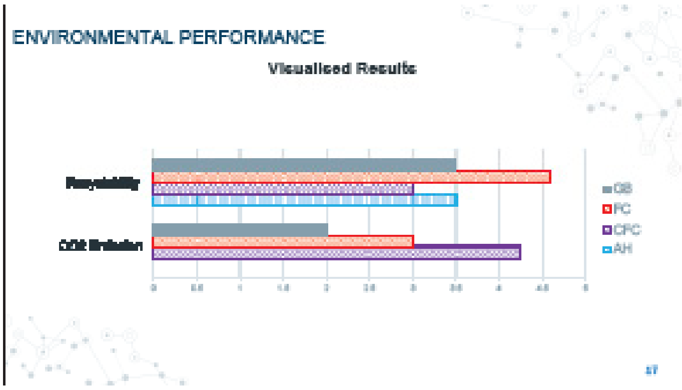
Indicator and Metrics		
Main Indicator	Metric	Direction
Greenhouse gas emission	Amount of CO_2 emissions /m³	Less is better
Recyclability	Percentage of material recycled (%)	More is better

Environmental Scoring Criteria		
	Amount of CO_2 emissions /m³	Percentage of material recycled (%)
Score 5 Performance	No Emission - 0 kg/m³	100%
Score 0 Performance	510 kg/m³	0%

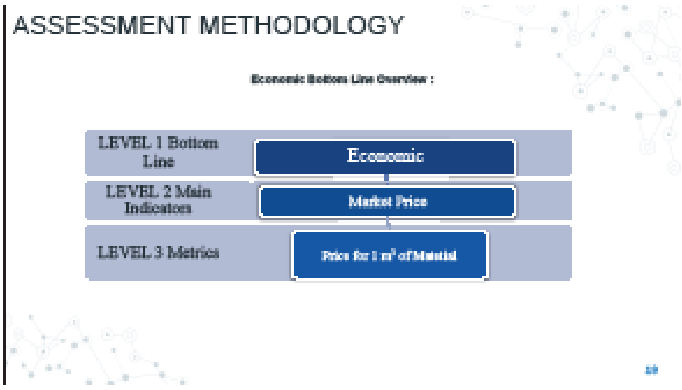
ENVIRONMENTAL PERFORMANCE

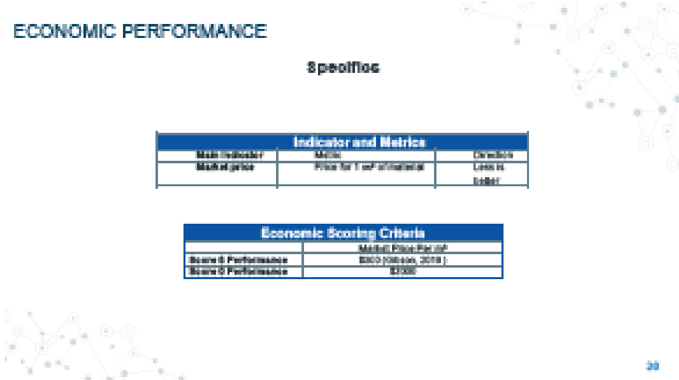
Results

	Amount of CO_2 emissions /m3	Percentage of material recycled (%)
Aluminium Honeycomb	2184.2 $kg\ CO_{2}eq/m^3$	70%
Cellulose fibre cement	76.4 $kg\ CO_{2}eq/m^3$	60%
Foam Concrete	196.9 $kg\ CO_{2}eq/m^3$	93-98%
Gypsum Board	301.8 $kg\ CO_{2}eq/m^3$	70%

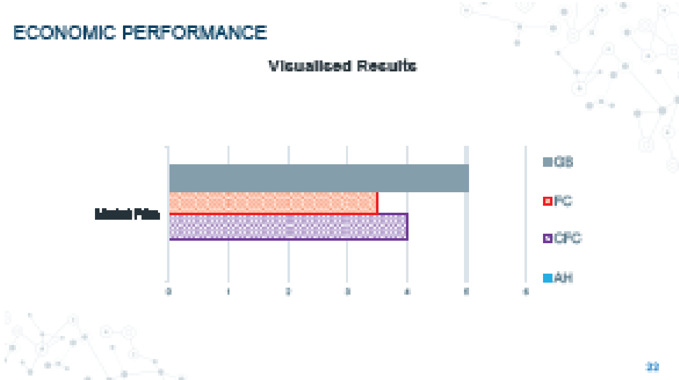

ENVIRONMENTAL PERFORMANCE
Visualised Results
Recyclability
CO2 Emission
GB
FC
CFC
AH
17

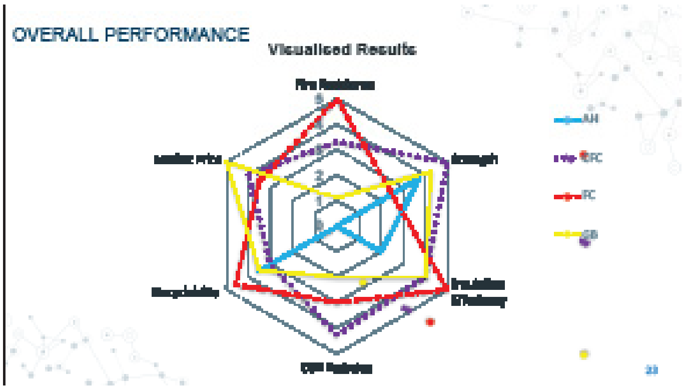

Economic Bottom line
18


ASSESSMENT METHODOLOGY
Economic Bottom Line Overview :
LEVEL 1 Bottom Line
Economic
LEVEL 2 Main Indicators
Market Price
LEVEL 3 Metrics
Price for 1 m³ of Material
19

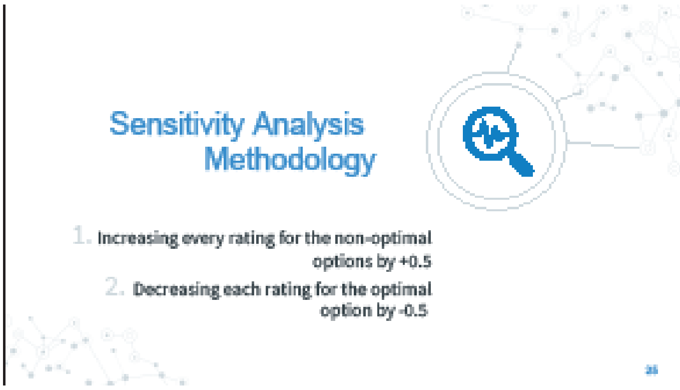

ECONOMIC PERFORMANCE
Specifics
Indicator and Metrics
Economic Scoring Criteria
20

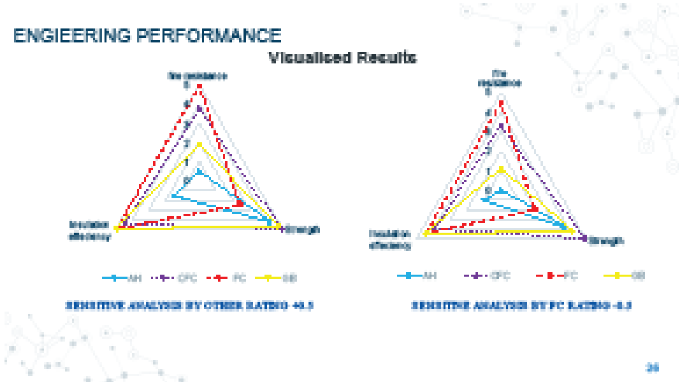

ECONOMIC PERFORMANCE
Results
Market Price per cubic materials
Aluminium Honeycomb
$3,000.00
Cellulose fibre cement
$617.28
Foam Concrete
$1,000.00
Gypsum Board
$59.00
21

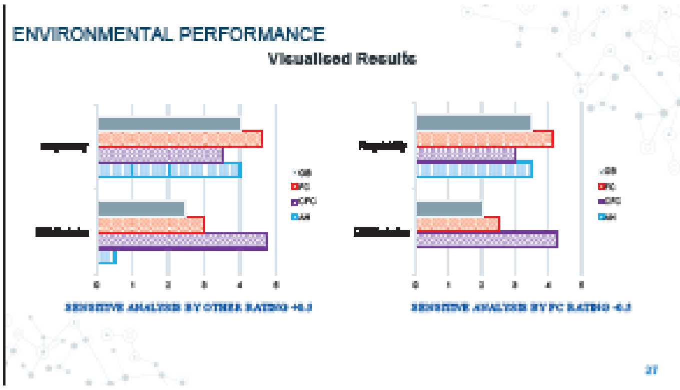

ECONOMIC PERFORMANCE
Visualised Results
Market Price
GB
FC
CFC
AH
22

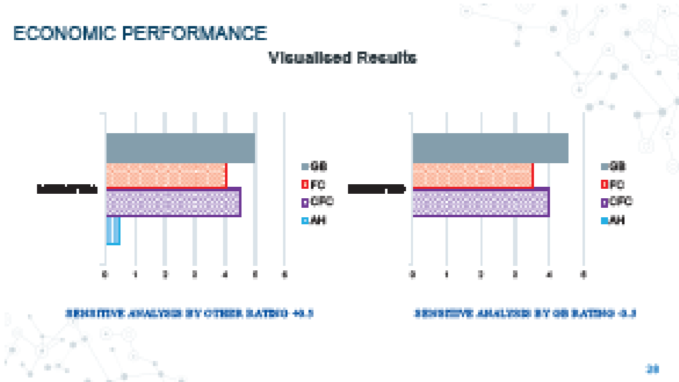

OVERALL PERFORMANCE
Visualised Results
Fire Resistance
Strength
Insulation Efficiency
CO2 Emission
Recyclability
Market Price
AH
CFC
FC
GB
23

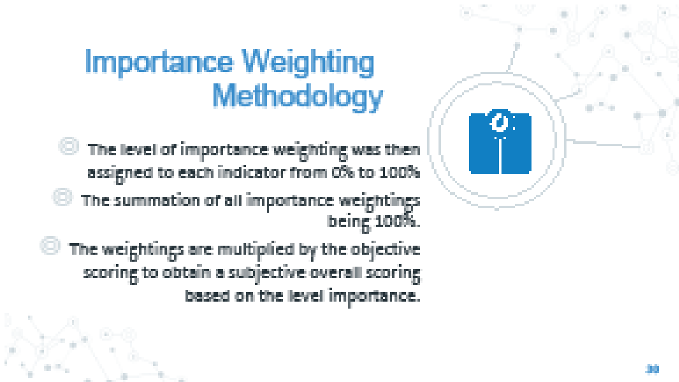

Sensitivity Analysis
24

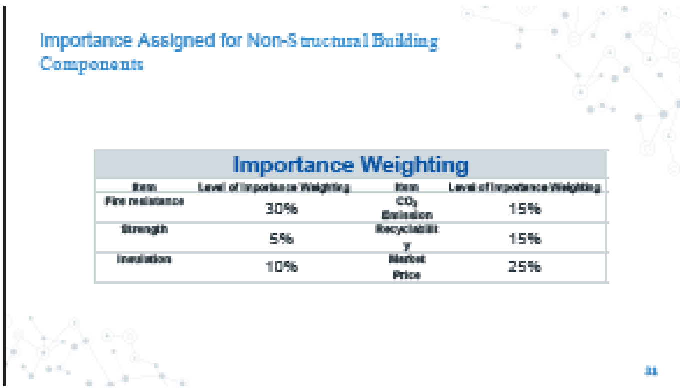






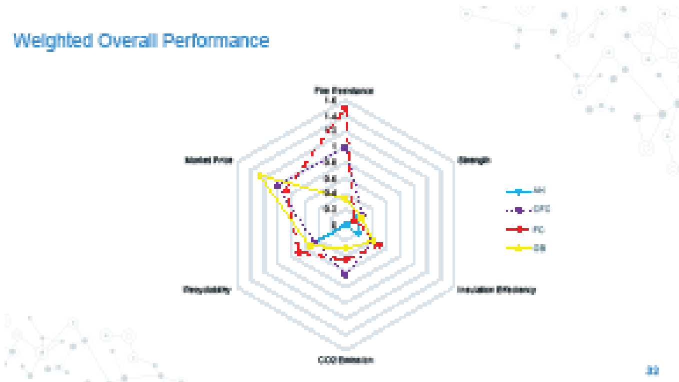




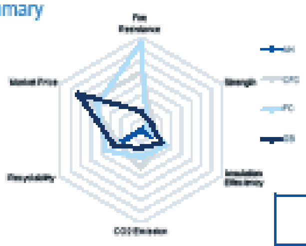


Importance Weighting

Item	Level of Importance Weighting	Item	Level of Importance Weighting
Fire resistance	30%	CO_2 Emission	15%
Strength	5%	Recyclability	15%
Insulation	10%	Market Price	25%



Summary



	Building Material Alternative			
	Aluminum Honeycomb	Cellulose Fibre Cement	Foam Concrete	Gypsum Board
Engineering			■	
Environmental			■	
Economic				■

Conclusion

Conclusion

foam concrete is a technically sound, relatively environmentally friendly and economically attractive material to be utilised in the construction industry as an alternative to the conventional materials.

Recommendations

- Recommend to researchers that this material alternative to be further investigated in order to see whether the embedded carbon can be further reduced by adopting different ingredients.
- Recommend to researchers to also look in to reducing the production price of foam concrete and aluminium honeycomb by altering the structure and/or the formula.

Next step

- Readjustment to level of importance weighting values of metrics based on specific cases or according to relevant to local government agencies.
- Addition of more indicators under each bottom line in order to provide an even more comprehensive and deep analysis

Life cycle performance of Cross Laminated Timber mid -rise residential buildings in Australia

Introduction

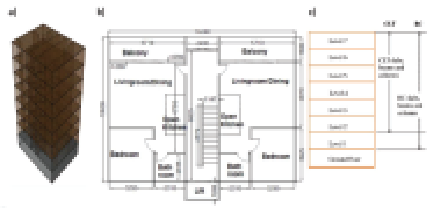
- Recent study by UoM compared the life-cycle greenhouse gas emissions (LCGHGE) and life-cycle cost (LCC) of CLT and traditional reinforced concrete (RC) residential buildings for three cities in Australia (Melbourne, Sydney and Brisbane).
- Life cycle analyses were conducted within the boundaries of the product and construction, operational and maintenance (O&M), and end of life (EOL) phases.
- The results are compared with a conventional RC building with a similar size, height and layout.

Method

- Assumptions and justifications for the analyses are provided as follows:
  - The discount rate was assumed to be 7% based on Infrastructure Australia (Assessment framework, 2018).
  - The concrete waste was assumed to be sent to landfill as suggested by (Senaratne et al., 2016).
  - The CLT wastes were assumed to be incinerated as they are not suitable for landfill because they contain chemicals for termite protection (Oliveria et al., 2018).
  - The locations of the building were assumed to be in the central business district (CBD) of each city.
  - CLT components were assumed to be supplied from an existing manufacturer located in Wodonga. Therefore, the transportation distances to the Melbourne, Sydney and Brisbane CBD were estimated as 323 km, 560 km and 1398 km, respectively.
  - The transportation distance from the concrete supplier to the construction site was assumed to be 80 km.
  - The construction time of CLT building was taken as 30% less than that of the RC Building (Kremer & Richa, 2018).

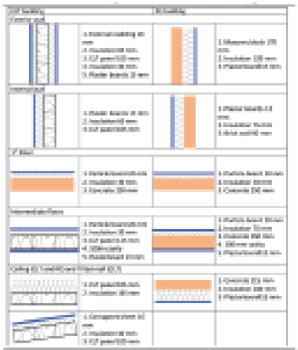
Case study building

- Two mid-to-high rise eight-storey residential RC and CLT buildings with similar dimensions were selected for LCGHGE and LCC analyses in this investigation (Fig. 1).
- Schematic diagram of the case study building: a) 3D view; b) plan view; and c) elevation view.



Case study building

- The area and height of these buildings are 158m2 and 25 m, respectively.
- The ground floor and foundation of both buildings is traditional RC.
- The thickness of the ground floor slab in RC building is 300 mm. The slab thickness of Level 2-7 of the RC building is 250 mm.
- Whilst the CLT building floor is constructed with 115 mm thick Australian Radiata pine CLT panels (i.e. CL3/115). The roof of the CLT building is constructed with 105 mm thick Australian Radiata pine CLT panels (i.e. CL3/105) and corrugated metal cladding.
- Details on the external and internal wall, and wall finishes are provided in Table 1.

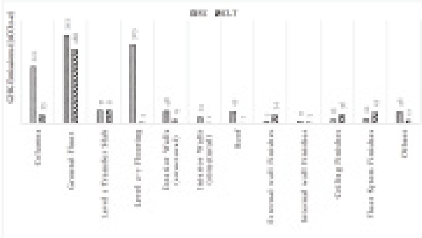


Case study building

- These case study residential buildings were categorised as NCC Class 2 buildings and designed according to the Australian standard AS/NZS 1170; ultimate limit state and serviceability.
- To account for the deemed to satisfy condition in National Construction Code (NCC), the fire resistance level of the CLT wall and floor was considered as 90/60/30 min, respectively for structural resistance/integrity resistance/insulation (Frangi et al., 2009).
- The 278 mm wall thick- ness, which includes the 115 mm thick CLT panel, floor finish and 113 mm ceiling with its cavity, satisfy the NCC acoustic and vibration criteria for floors (Pagnoncelli and Morales, 2016).

Results

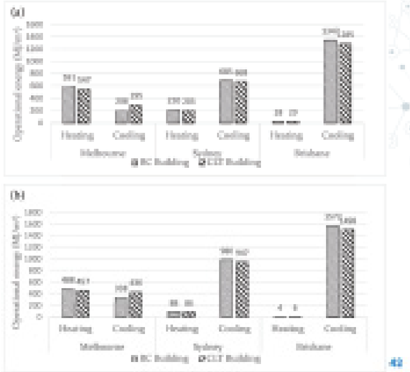
- **Life cycle GHG emissions**
  - ✓ Breakdown of GHG emissions related to the construction phase of the CLT and RC buildings



41

Results

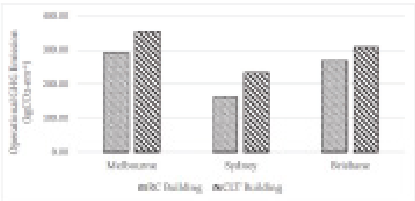
- **Life cycle GHG emissions**
  - ✓ Breakdown of the heating and cooling operational energy for a 50-year life span of the building for the three cities.



42

Results

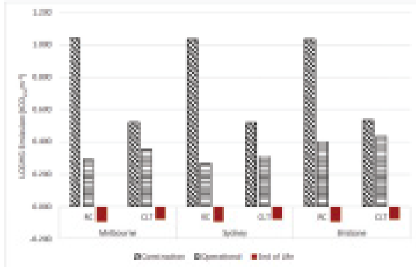
- **Life cycle GHG emissions**
  - ✓ Breakdown of GHG emissions for the operational phase were calculated with the GHG emission factors for electricity in different cities and recurring GHG emissions from the replacement of components.



43

Results

- **Life cycle GHG emissions**
  - ✓ Breakdown of total GHG emissions related to the construction, operation and end of life phases of the RC and CLT building.



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Results

- **Life Cycle cost**
  - ✓ Comparison between the initial costs of RC and CLT buildings in Melbourne, Sydney and Brisbane.

Initial costs ($ k) of RC and CLT buildings.

Elements	Melbourne			Sydney			Brisbane		
	RC	CLT	*Variation (%)	RC	CLT	*Variation (%)	RC	CLT	*Variation (%)
Columns	271	41	85	288	42	85	318	48	85
**Ground floor	108	99	8	117	109	8	118	109	8
Level 1 Transfer Slab	47	40	14	48	42	9	48	49	1
Levels 2-7 Flooring	266	183	32	277	183	35	264	184	29
External Walls (structural)	45	128	-173	46	122	-178	45	123	-178
Internal Walls (structural)	34	61	-338	36	61	-338	16	61	-338
Roof	39	40	3	40	31	-6	40	29	-27
External Wall Finishes	45	118	-163	45	117	-171	48	127	-163
Internal Walls Finishes	71	41	42	72	46	35	75	32	58
Floor Finishes	72	118	-63	60	129	-112	55	124	-126
Ceiling Finishes	24	35	-51	25	35	-40	21	46	-104
Kitchens	349	349	0	368	368	0	368	368	0
[illegible] & Fire Engineering	0	40	0	0	40	0	0	40	0
Labour cost	205	163	20	208	155	34	204	170	20
Transport	5	4	3	7	8	-5	17	18	-1
Machinery	67	52	23	67	52	23	67	52	23
[illegible]	140	138	1	143	143	1	148	148	0
***Others	383	269	30	359	289	23	411	311	24
Total	2174	1947	10	2103	1938	8	2250	2069	8

* Variation = (cost of RC-cost of CLT)/cost of RC
** Ground floor, which including foundation, piling, slab
*** Others include reinforced concrete lift wall, windows, doors, balcony fencing, CLT connectors, crane, waste management, insurance, fees, site office, and toilets.

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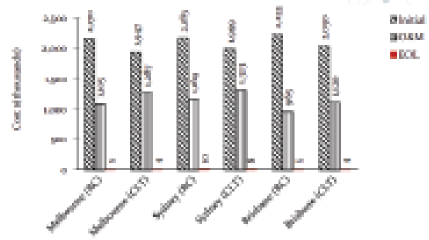
Results

- **Life Cycle cost**
  - ✓ Comparison between the total OB&MCs of RC and CLT buildings in Melbourne, Sydney and Brisbane.



46

Conclusions

- The embodied GHG emissions of the CLT building in the product and construction phase is 50 % lower than that of RC building. This is due to significant reduction of energy intensive material usage in the CLT building.
- The CLT building has slightly lower operational GHG emissions in Sydney and Brisbane, but slightly higher operational GHG emissions in Melbourne.
- The recovery of energy via incineration of CLT components in EOL stage showed significant saving in GHG emissions.
- CLT building has less initial cost than that of RC building, the savings ranging from 8-10%, depending on the city. During the operation phase, the CLT building was found to be 13-18% more expensive than the RC option.
- The lower demolition, transportation and recycling cost of CLT over RC building at the end-of-life phase can be primarily attributed to the lighter weight of CLT.
- The total life cycle cost of CLT building is 0.9-1.3% lower than that of the conventional RC building.

47

Future Recommendations

- Based on the life cycle perspective for a period of 50 years, the CLT building has outperformed RC building in the product and construction phase.
- However, optimisation of energy, GHG emissions and cost during the operational phase with new methodologies is required to realise the net benefits of CLT as a sustainable mate- rial.
- Furthermore, more sustainable strategies for timber products at the end of its life span can be used to add value to CLT products.

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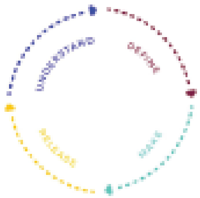
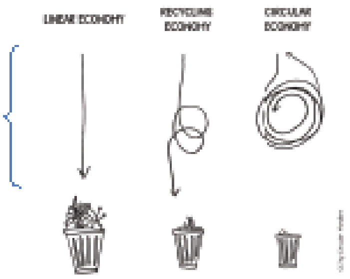
CIRCULAR DESIGN PRINCIPLES



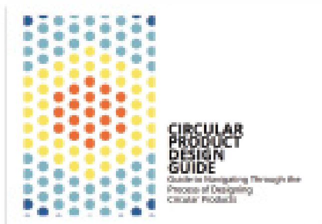
Service Life

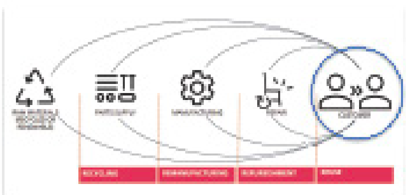


The "Pillars" of Circular Design

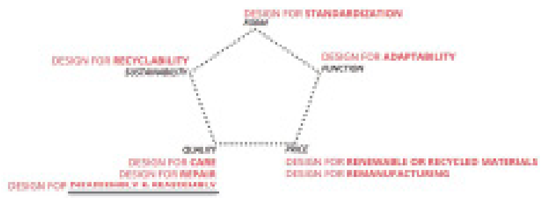
- Design out waste and pollution - *waste is a design flaw*
- Keep products and materials in use - *design for alteration, repair and remanufacture*
- Regenerate natural systems - *design processes and products that give back to the environment*

IKEA Guidelines





Defining circular loops through continuous engagement with Customers



Scoring System: No = 0, Somehow = 1, Yes = 2

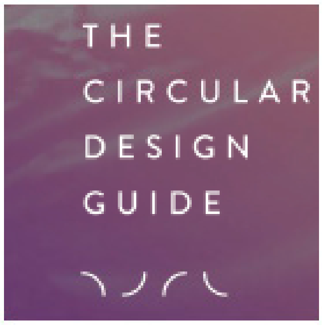
The Wedge Dowel Concept

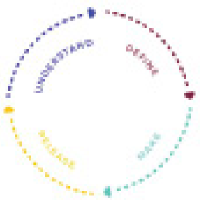
≠

Circularity principles for internal walls?

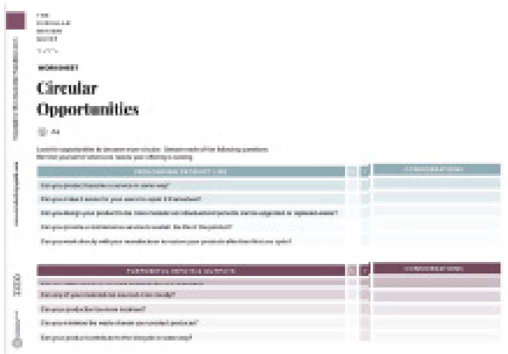
- Long service life
- Location specific
- Adaptability limits
- Volume to cost ratio
- Standardisation vs identity
- Etc...

IDEO's Design Guide





- Understand - Get to know the user and the system
- Define - Put into words the design challenge and your intention as the designer
- Make - Ideate, design, and prototype as many iterations and versions as you can
- Release - Launch your design into the wild and build your narrative - create loyalty in customers and deepen investment from stakeholders by telling a compelling story

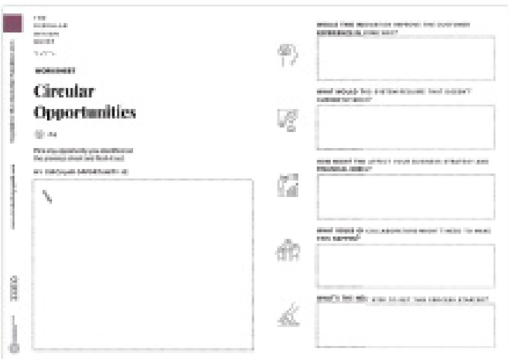


Understand

Define

Make

Release



Understand

Define

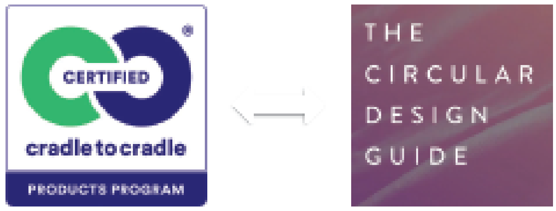
Make

Release

Can this lead to circular product development or to the definition of company-level circular design guidelines?

CIRCULAR DESIGN FRAMEWORK

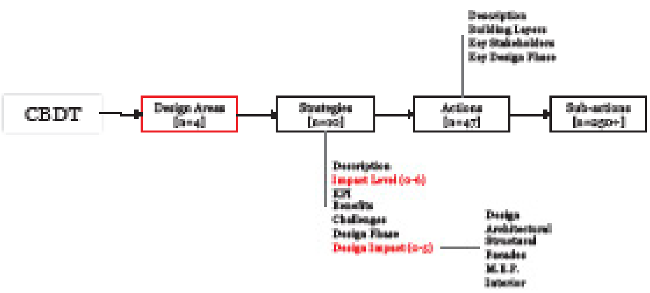
For Internal Wall Systems

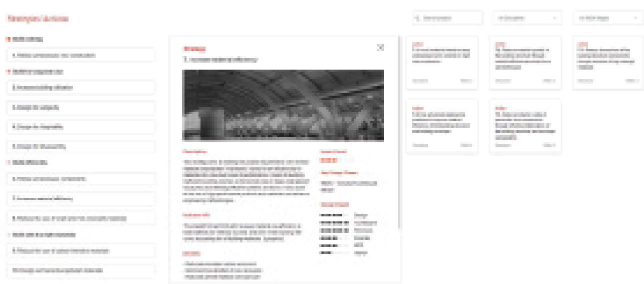


ARUP's Circular Building Design Toolkit (CBDT)

CBDT Strategies

- Build nothing
  - *refuse new construction*
- Building for long term value
  - *increase building utilisation*
  - *design for longevity*
  - *design for adaptability*
  - *design for disassembly*
- Building efficiently
  - *refuse unnecessary components*
  - *increase material efficiency*
  - *reduce the use of virgin materials*
- Building with the right materials
  - *reduce the use of carbon intensive materials*
  - *design out hazardous/polluting materials*





CBDT Strategies

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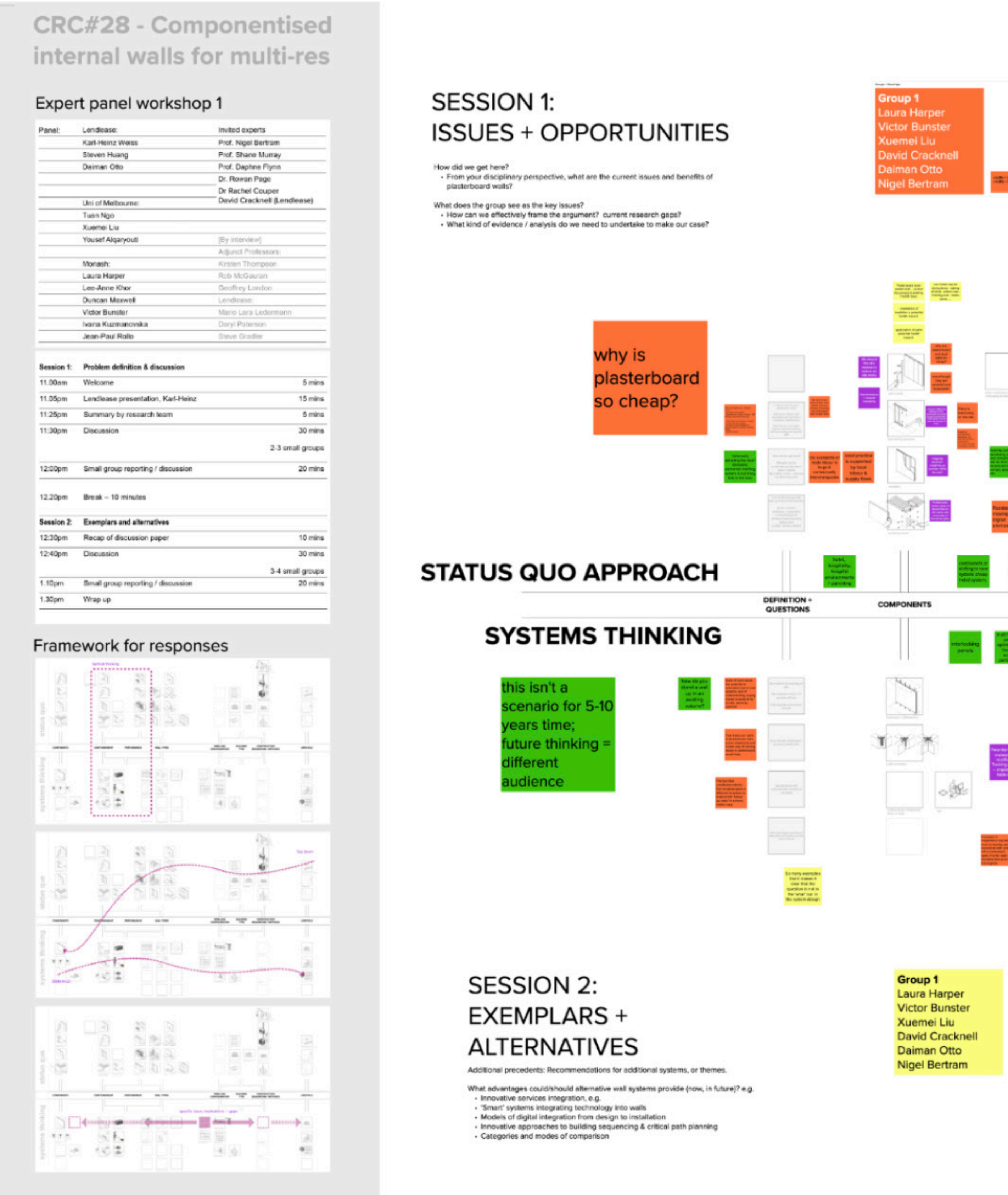
7.4 Workshops and outcomes
EP1 documentation



Group 2
Lee-Anne Khor
Ivana Kuzmanovska
Tuan Ngo
Rowan Page
Karl-Heinz Weiss
Shane Murray
Group 3
Jean-Paul Rollo
Duncan Maxwell
Yousef Alqaryouti
Daphne Flynn
Steven Huang
Rachel Couper
Entekra
never buy a car in it's first year of manufacture! >>> continuous improvement built into the 'commercial product roadmap'
CRAFTSMANSHIP
PERFORMANCE
WALL TYPES
DWELLING CONFIGURATION
BUILDING TYPE
CONSTRUCTION SEQUENCING / METHODS
LIFECYCLE
Digital integration with health and well being
New system to provide a clearly defined & flexible product suite in response to market needs and production capability — companies with wall-based product platforms that inform the 'higher-order' product offering (building-level)
Establish clear future-focused product development horizon with regards digital sensor integration — awareness of sensor r+d trajectory
Implications for digital data with regards maintenance, market, business model of delivery company?
Group 2
Lee-Anne Khor
Ivana Kuzmanovska
Tuan Ngo
Dr. Rowan Page
Karl-Heinz Weiss
Shane Murray
Group 3
Jean-Paul Rollo
Duncan Maxwell
Yousef Alqaryouti
Daphne Flynn
Steven Huang
Rachel Couper
Life span requirment of interior wall system
- Maximise opportunities for improving health and wellbeing, health monitoring systems, retrofitting for different users (aged care etc)
- Maximise opportunities for improved LCA/ Sustainability
- Acknowledge that new systems alter the traditional processes of design development, requiring a more integrated digital design process
Potential for reuse of wall components

7.4 Workshops and outcomes
EP1 outcome summary

COST

Can we reduce the amount of walls built – does this provide spatial benefits and cost benefits

Walls as a service – a subscription model

On-site experience demonstrates that the use of typical plasterboard wall systems is always cheaper – often half the time and one-third of the cost

TIME

Innovative approaches to building sequencing & critical path planning

Models of digital integration from design to installation

Once the stage of hanging plaster is reached, the process is fast

Other trades may take more time, e.g. wet trades require drying times, the setting of joints, primer coats and finishing coats, mastic joints

New requirements for regulatory site inspections increase time and cost

AVAILABILITY

The availability of common systems is known and there are many suppliers

The current skill-set and availability of trade labour to deliver the status quo is large and contractually interchangeable

What is the business viability for offsite facilities? This requires a large enough volume of work.

What is the logistics? If you take making off-site, you require a factory – space, weight, handling. Off-site construction relies on an off-site facility being within a reasonable distance from the site

FAMILIARITY

Could 'system' design begin with the design of supply chains in a particular context

A resistance to change – currently there is a familiarity across the board – from clients, architects, building designers, builders and building surveyors. New systems will require upskilling of trades. There are new challenges with moving to digital environments

ADAPTABILTY

How can joints in wall systems become useful? – live joints, lighting track systems

Explore the possibility of walls systems allowing for flexible rearrangement of interior spaces

So often, a suitable construction system is about the context. A 'system' will never fit every situation.

What is the lifespan requirement of interior wall systems

The standardisation and material modularity of the material provide a responsiveness of the product for different project scenarios

Plasterboard is perfect for hiding all manner of ills, damage, and workarounds. It acts as the final layer of "polish", hiding everything behind it.

The tolerance of junctions e.g. top and bottom junctions

Some repair work is required to install or integrate future services within an existing wall

HEALTH

Establish clear future-focused product development horizon with regards digital sensor integration — awareness of sensor R&D trajectory

'Smart' systems integrating technology into walls

The processing of plasterboard on site i.e. cutting and sanding can be a health issue

The application of paint is another health hazard

COMPLIANCE

What are the similarities between contexts? What are the things that everywhere has to deal with?

Contextual / universal. Local codes, local practices, local materials adapted to a universal

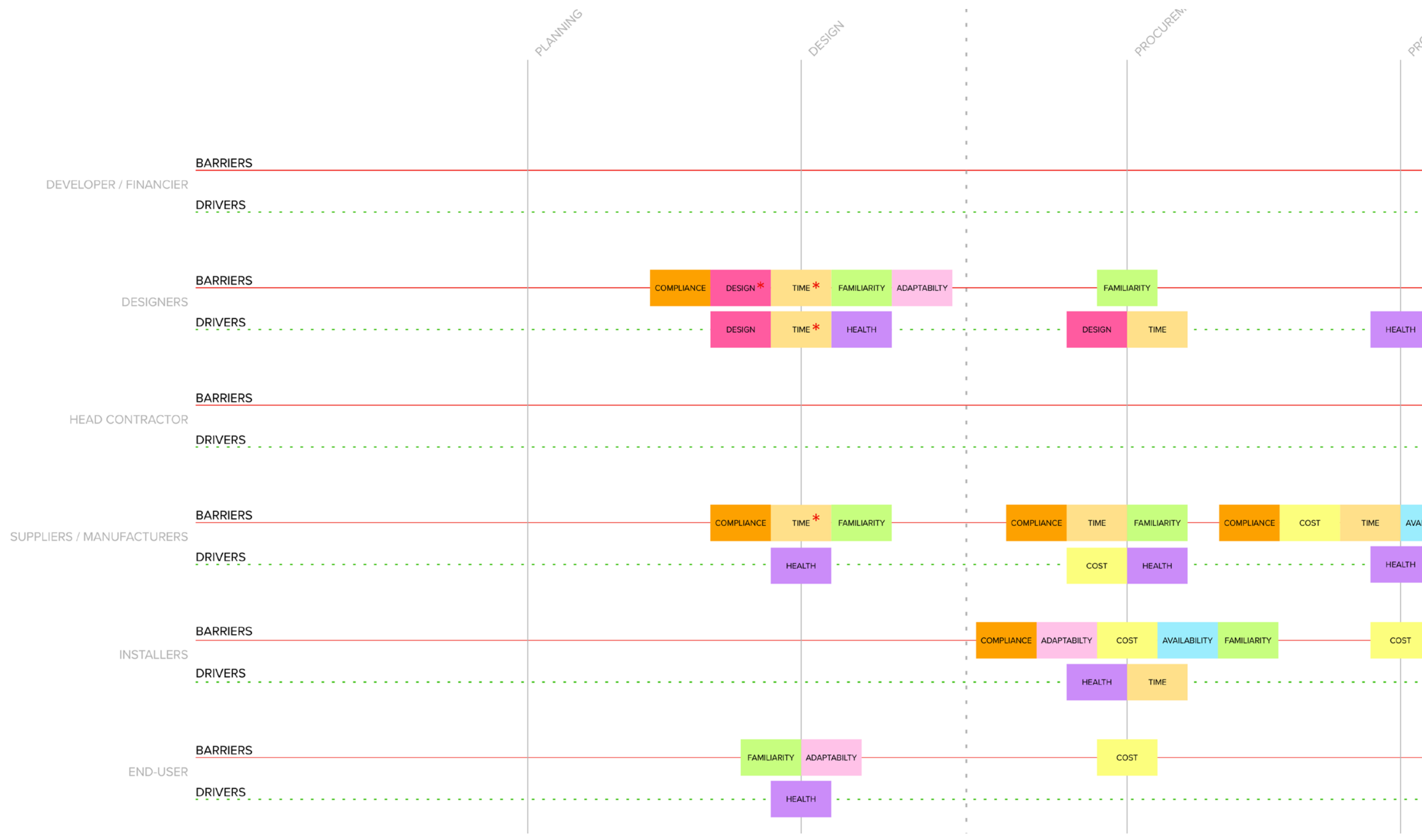
Increasing regulatory demands

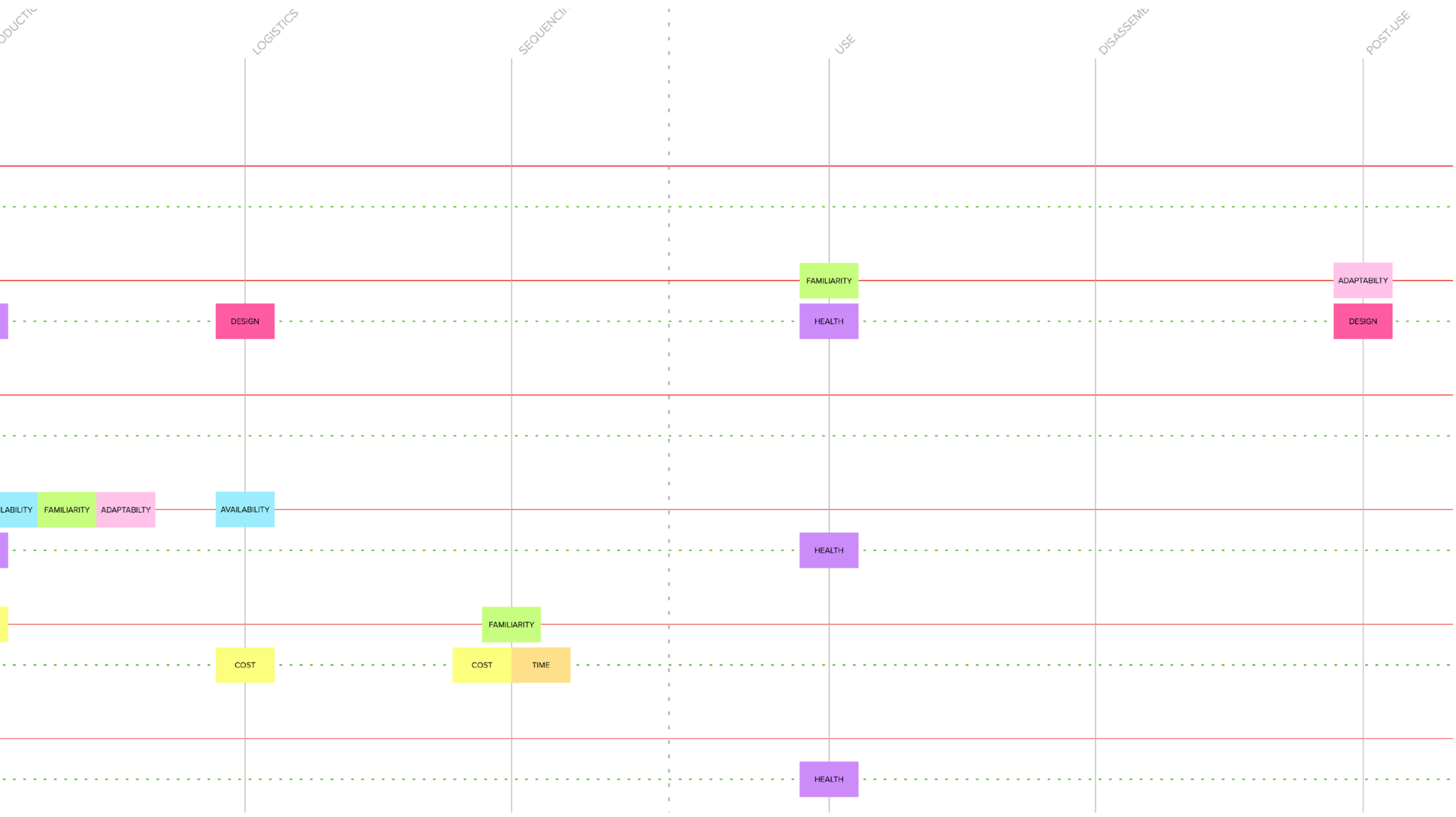
Fire performance is questionable for demountable wall types.

DESIGN

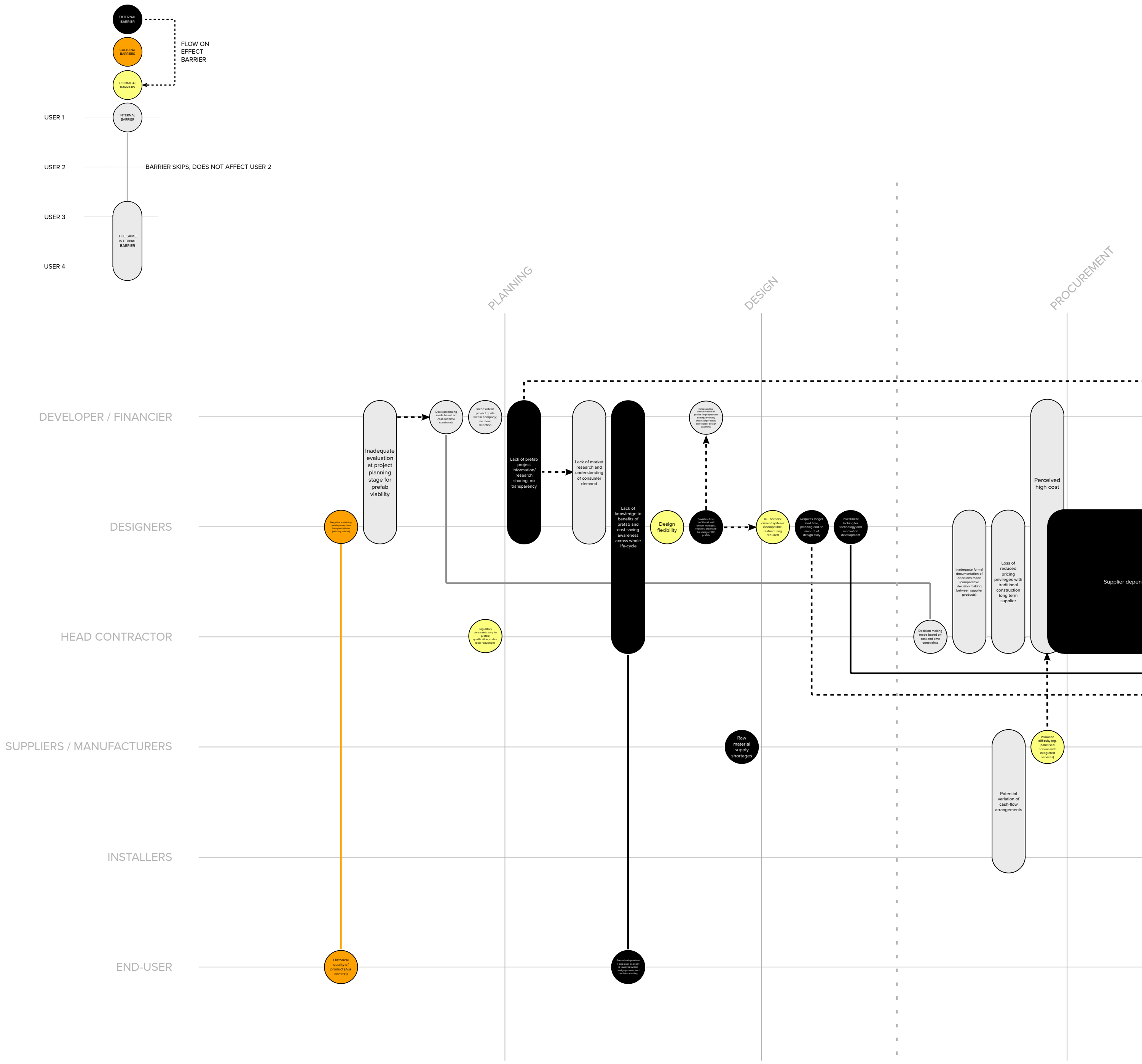
Explore the possibility of walls systems allowing for flexible rearrangement of interior spaces

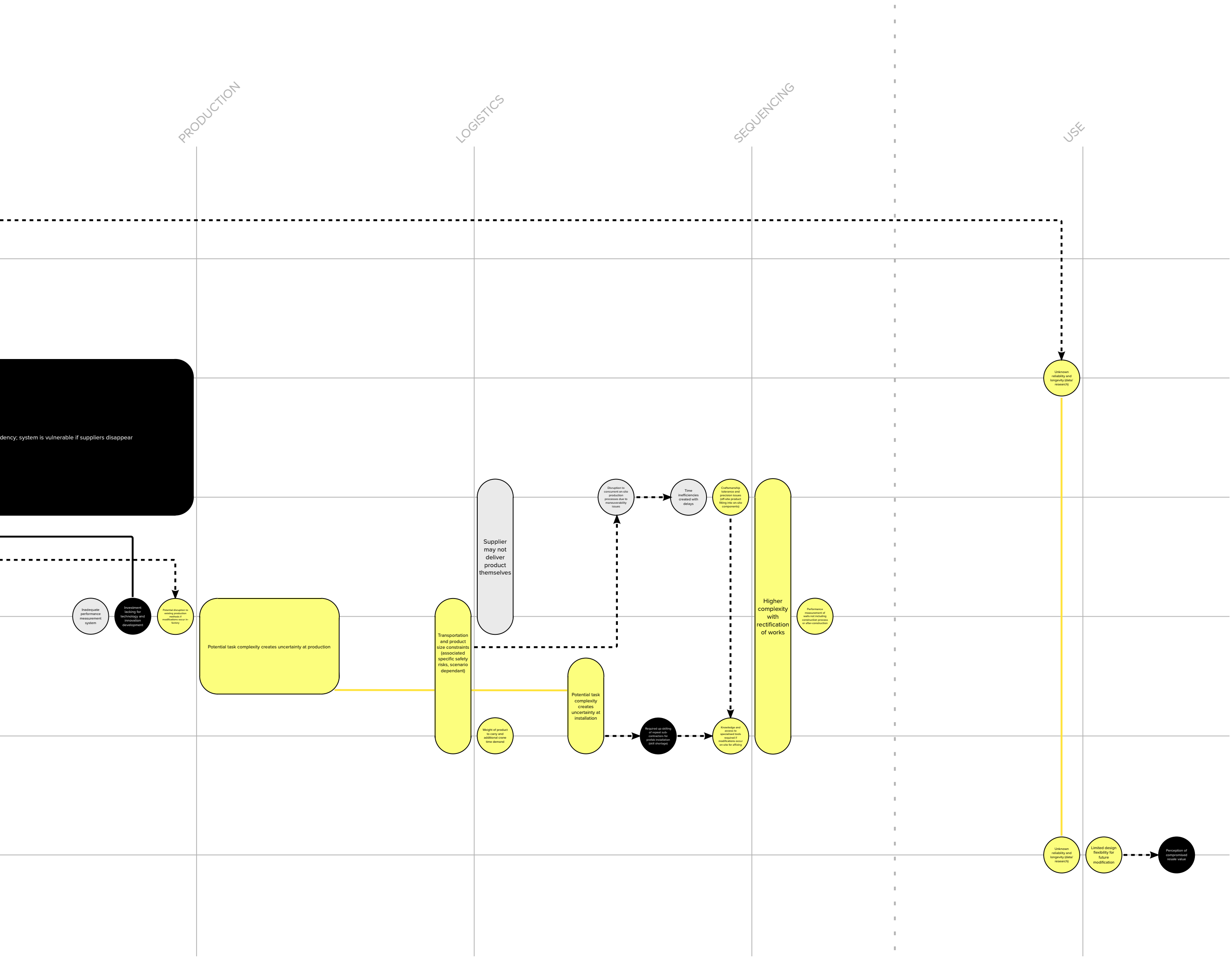
Acoustic separation of spaces through alternative methods like noise sampling and curtains




LOGISTICS
USE
POST-USE
FAMILIARITY
ADAPTABILTY
DESIGN
HEALTH
DESIGN
FAMILIARITY
ADAPTABILTY
AVAILABILITY
HEALTH
FAMILIARITY
COST
COST
TIME
HEALTH

7.4 Workshops and outcomes
EP2 barriers to adoption - diagram




PRODUCTION
LOGISTICS
SEQUENCING
USE
dency; system is vulnerable if suppliers disappear
Inadequate performance measurement system
Investment lacking for technology and innovation development
Potential disruption to existing production methods if modifications occur in-factory
Potential task complexity creates uncertainty at production
Transportation and product size constraints (associated specific safety risks, scenario dependant)
Supplier may not deliver product themselves
Weight of product to carry and additional crane time demand
Disruption to concurrent on-site production processes due to maneuverability issues
Time inefficiencies created with delays
Craftsmanship tolerance and precision issues (off-site product fitting into on-site components)
Potential task complexity creates uncertainty at installation
Required up-skilling of repeat sub-contractors for prefab installation (skill shortage)
Knowledge and access to specialised tools required if modifications occur on-site for affixing
Higher complexity with rectification of works
Performance measurement of walls not including construction process or after-construction
Unknown reliability and longevity (data/research)
Unknown reliability and longevity (data/research)
Limited design flexibility for future modification
Perception of compromised resale value

7.5 Interviews

The record of transcripts from interviews is not available to the public.

7.6 Student work from studies unit Wall Party!

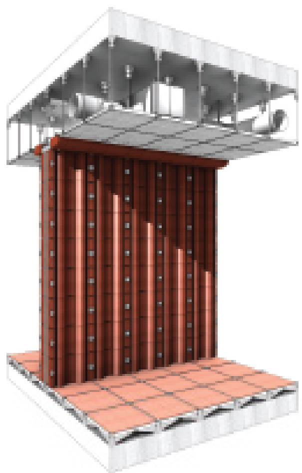
Catalogue

Monash Architecture Studies Unit

2021

WALL PARTY!

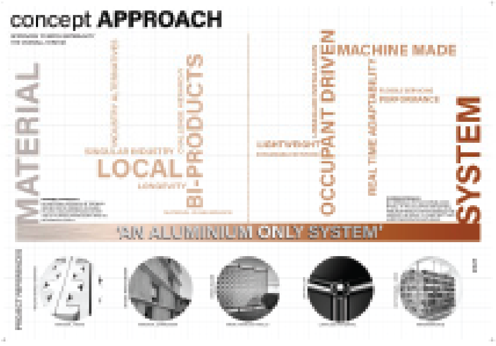
3



Clay Silver

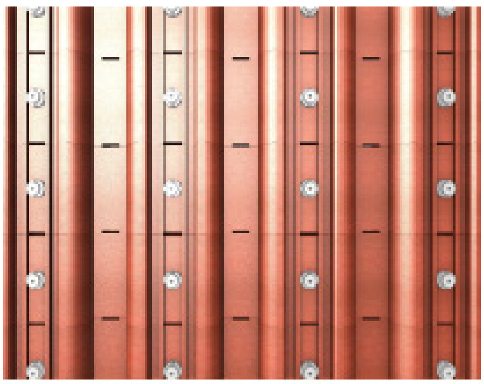
4

Critical approach



5

Materials



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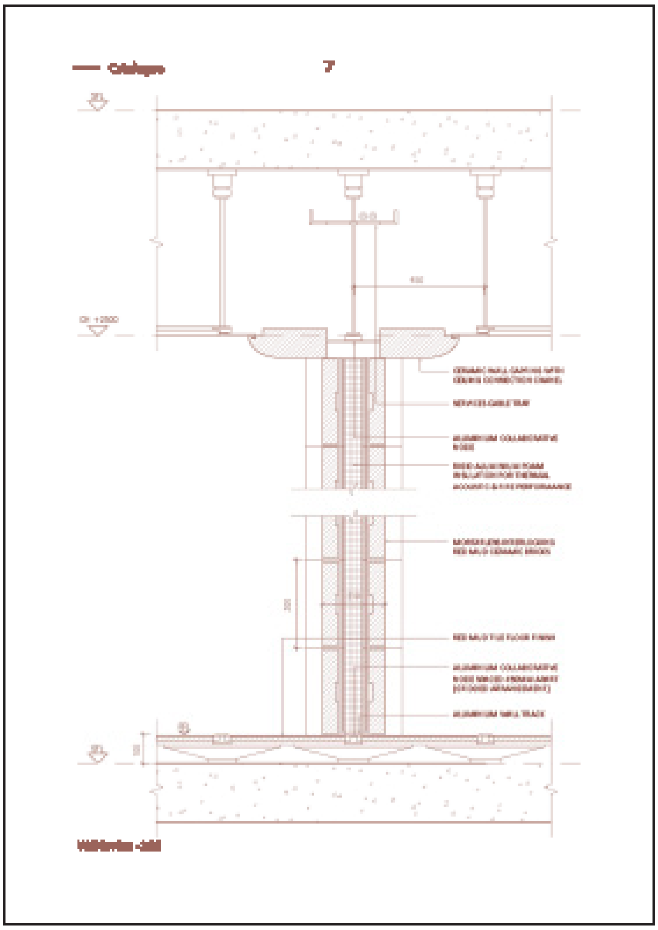

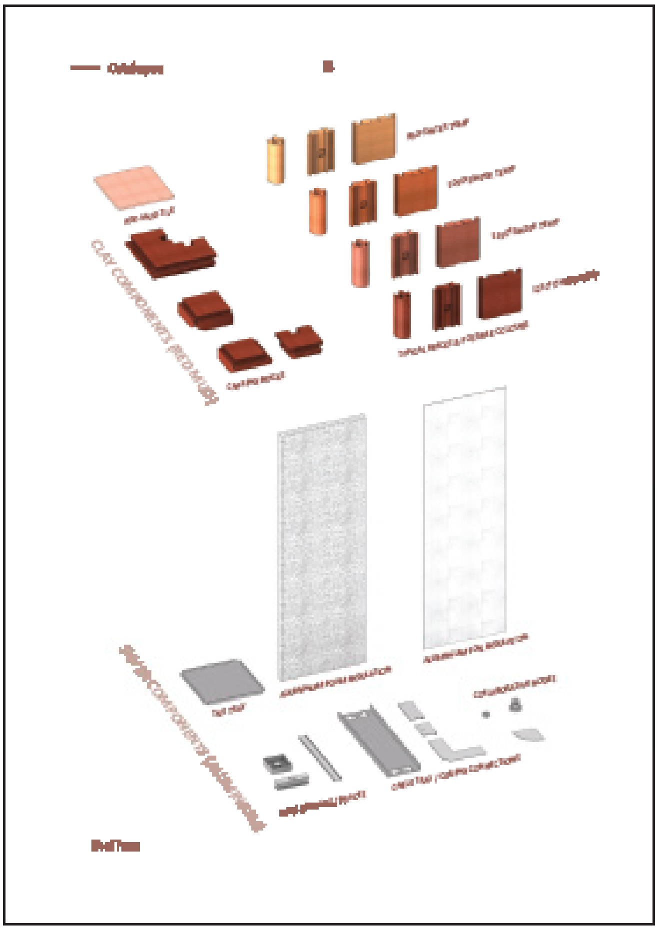

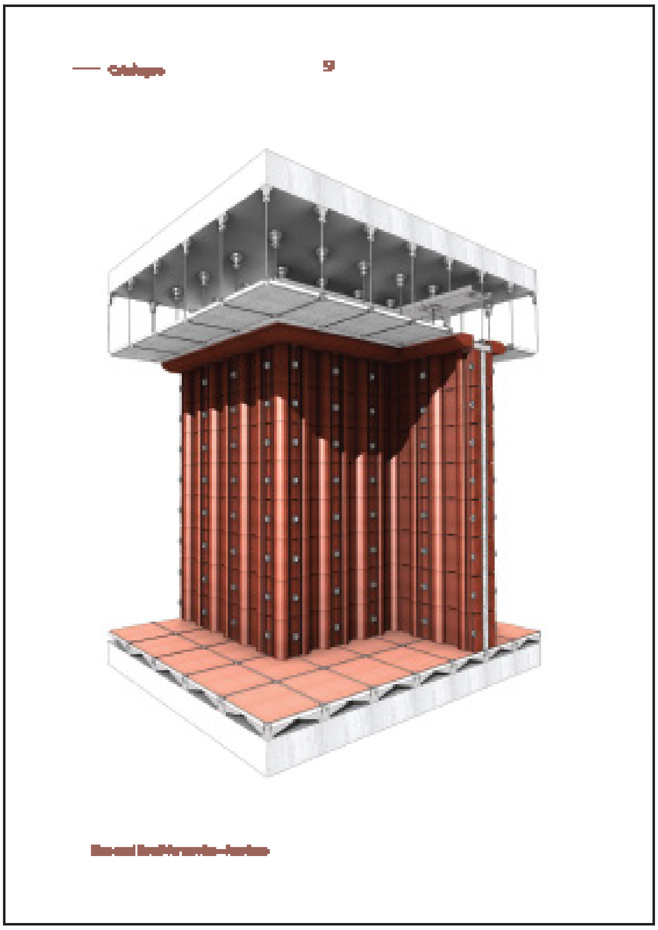

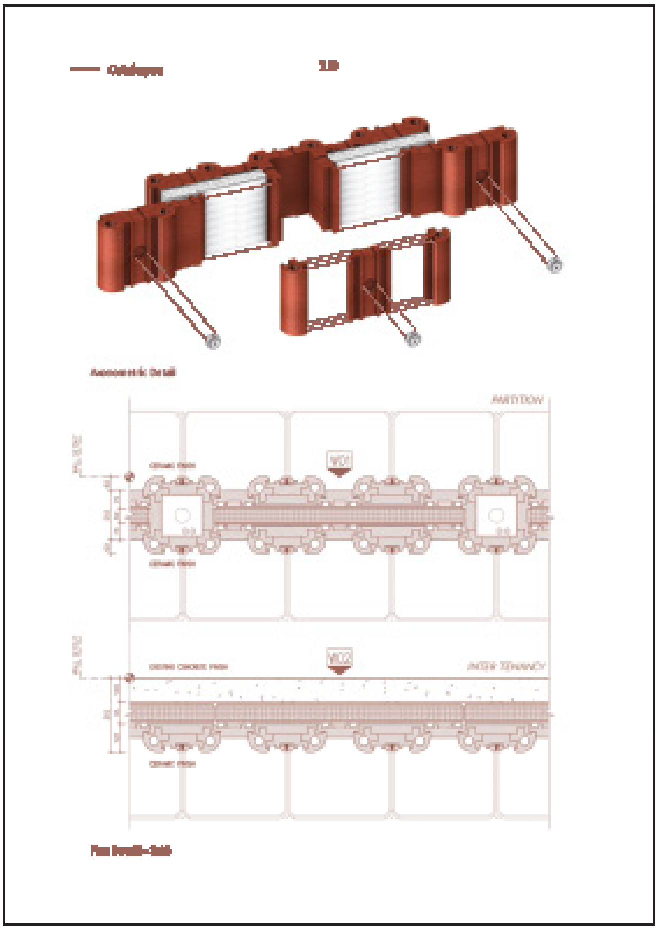

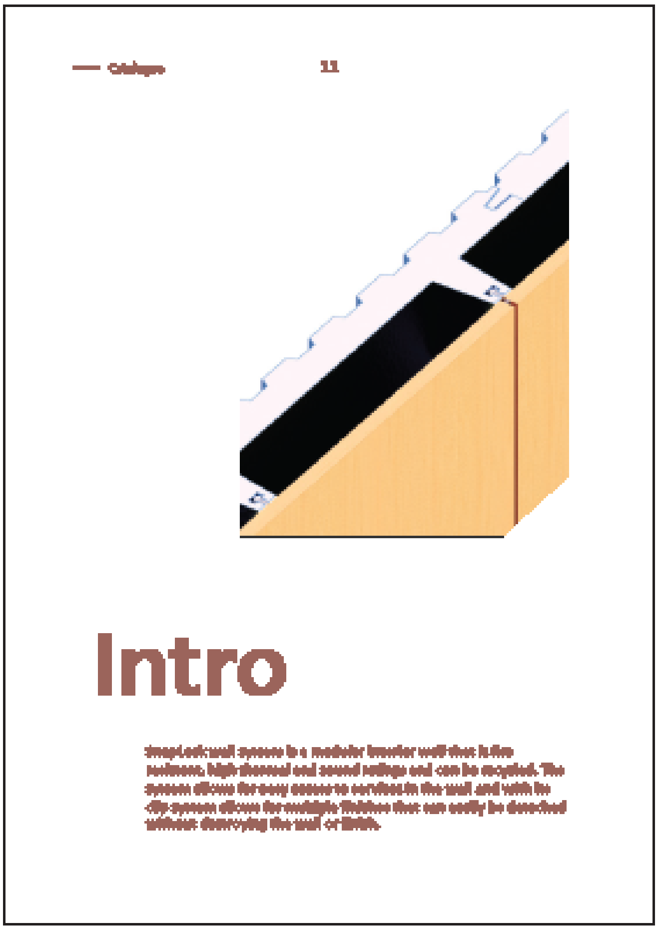
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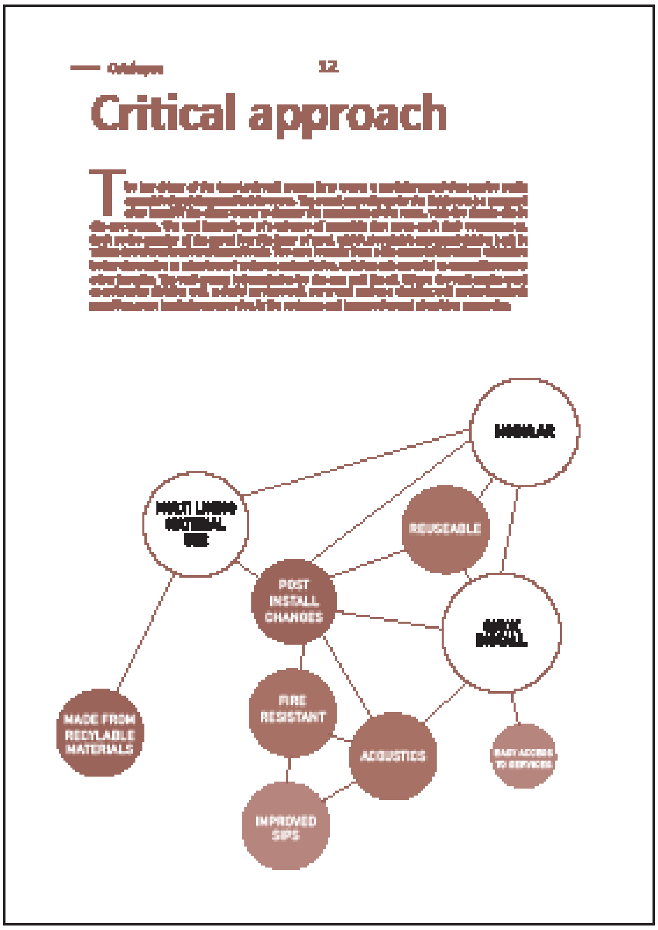
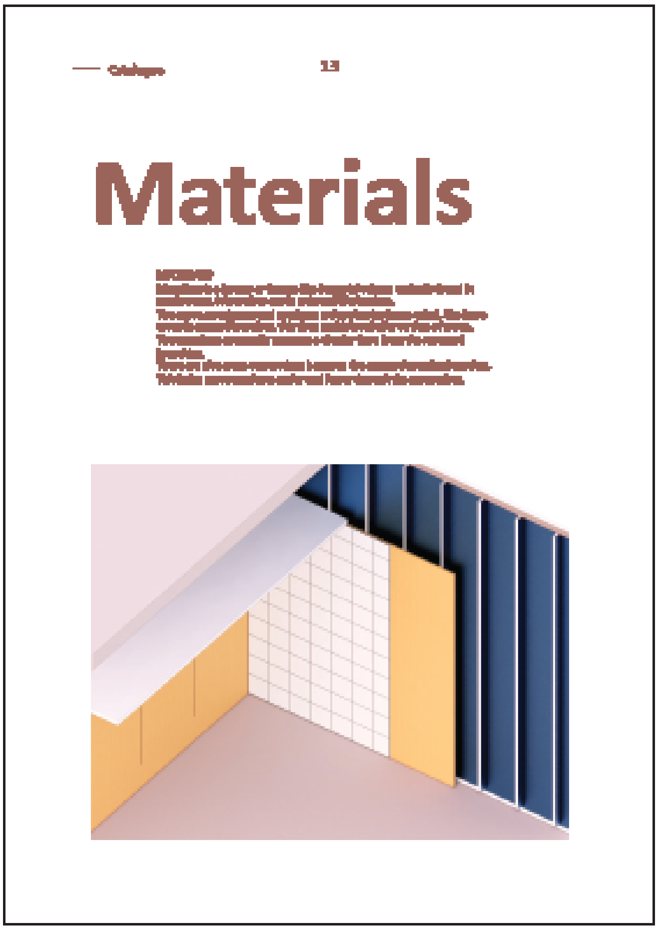
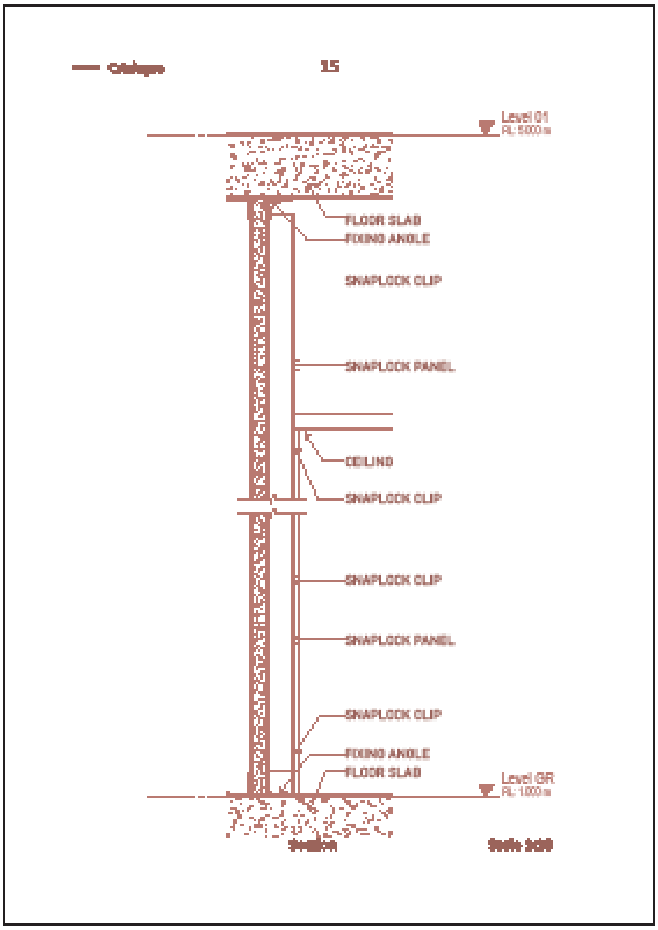
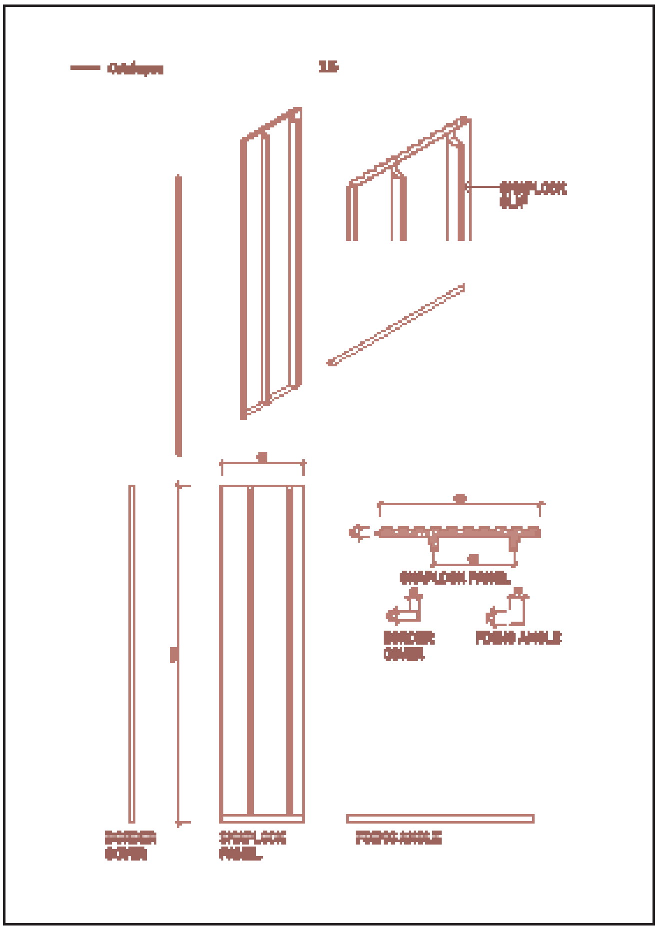
Intro

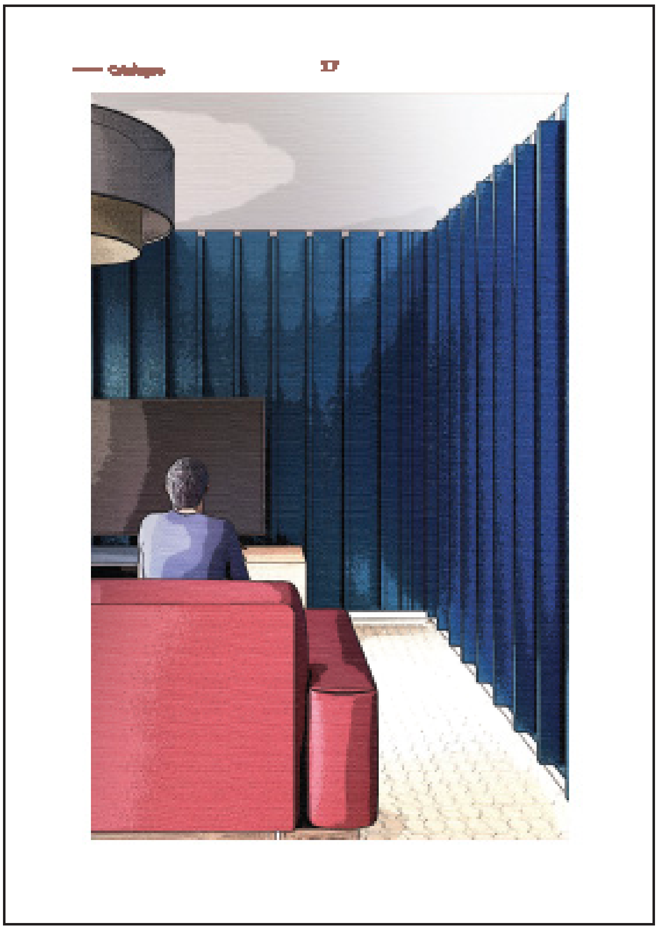

12
Critical approach
MODULAR
MULTI LINING MATERIAL USE
REUSEABLE
POST INSTALL CHANGES
QUICK INSTALL
MADE FROM RECYCLABLE MATERIALS
FIRE RESISTANT
ACOUSTICS
EASY ACCESS TO SERVICES
IMPROVED SIPS


13
Materials


14
STEEL
MYCELIUM
DURRA PANEL
FC SHEETING
PLYWOOD


15
Level 01
FLOOR SLAB
FIXING ANGLE
SNAPLOCK CLIP
SNAPLOCK PANEL
CEILING
SNAPLOCK CLIP
SNAPLOCK CLIP
SNAPLOCK PANEL
SNAPLOCK CLIP
FIXING ANGLE
FLOOR SLAB
Level GR


SNAPLOCK PANEL
FIXING ANGLE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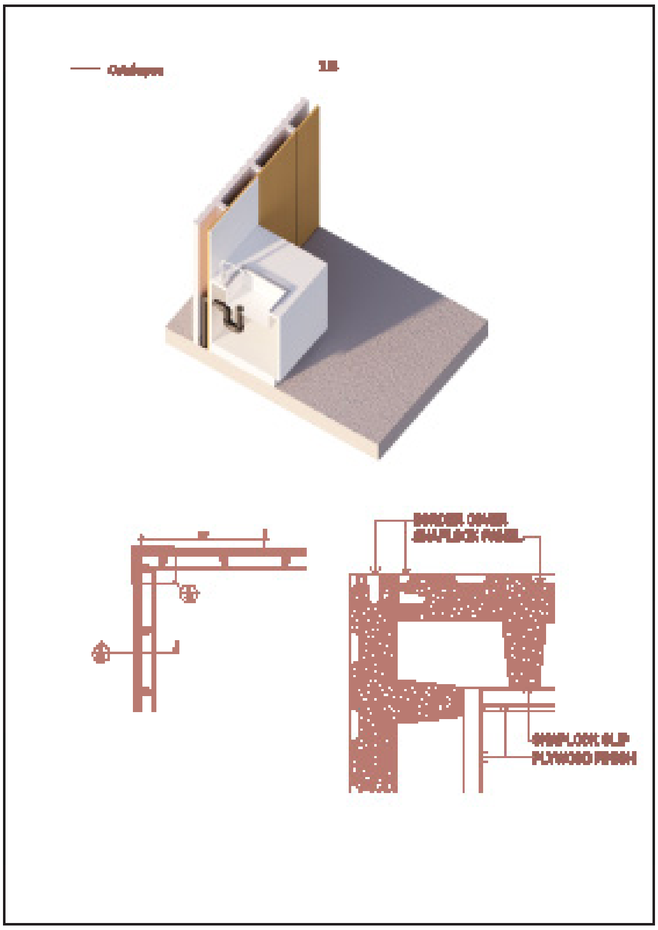
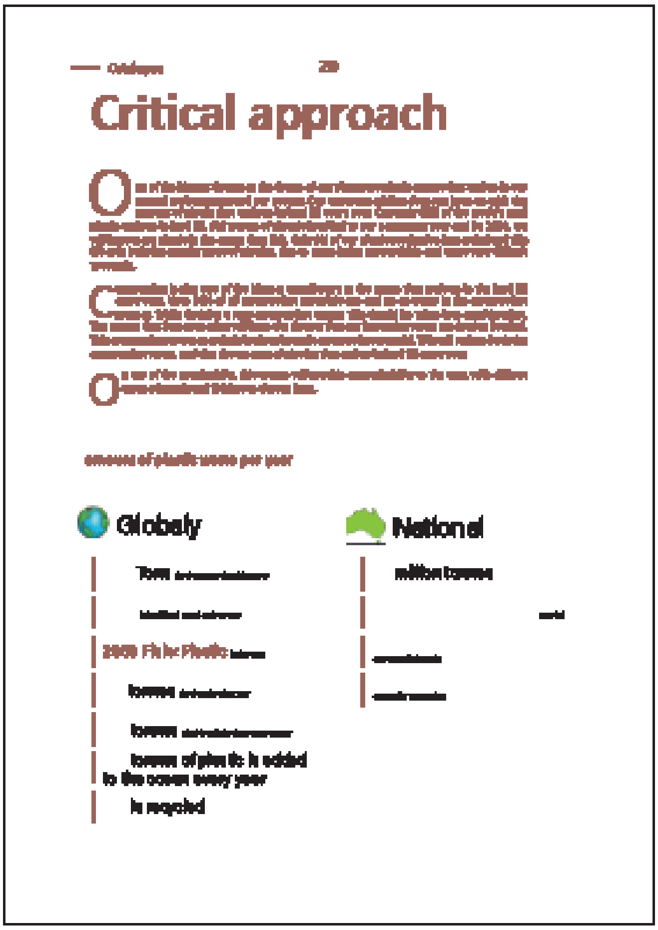
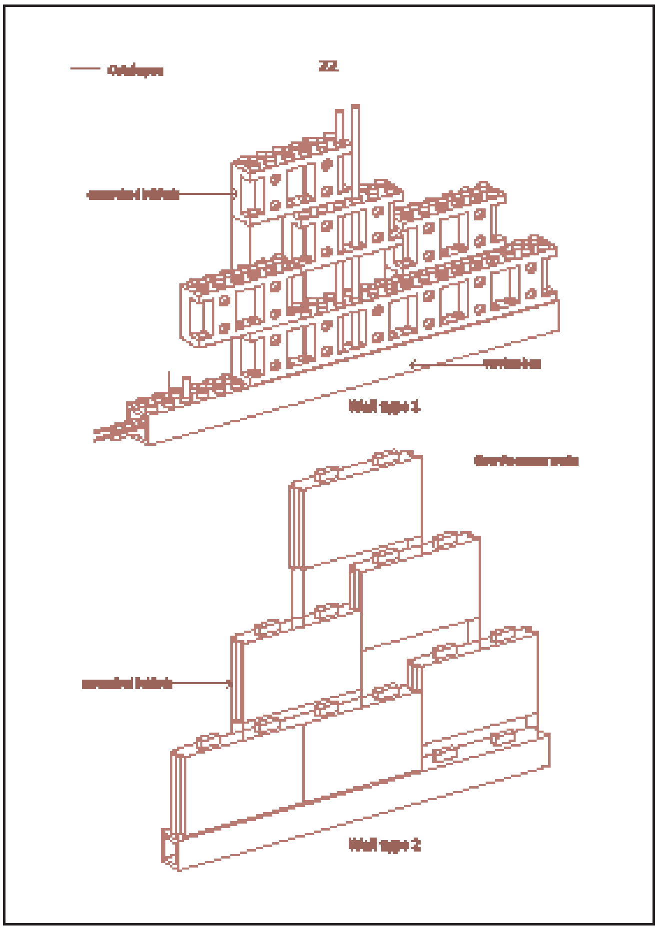
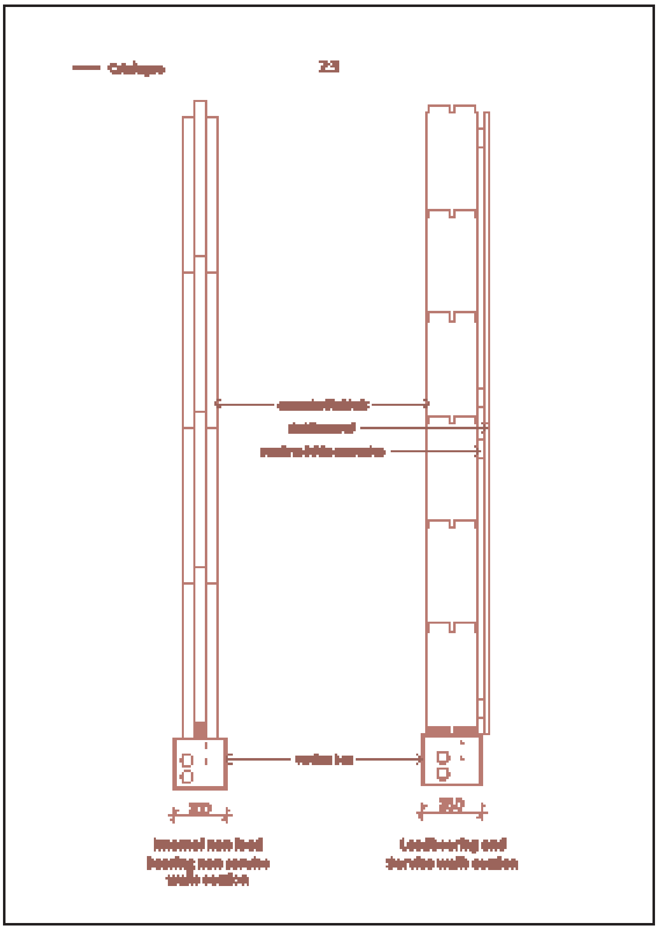

18

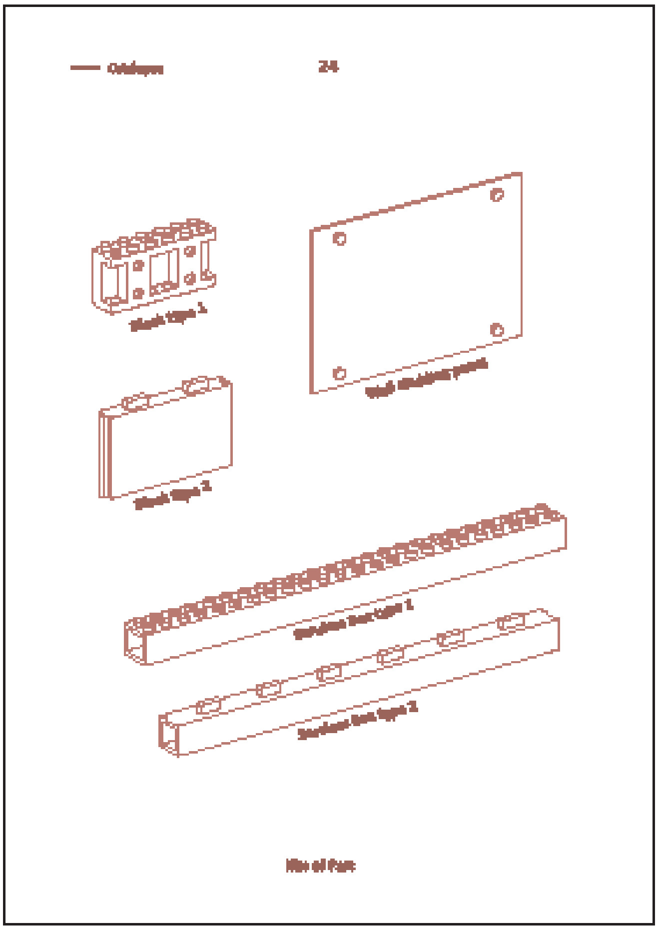

anti-plastic
plastic walls


Critical approach
Globaly
National
tonnes of plastic is added
to the ocean every year
is recycled

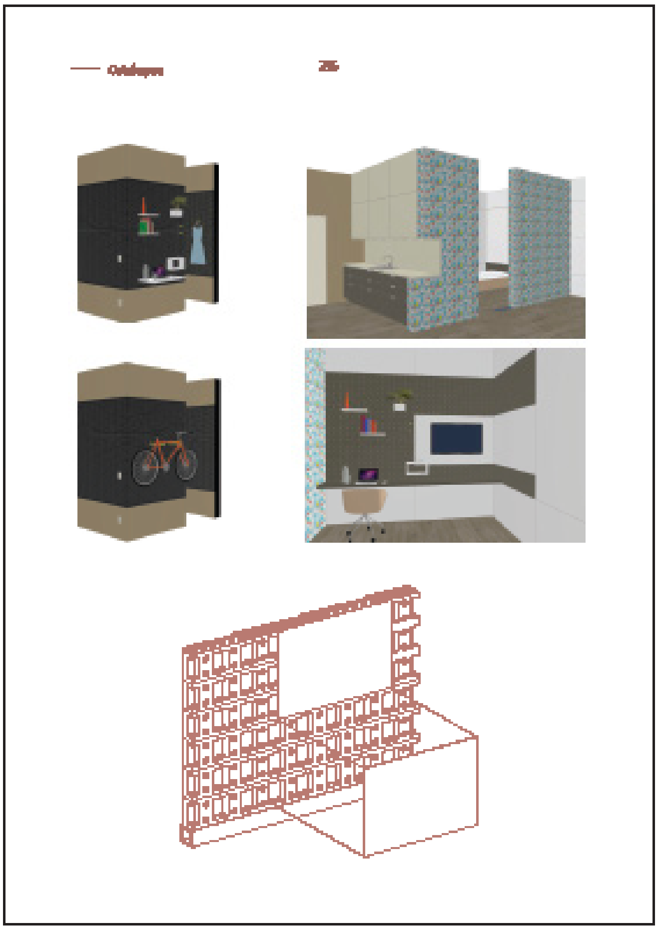

Materials
1
2
3

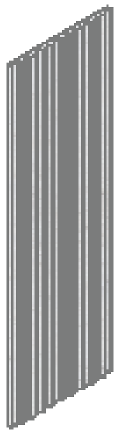



Catalogue
23
200
250
Loadbearing and Service walls section


Catalogue
24
Block type 1
Block type 2


Catalogue
25


Catalogue
26



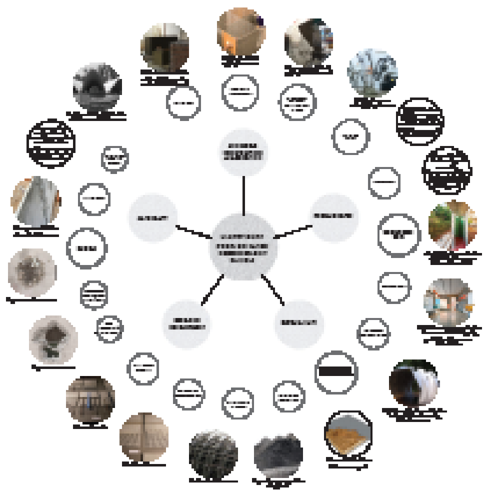
Ferrocement Panels

Annabelle Low

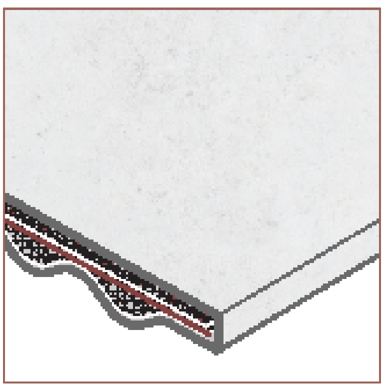
The key to the concept of these wall panels is in the material. They are made from ferrocement a mesh reinforced cementitious composite material. It can be fabricated using both new technology and low-level technology and uses low-cost materials making it accessible.

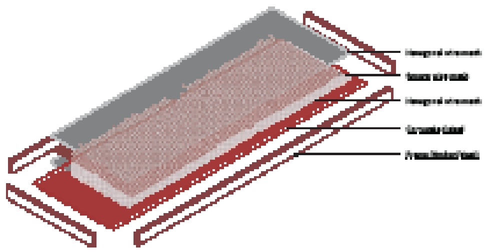
Critical approach

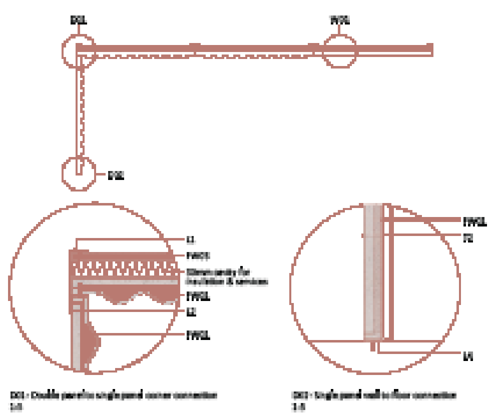
Ferrocement is a material that has been used extensively and researched by the architect Anupama Kundoo as seen in her project 'Full Fill Homes' - a proposal for low-cost modular housing made from hollow ferrocement blocks. It is not widely used in developed countries due to the traditional labour-intensive fabrication method. However, with the development of technology such as 3D printing concrete, ferrocement has the potential to be used for wall panels as well as other building elements in Australia.

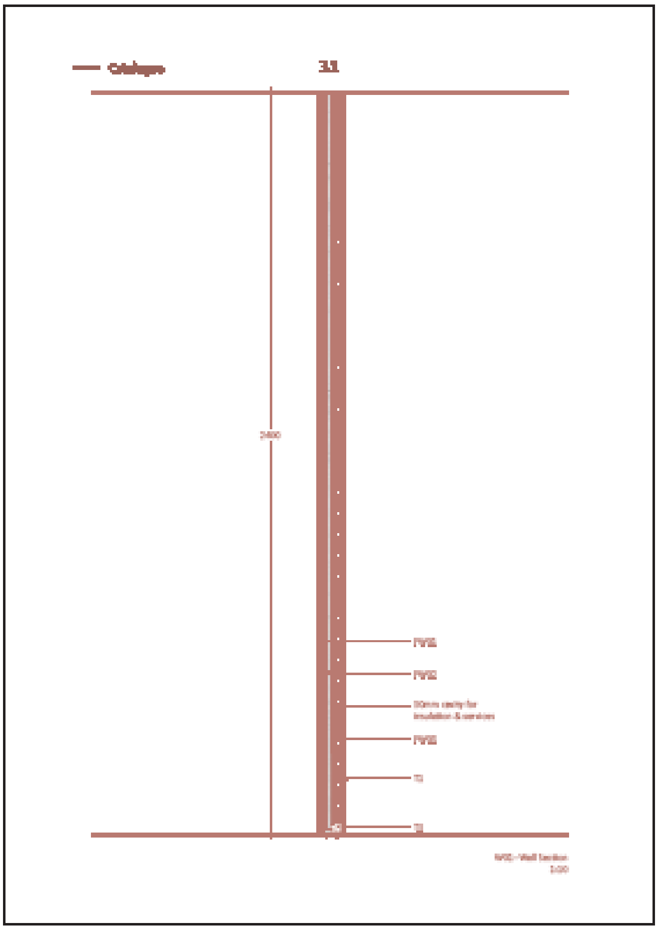


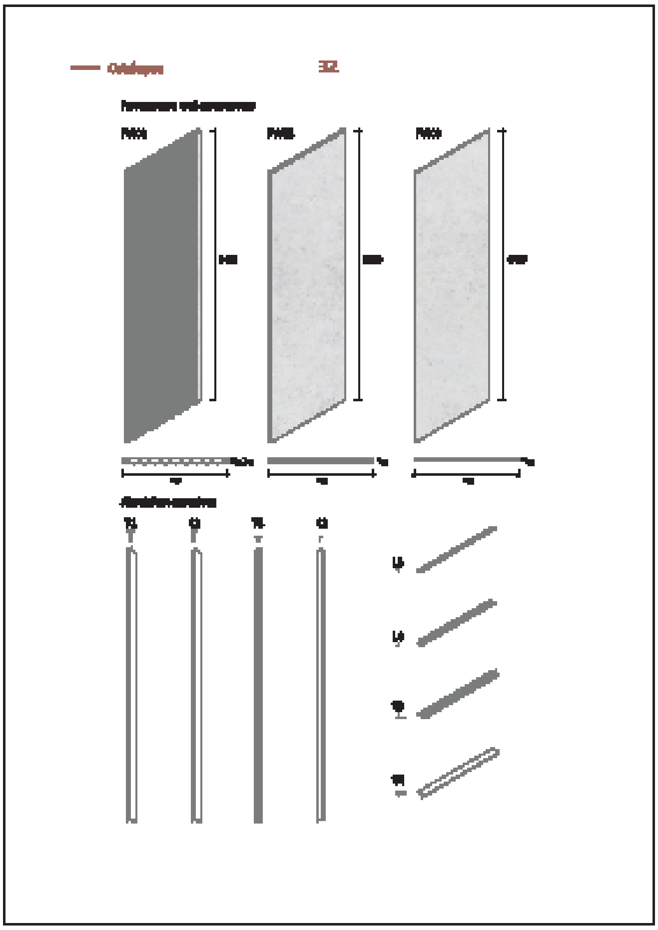
Materials

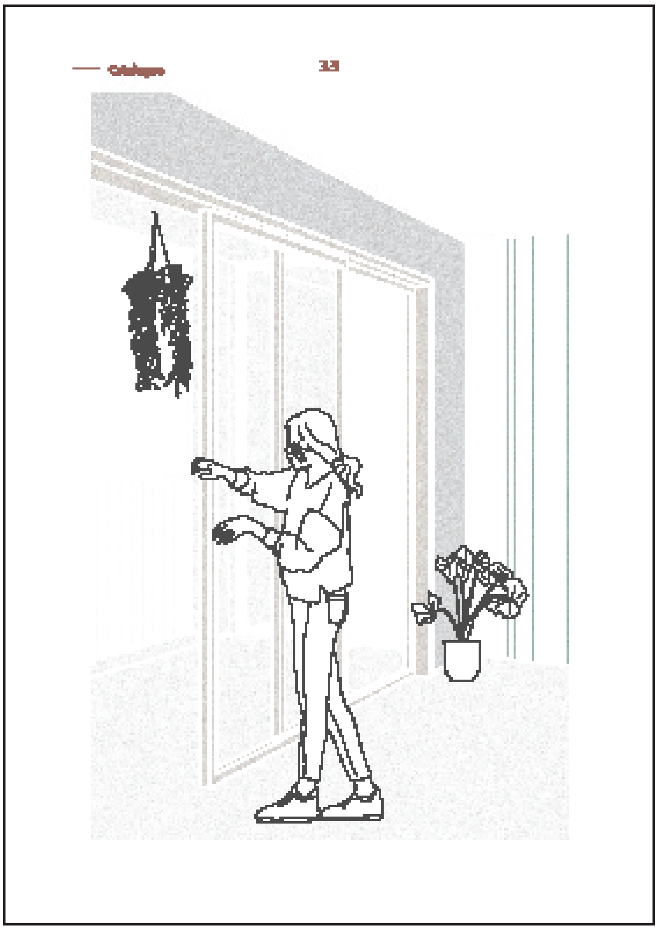


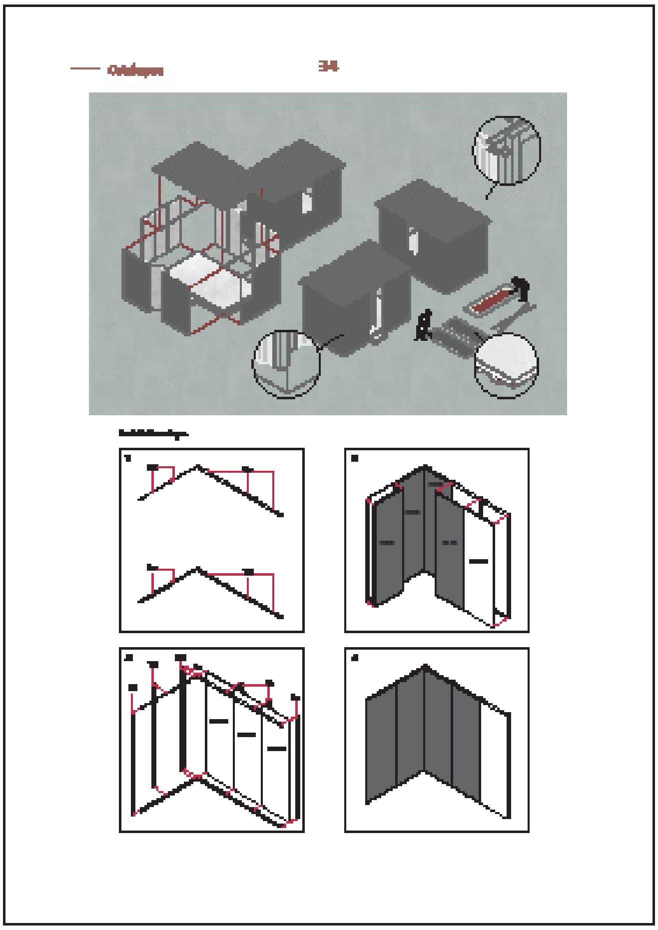


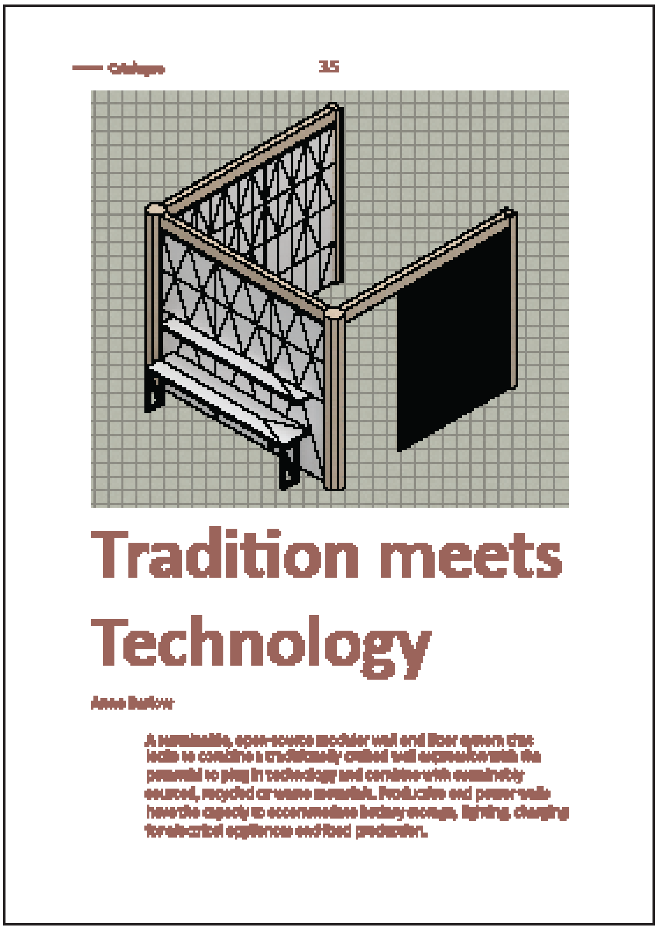


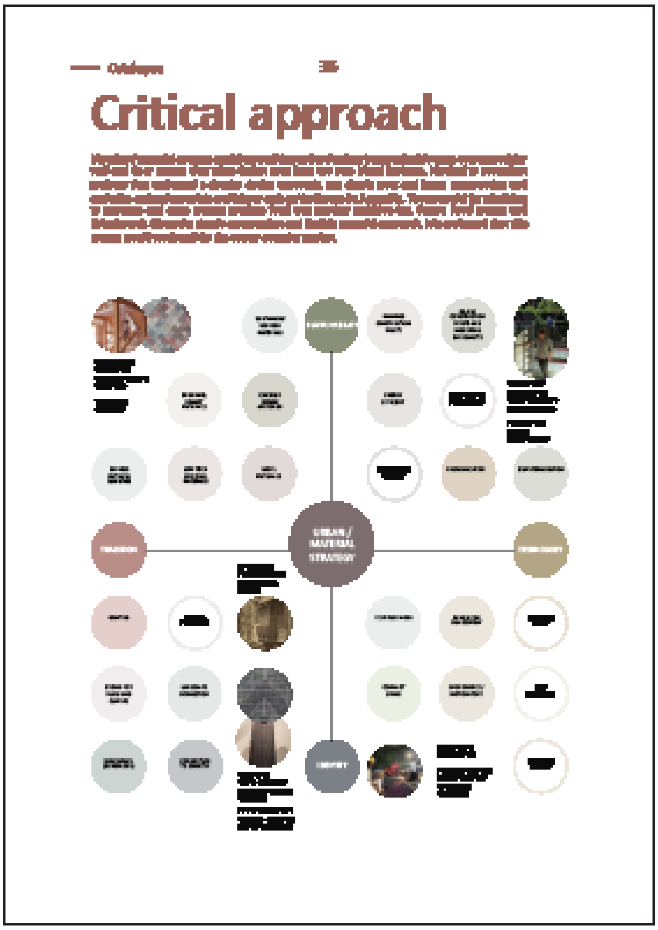


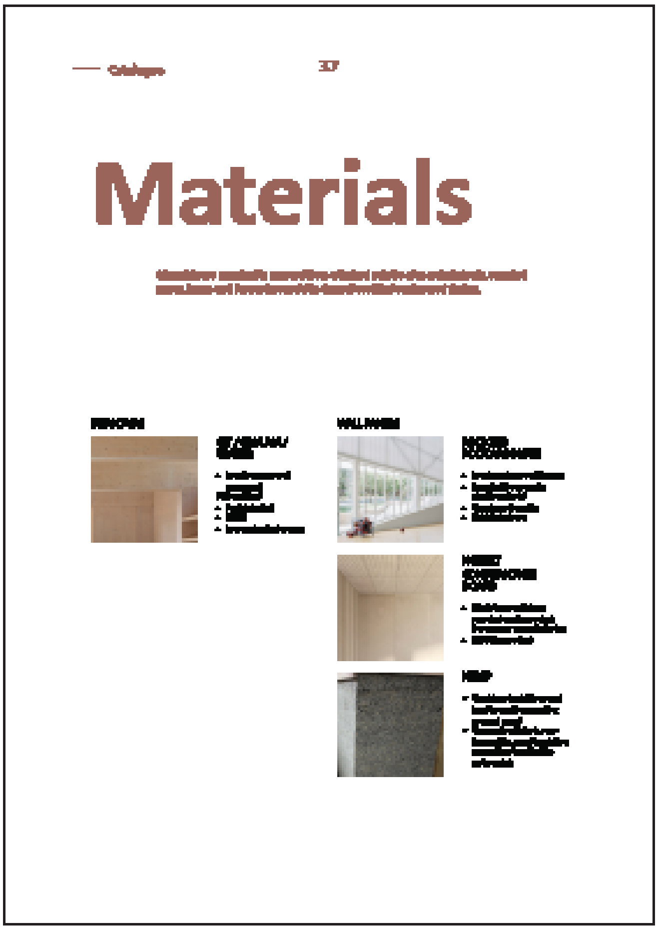







Tradition meets
Technology


Critical approach
URBAN / MATERIAL STRATEGY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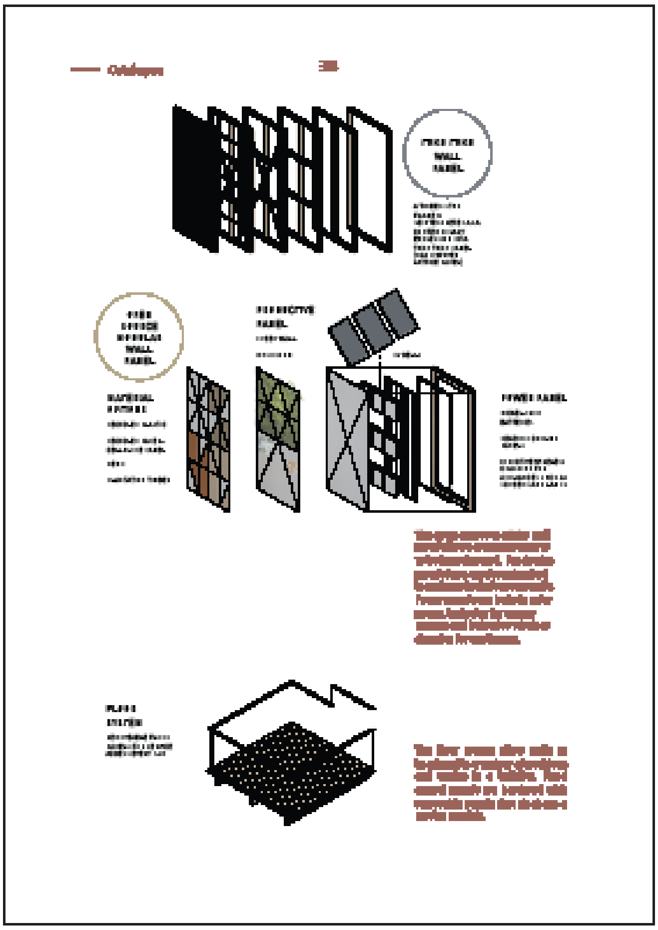
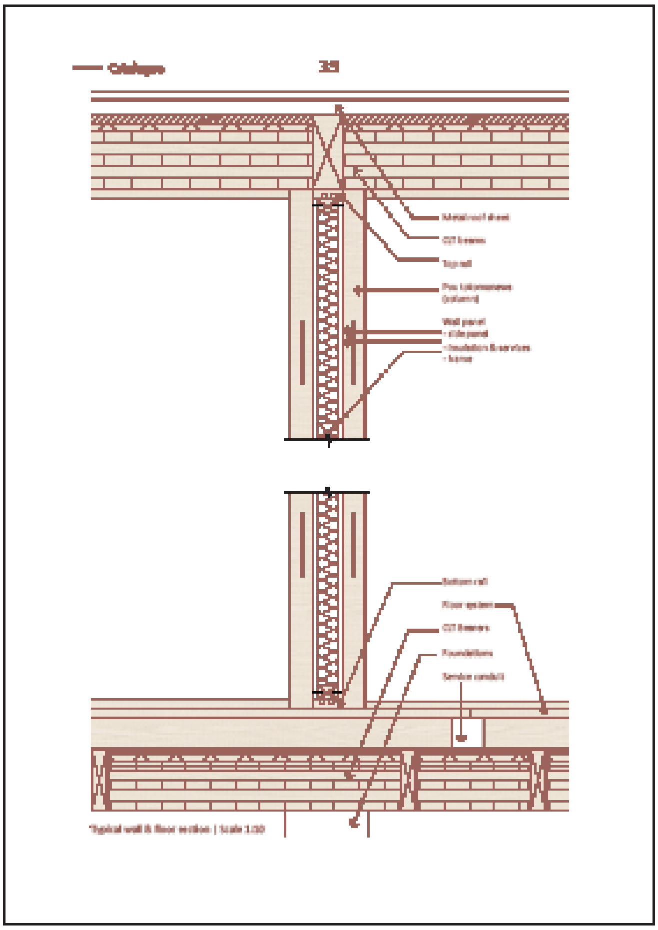
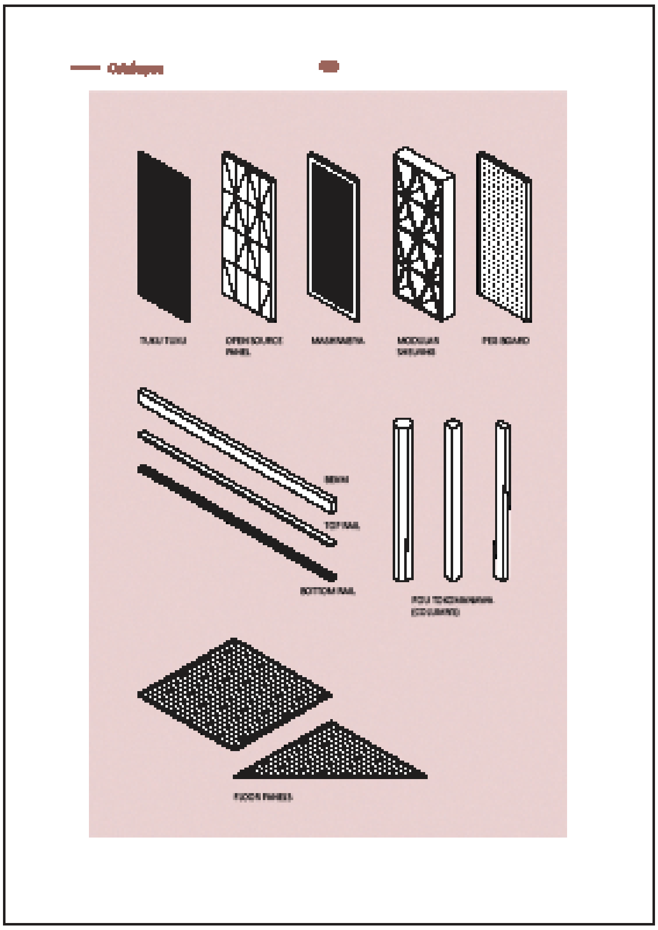
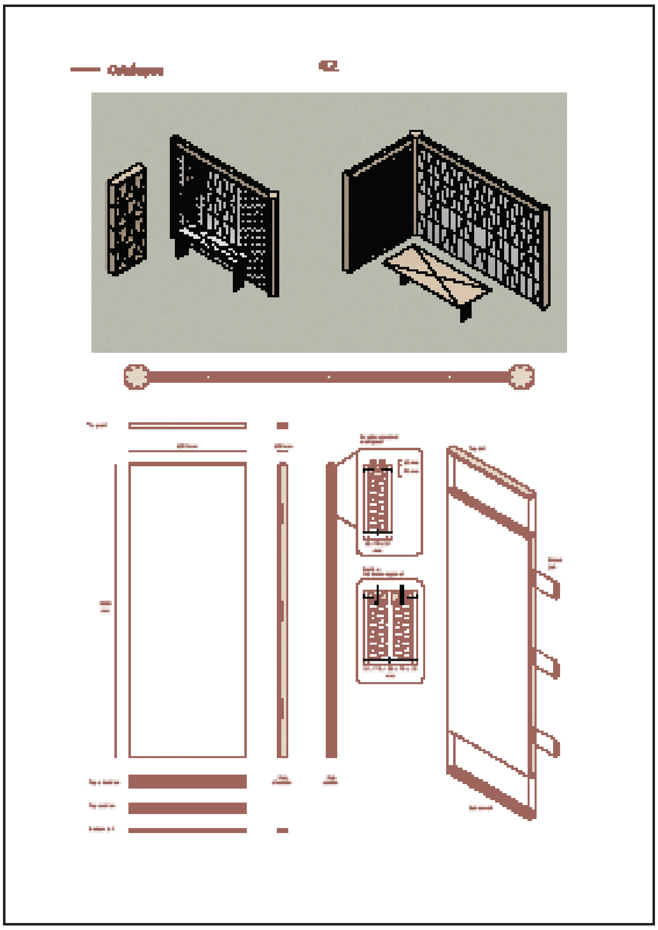


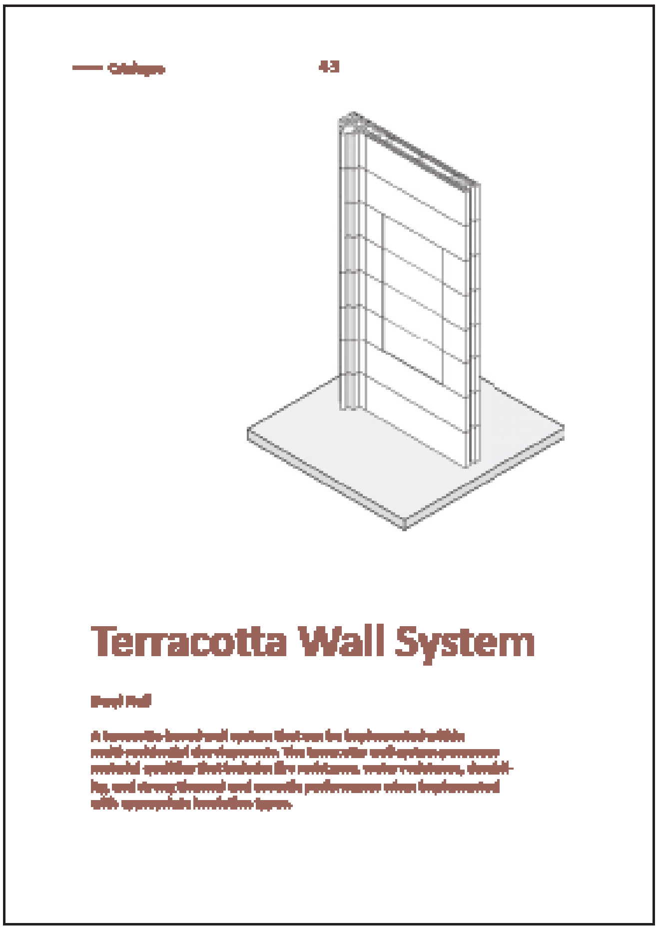


Metal roof sheet
CLT beams
Top rail
Wall panel
Bottom rail
Floor system
CLT Bearers
Foundations
Service conduit
*Typical wall & floor section | Scale 1:20



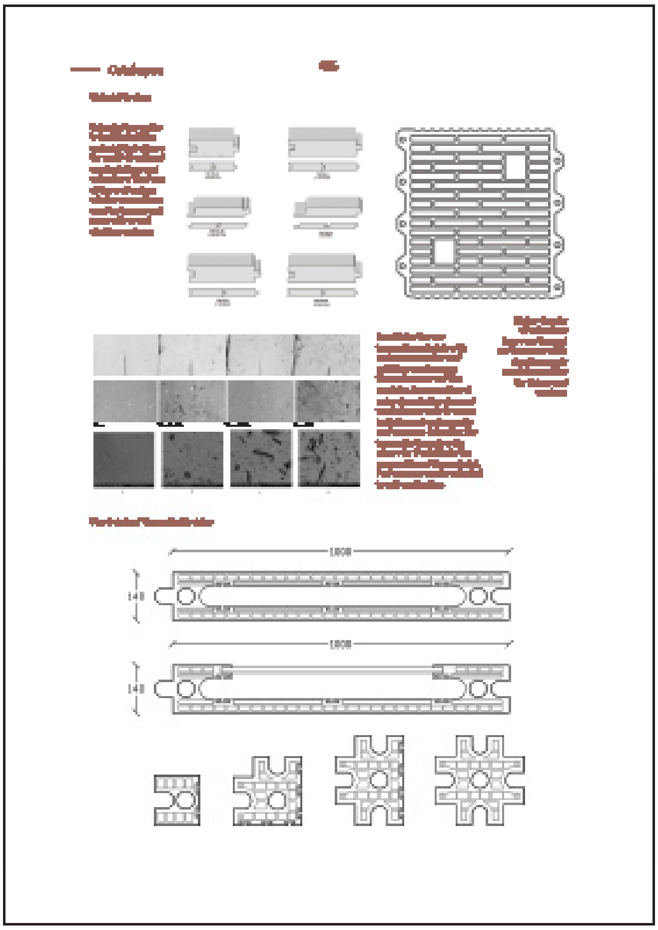
TUKUTUKU
OPEN SOURCE PANEL
MODULAR SHELVING
PEG BOARD
BENCH
TOP RAIL
BOTTOM RAIL
POU TOKOMANAWA (COLUMNS)
FLOOR PANELS




43
Terracotta Wall System


44
Critical approach
TERRACOTTA
BENTONITE & KAOLIN
BRICK WORKS
NATURAL GAS FIRING
FINISHES
DURABILITY & REUSE
DISPOSAL


45
Materials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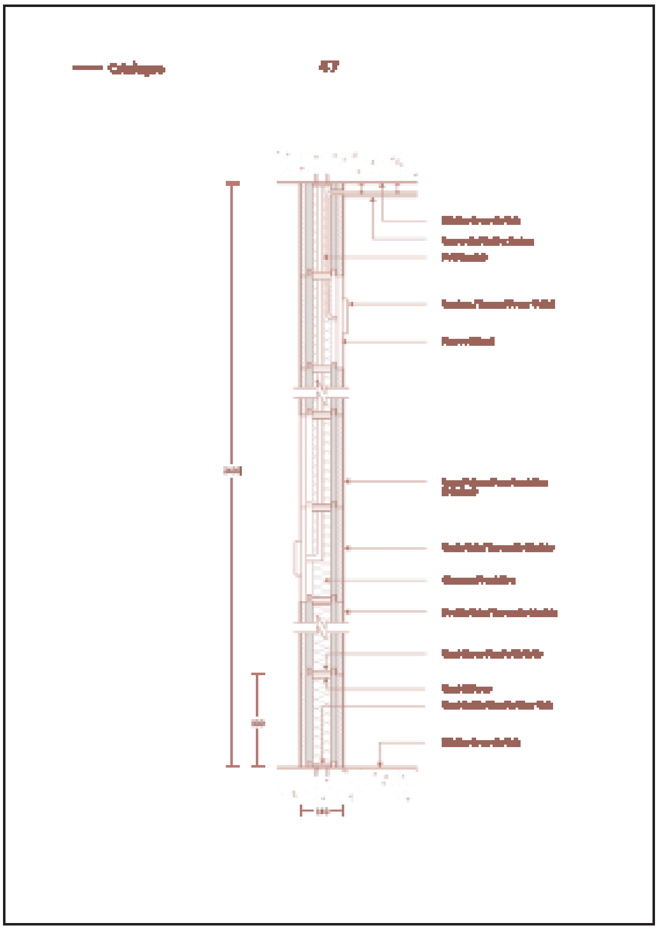
140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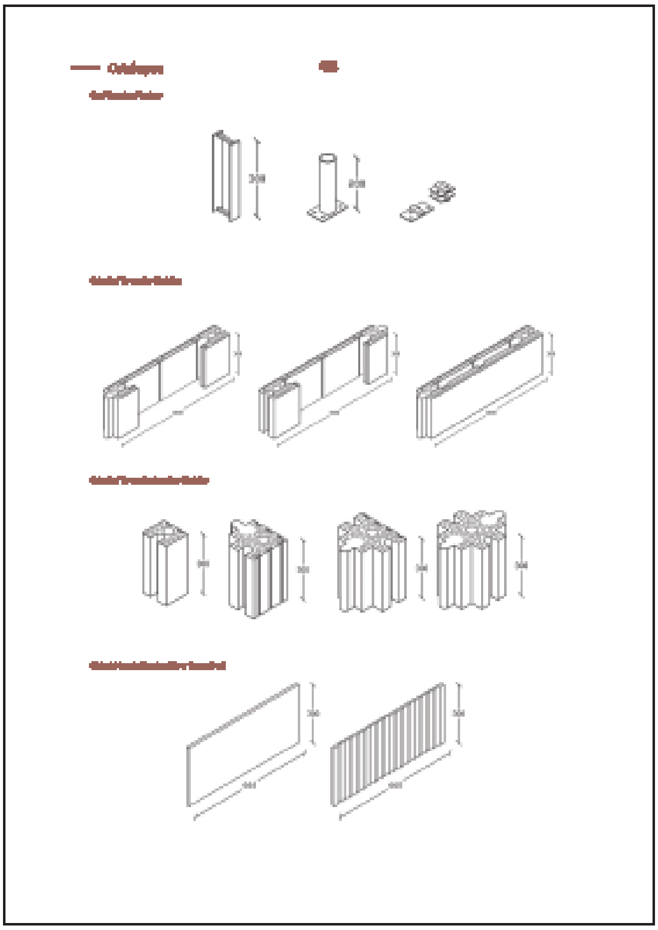
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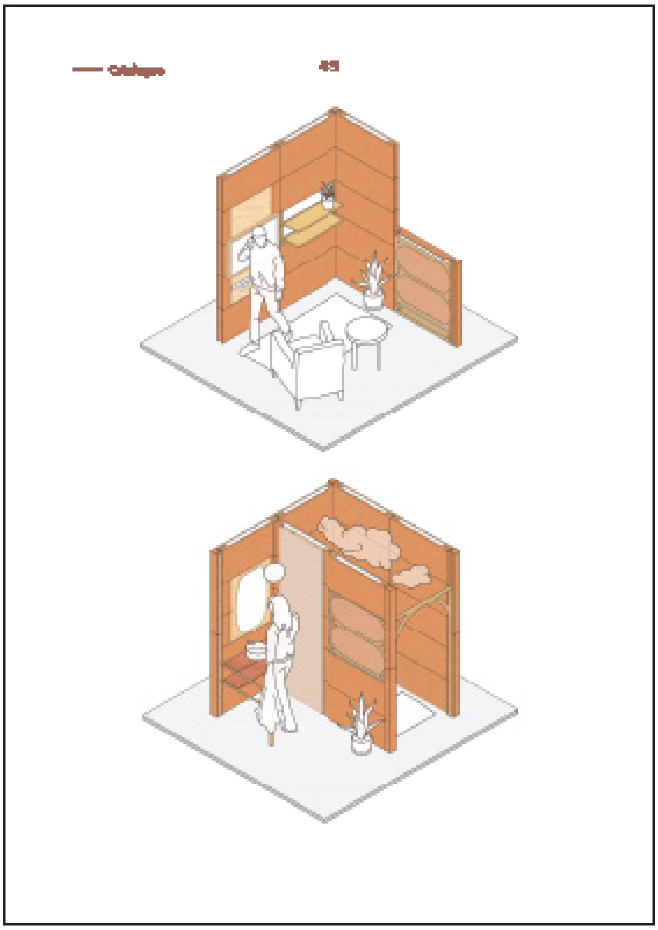
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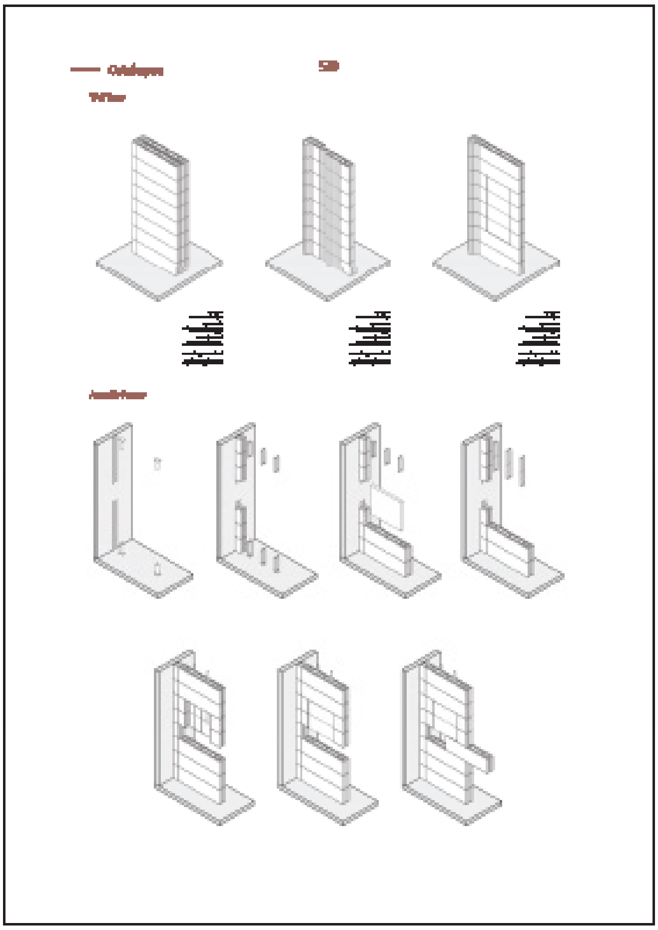
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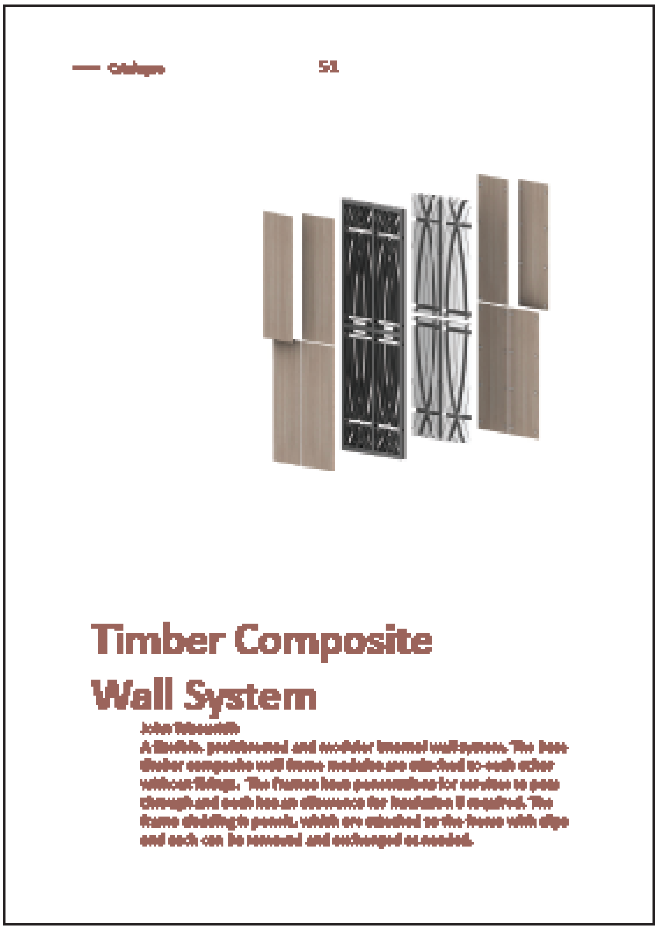

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Timber Composite Wall System

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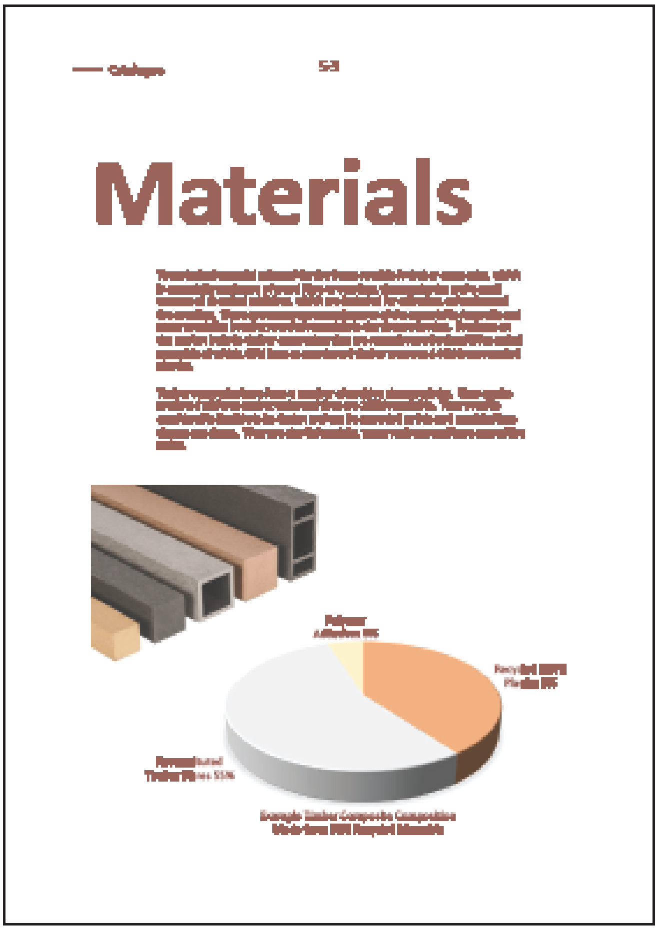
Critical approach



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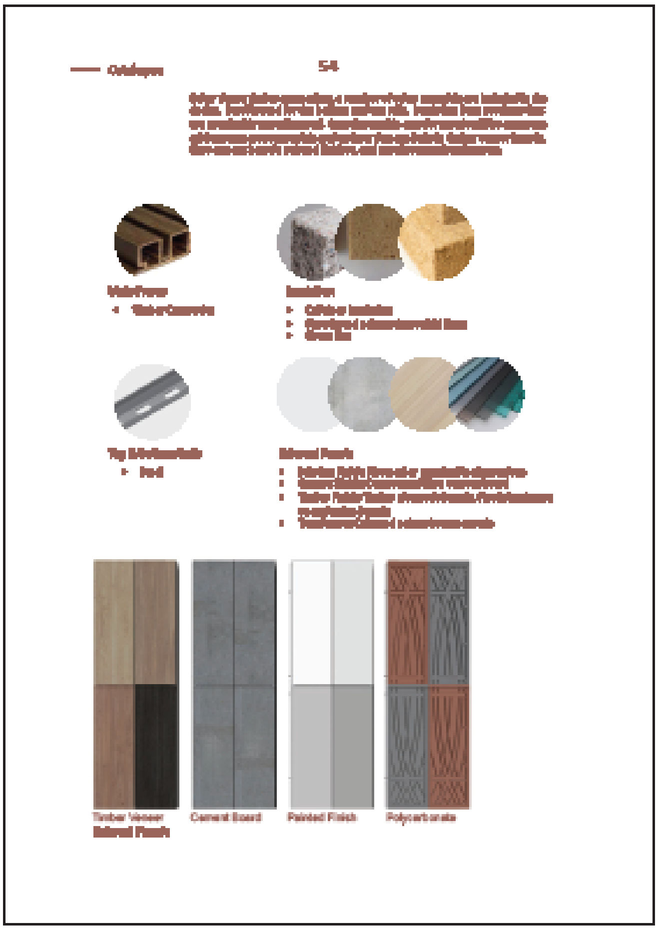
Materials



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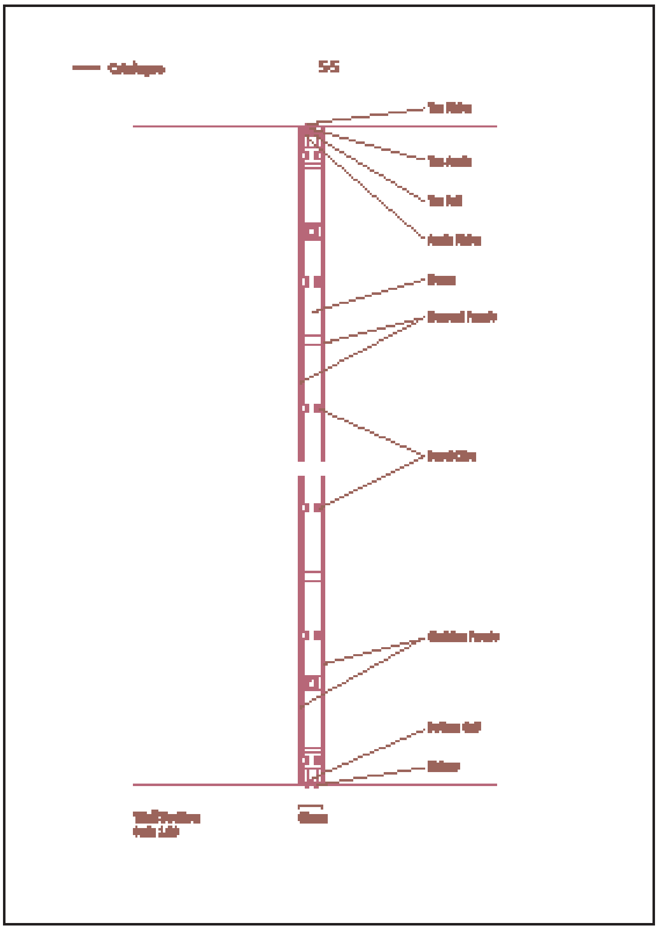
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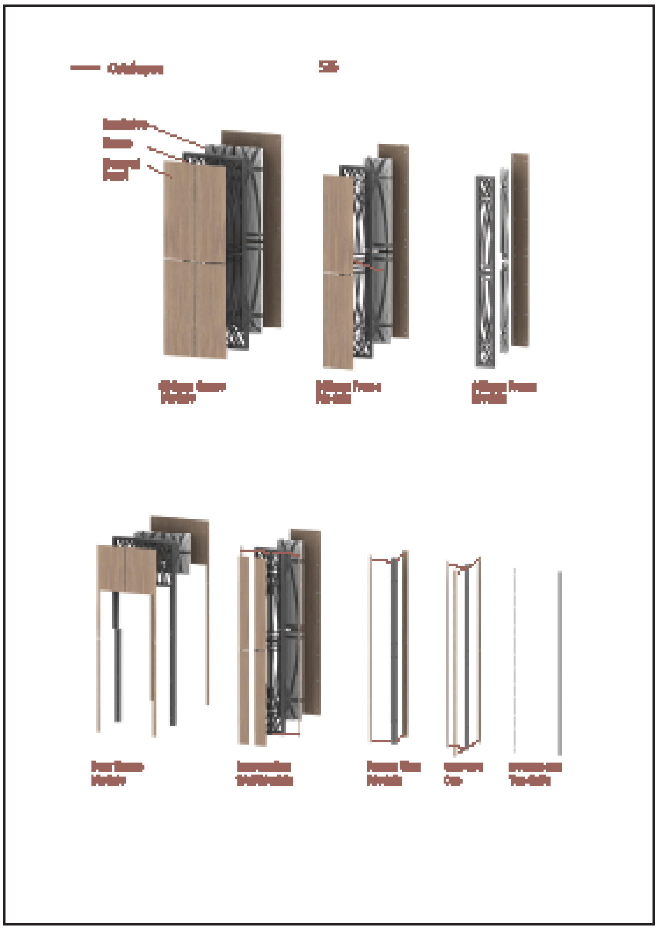
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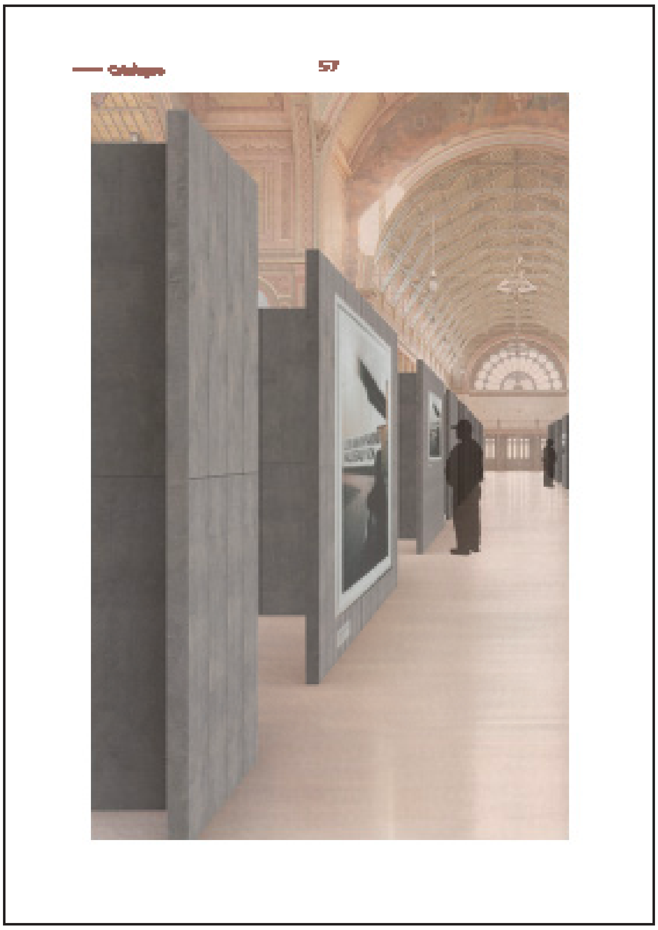
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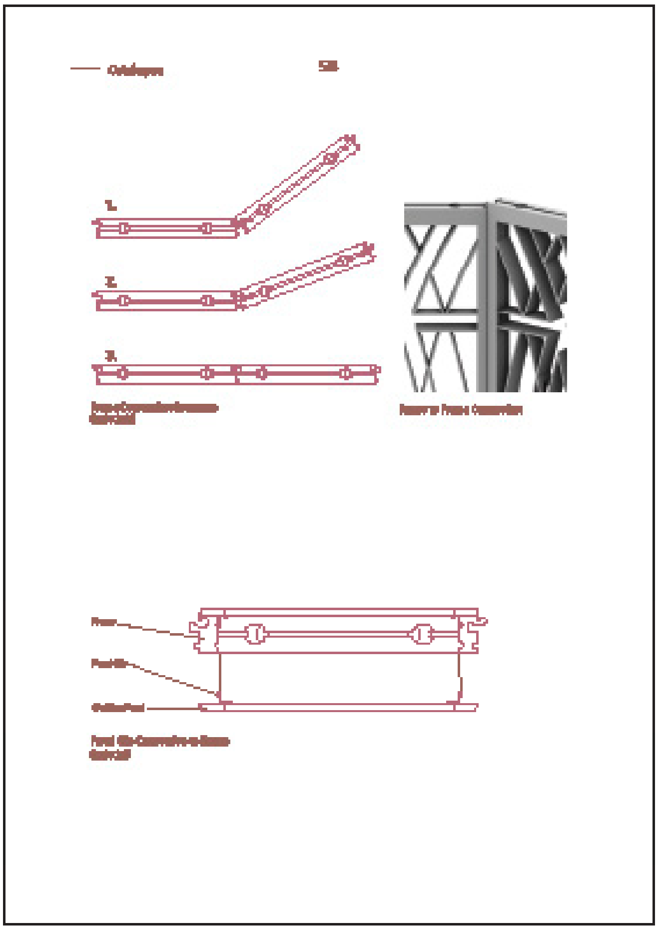
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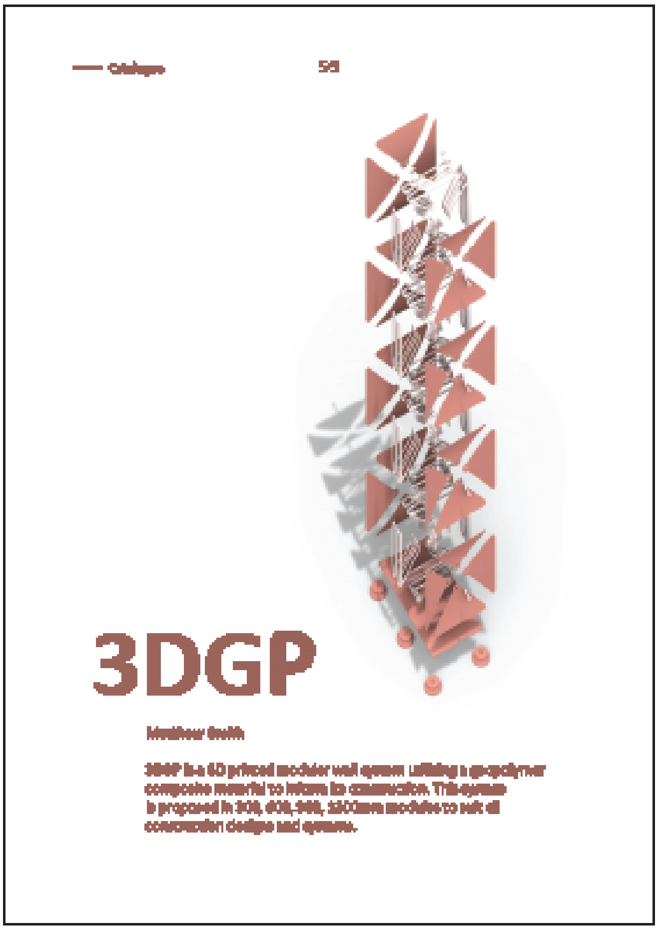
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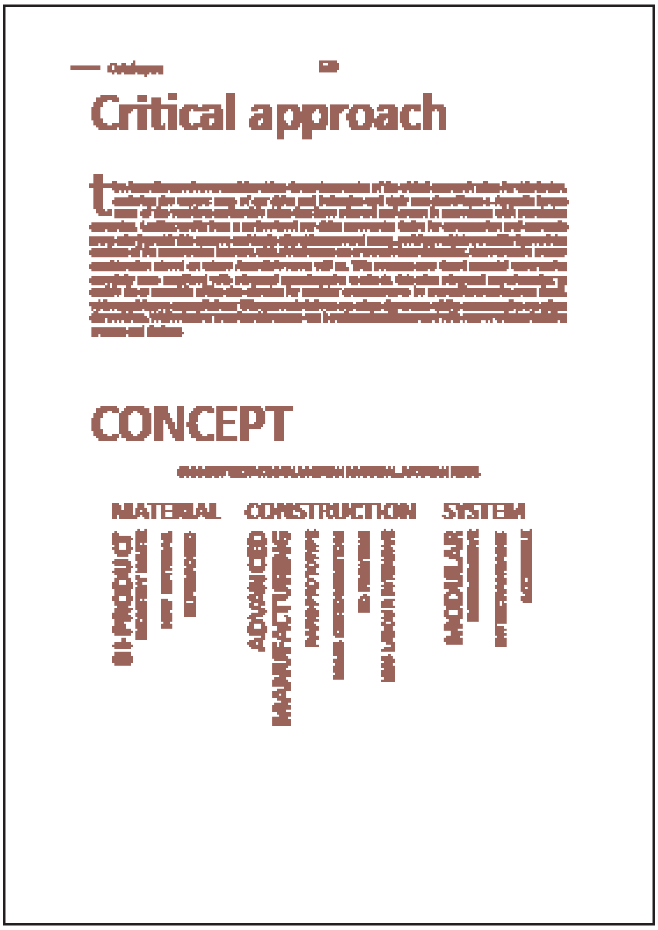
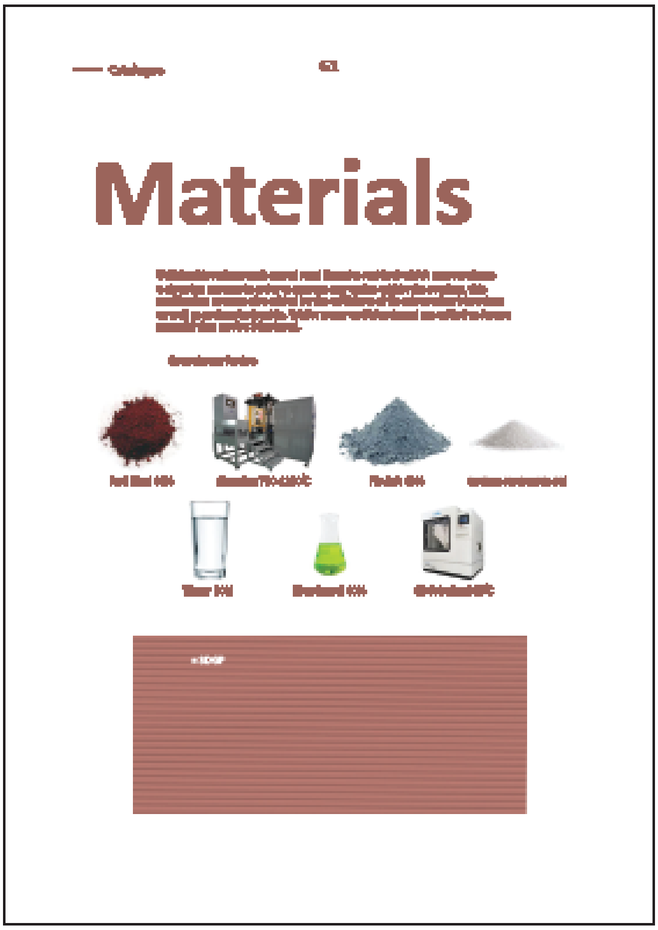
3DGP


Critical approach
CONCEPT
MATERIAL
CONSTRUCTION
SYSTEM
BI-PRODUCT
ADVANCED MANUFACTURING
MODULAR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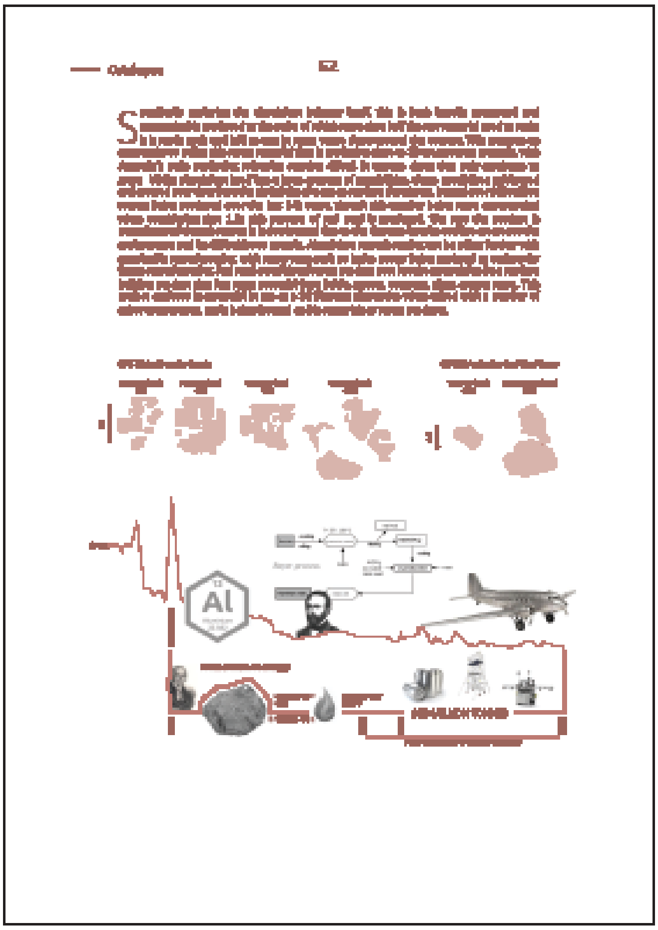
Materials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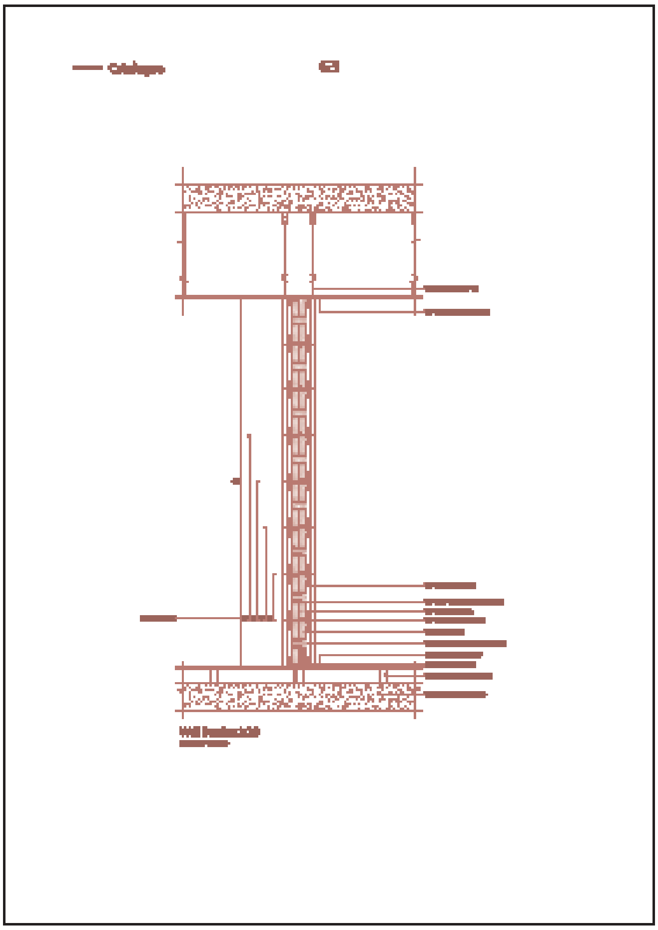
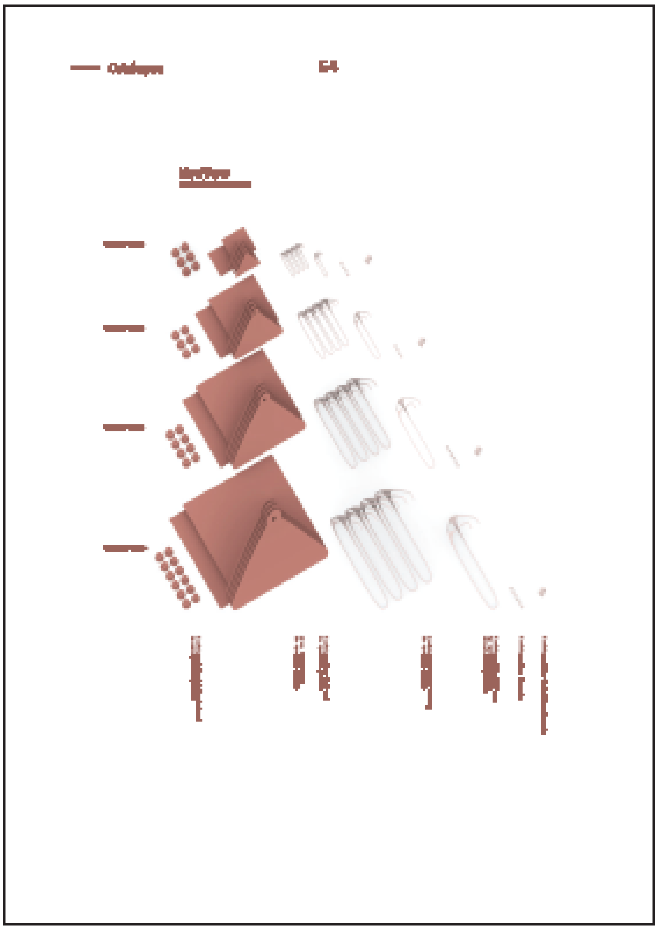
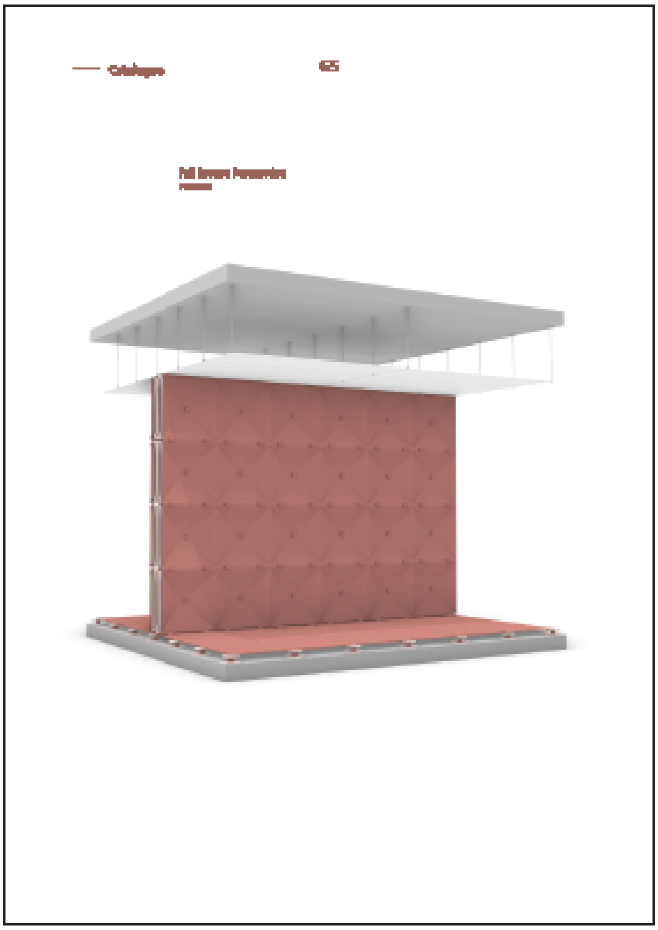
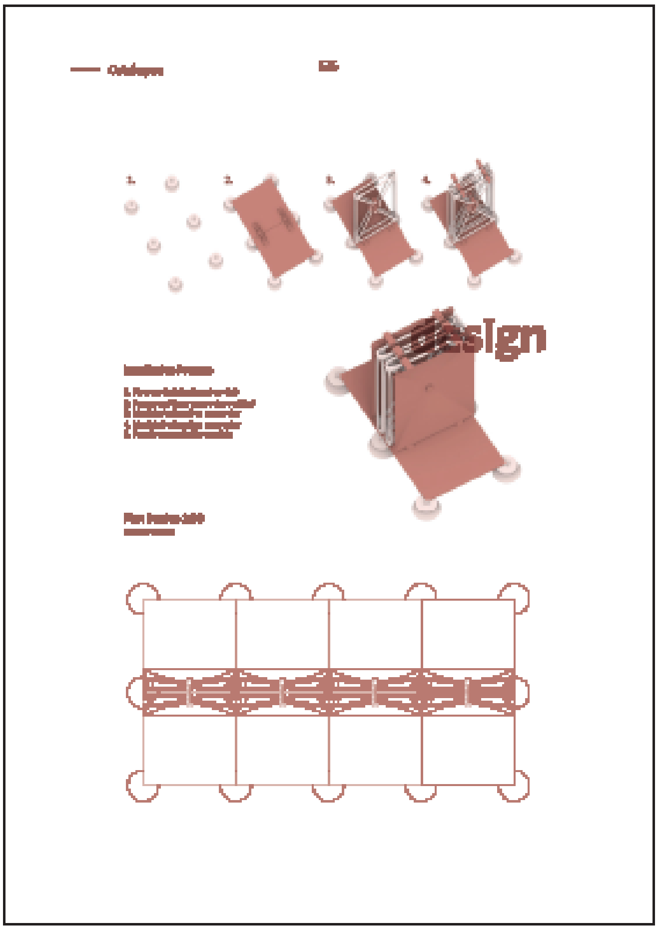
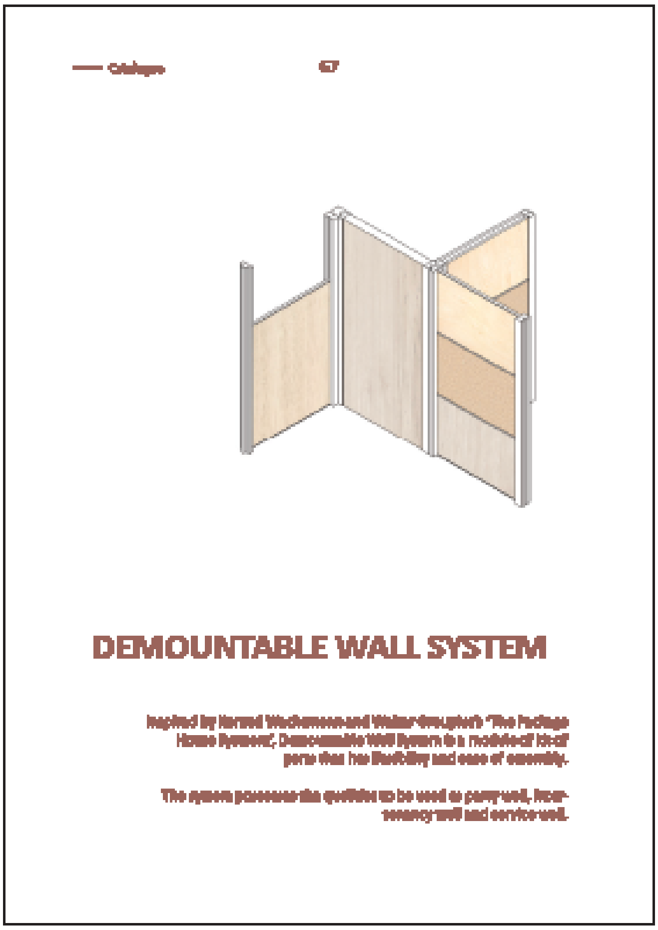
Al

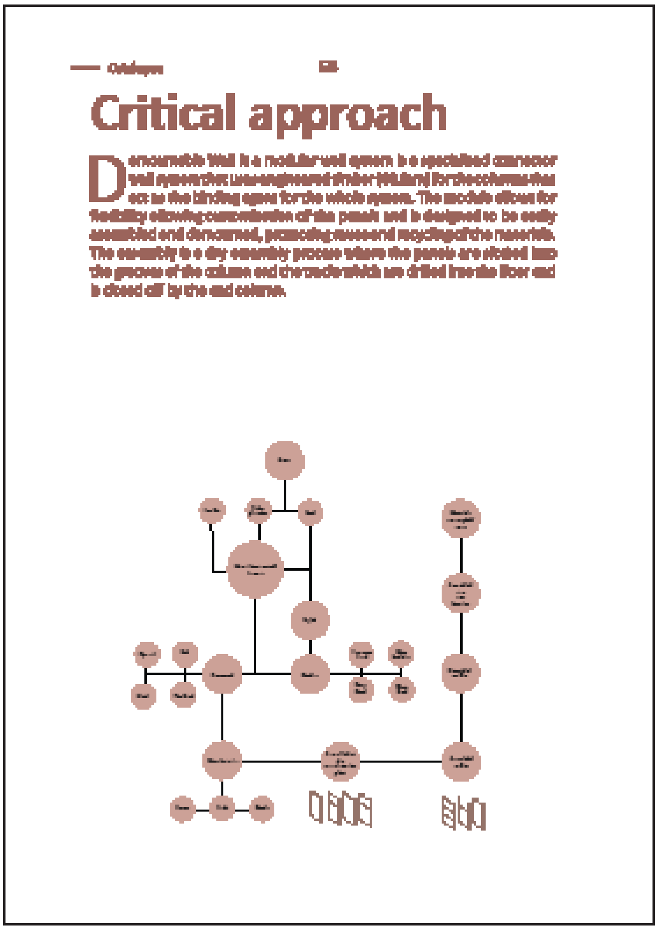


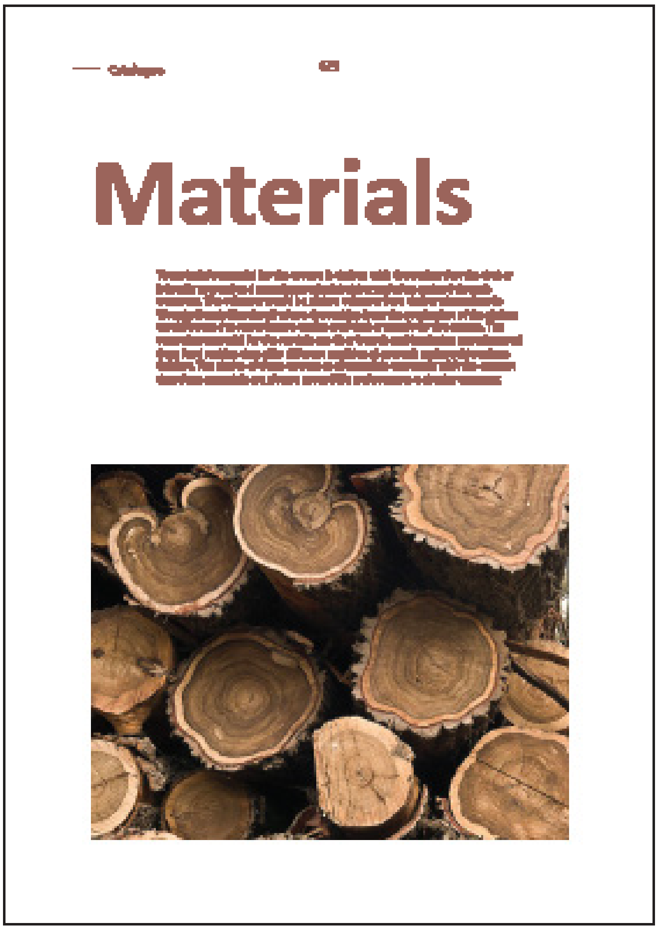







DEMOUNTABLE WALL SYSTEM


Critical approach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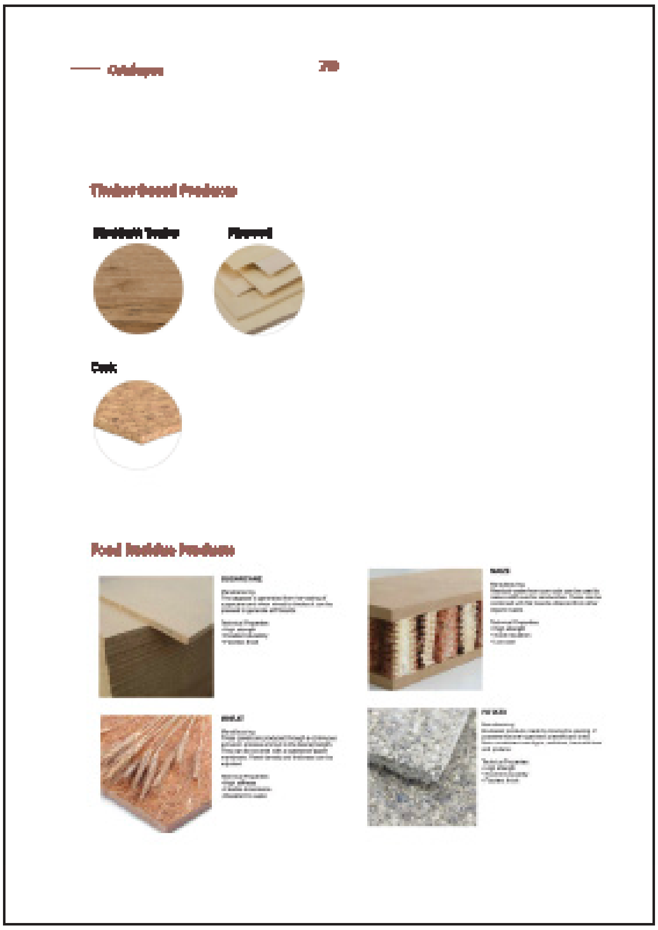
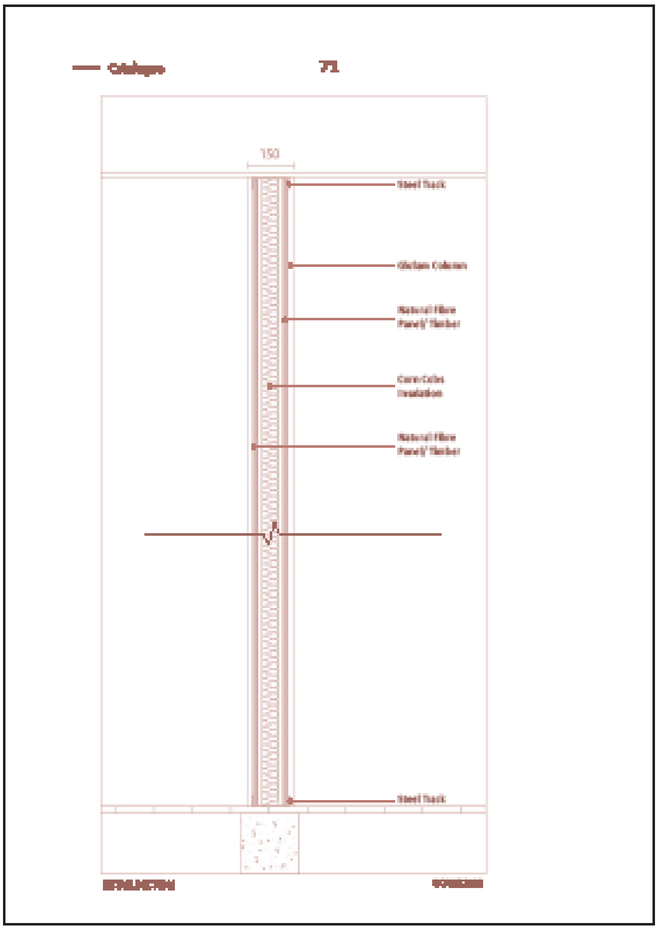
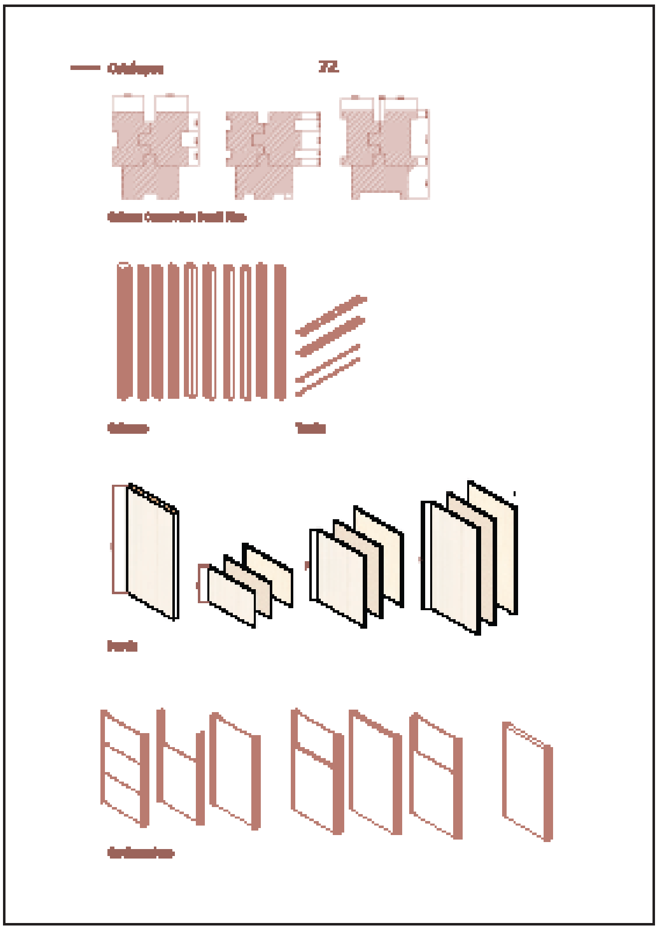



71
150
Steel Track
Steel Track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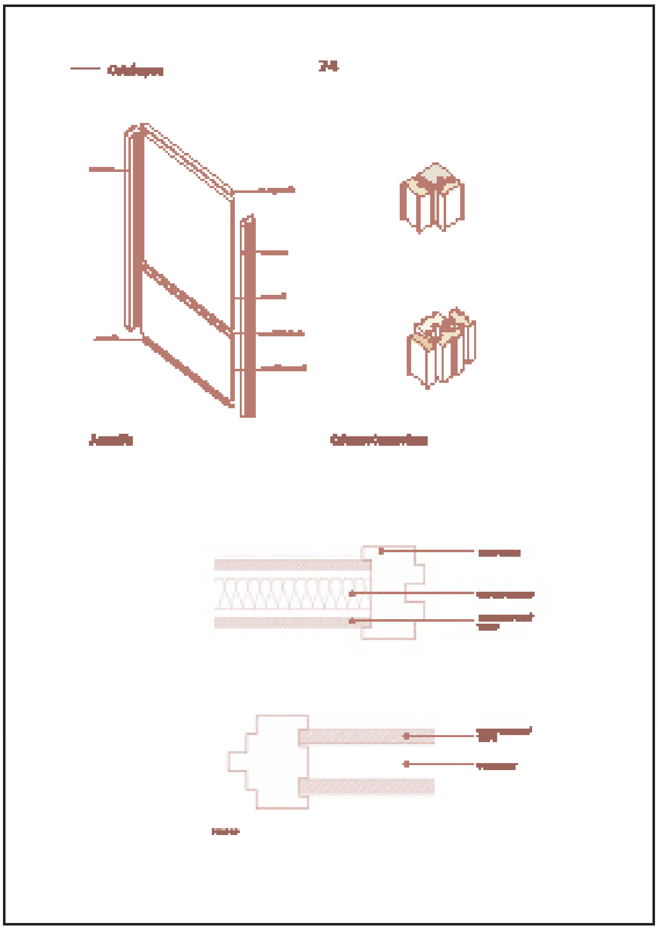
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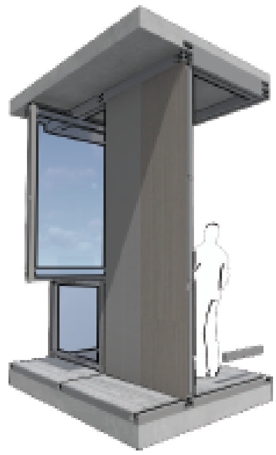


THE FLEX

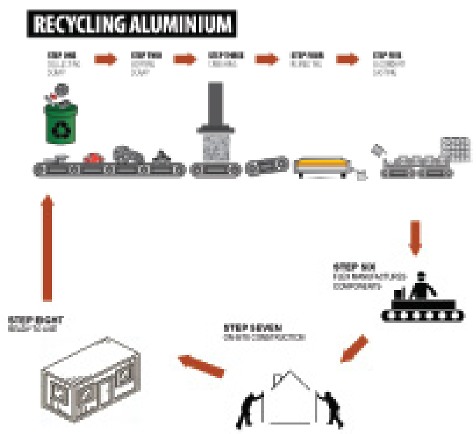
The Flex system solves an internal problem of the multi-residential development by using multi-directional/movable walls to create functional spaces for occupants. The system can be easily assembled and removable as a temporary solution in housing construction.

Critical approach

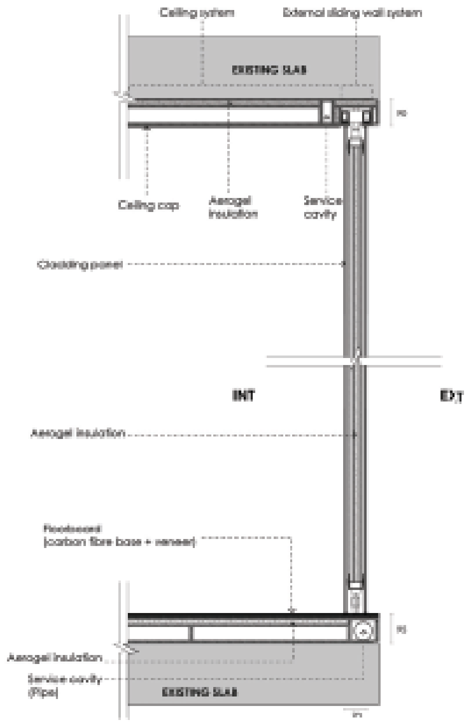
The Flex system explores the possibilities of a multifamily residential by using a system of movable walls that could generate a variety of flexible spaces. The system was considered a temporary solution in which simple assembly and lightweight are primary critical points of the system. Components of the system include a grid system and sliding walls that are customized and modified to fit with the existing structure. Sliding walls are produced and presented in various cladding finishes as timber veneer, marble, etc., as aesthetic aspects. The Flex uses aluminium as a lightweight and durable material to be easily fabricated in the factory and installed on-site. These aluminium-made components are environmentally friendly as they can easily be disassembled and recycled after a long time.

Materials

Australia is the fifth largest aluminium producing country, with 1.48 million tonnes of aluminium in 2017. Furthermore, aluminium is one of the most abundant elements on the earth, in which 75% of today-used aluminium can be recycled without losing its properties or quality. Moreover, recycling aluminium will save 95% of the energy compared to producing new aluminium materials.
In that case, we can take advantage of the aluminium's attractive benefits to create the Flex system that is both economical and eco-friendly.

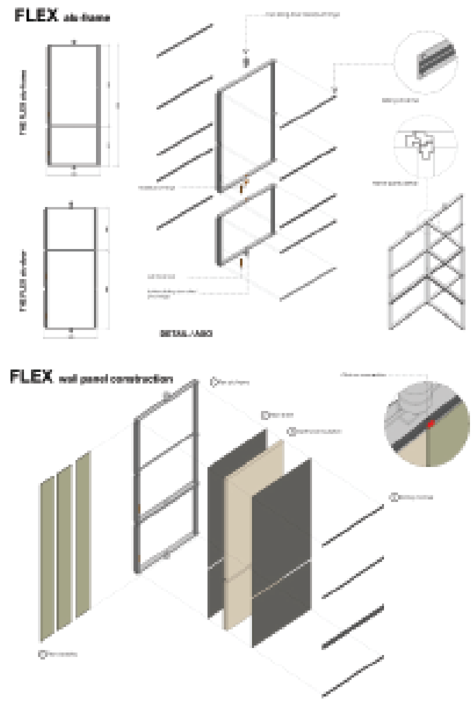


Catalogue 79



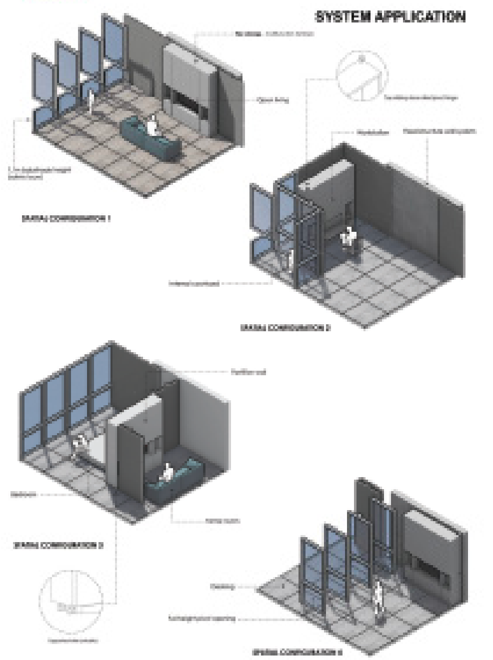
CEILING/FLOOR SECTION - SLIDING WALL Scale 1:10

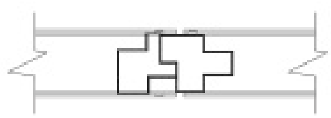
Catalogue 80



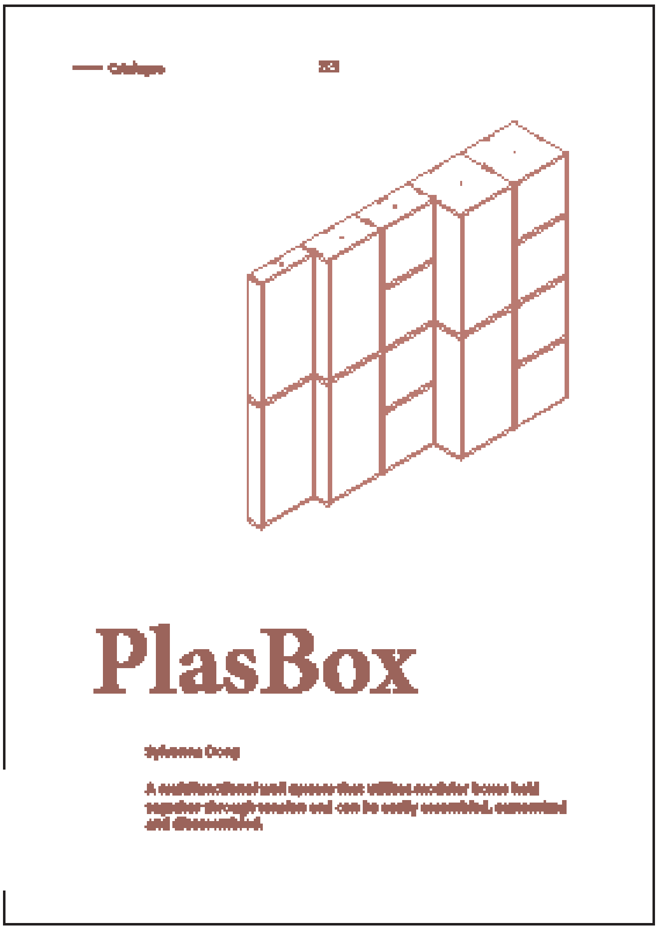
Catalogue 81

Catalogue 82

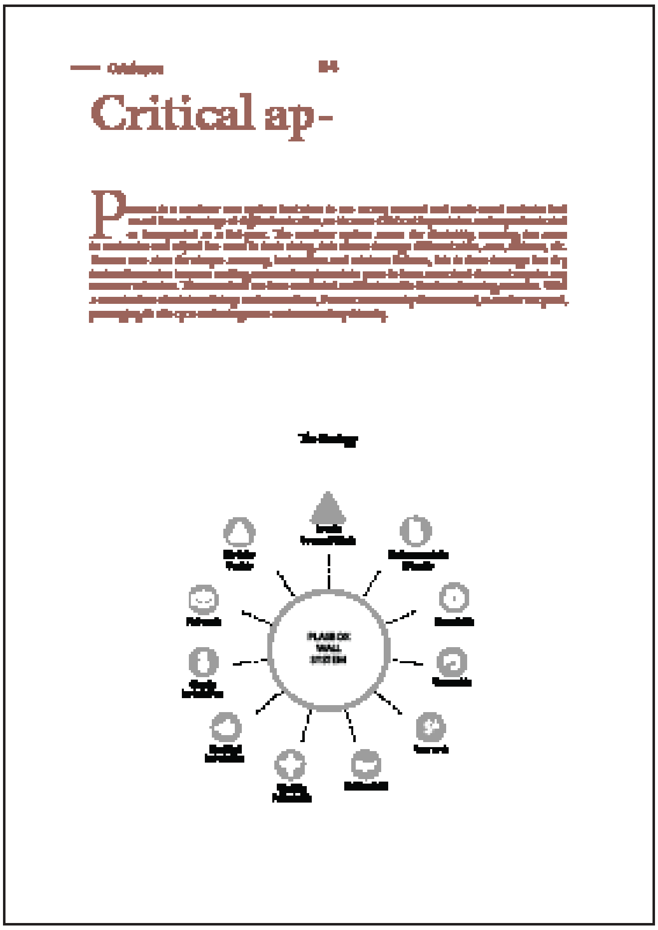




Frame connection
Plan 1:50



PlasBox



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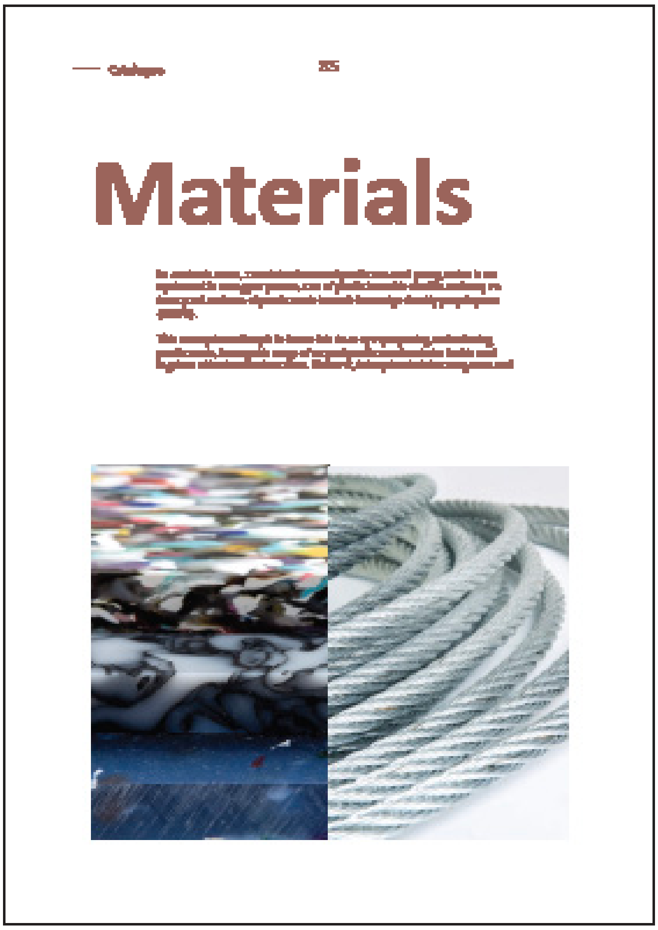
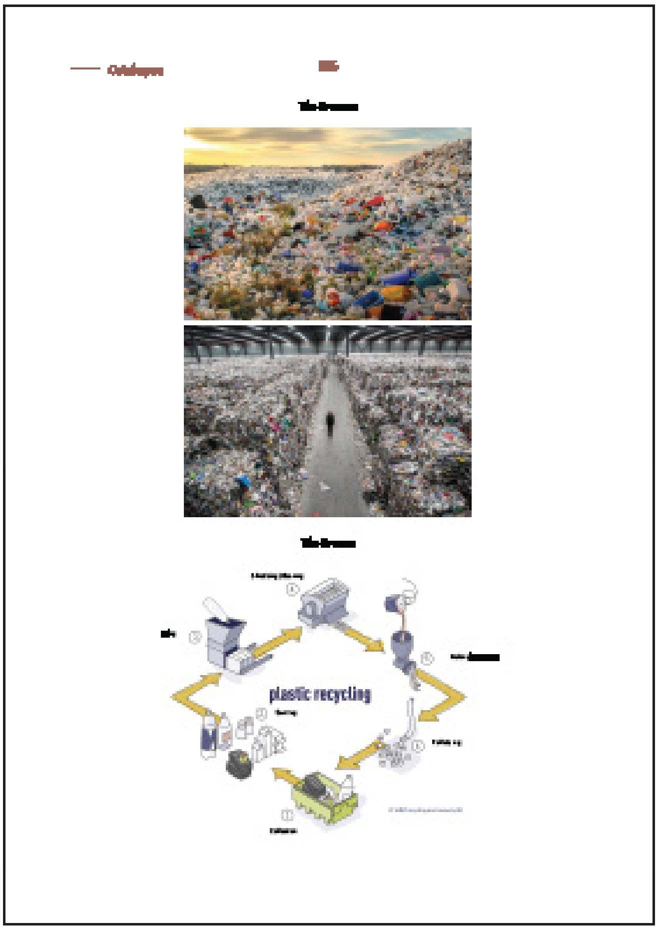
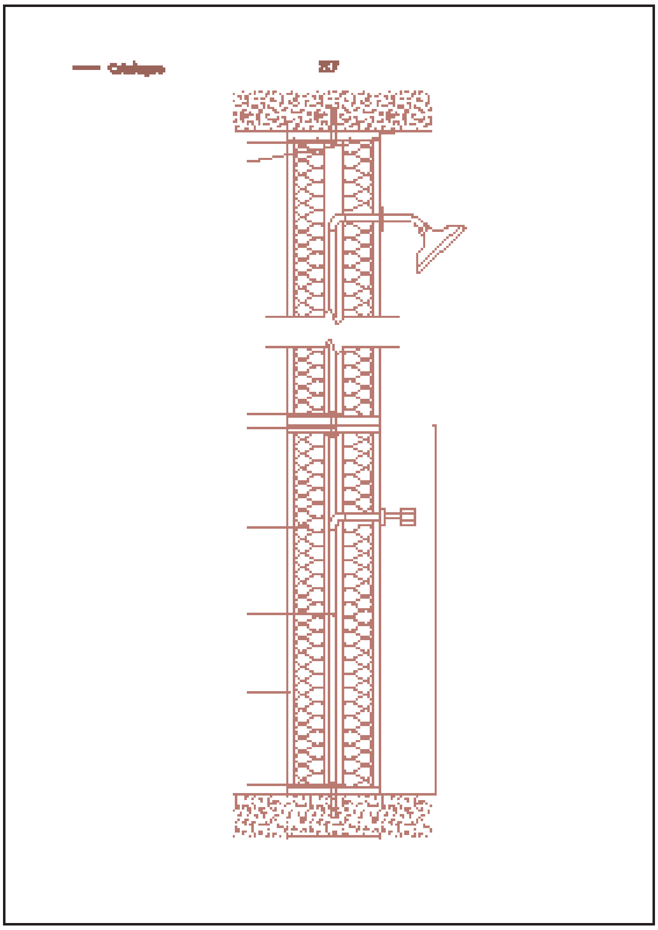
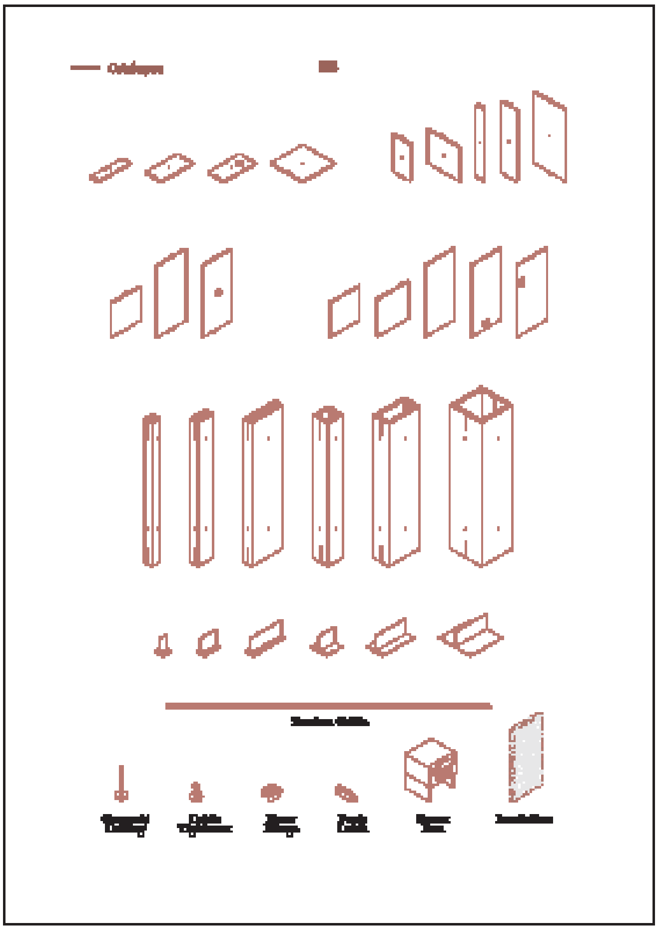
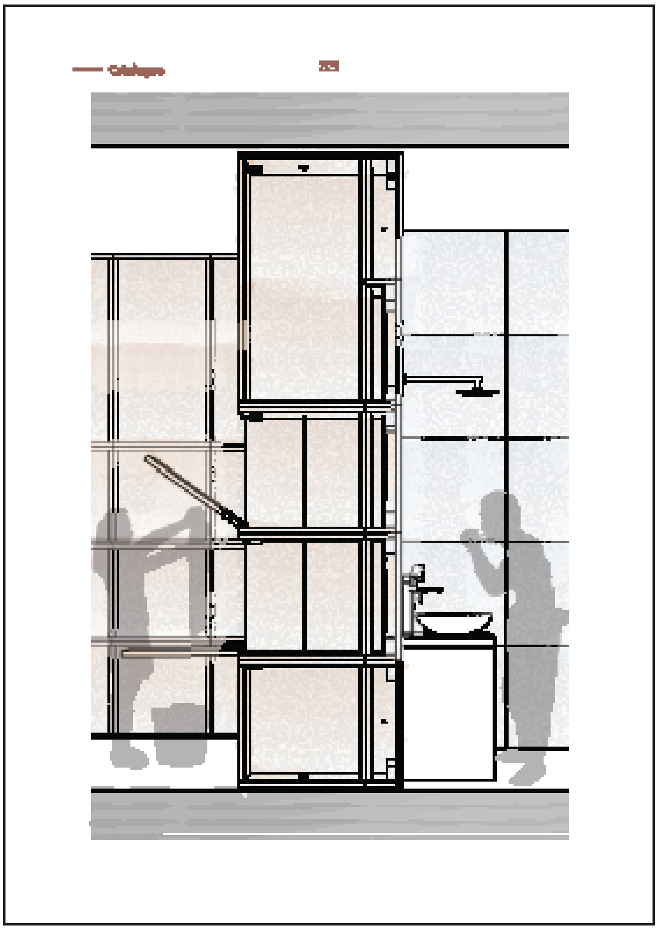


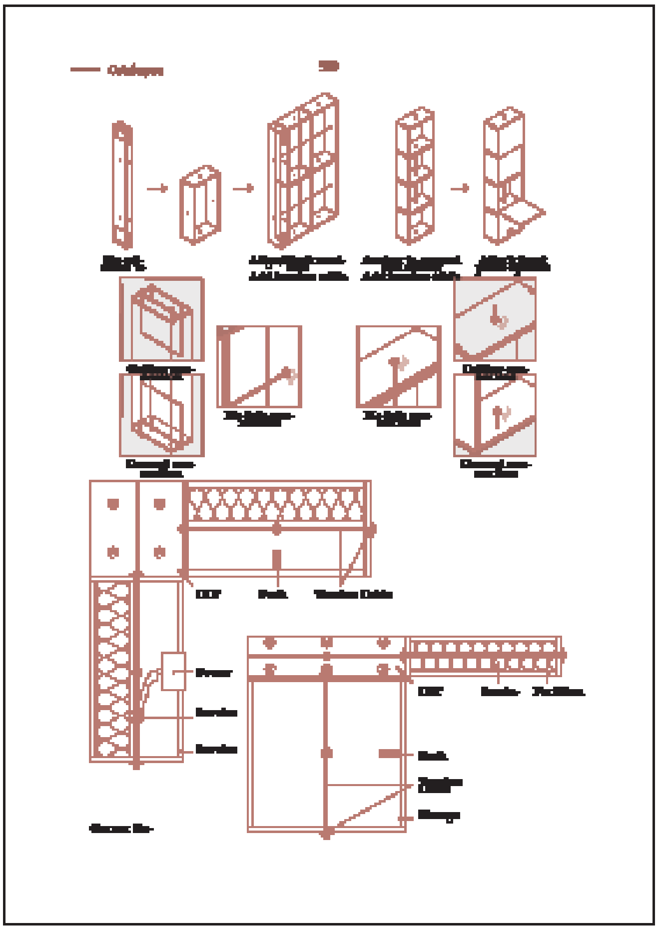
Materials

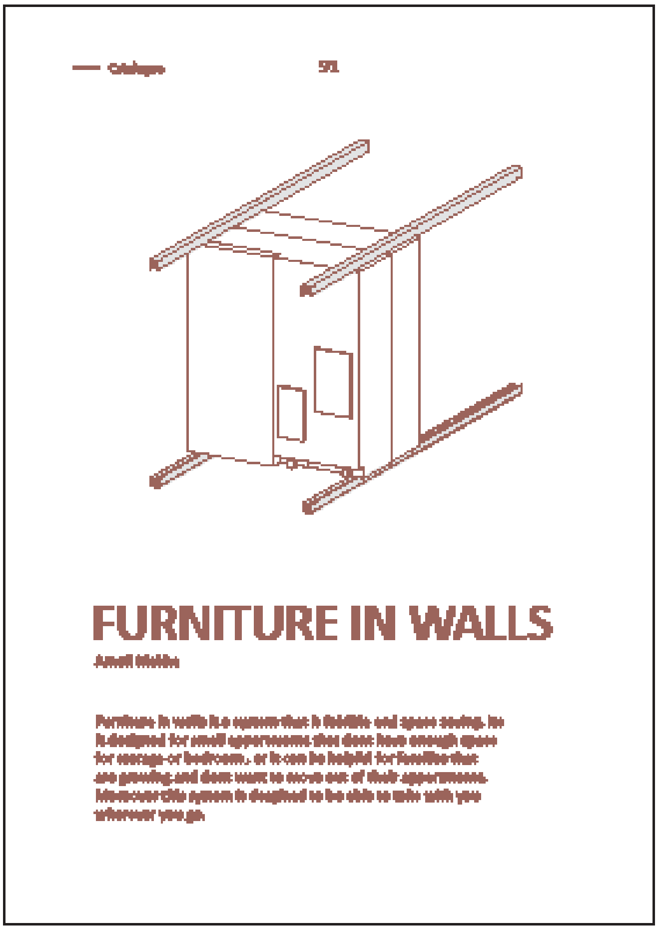








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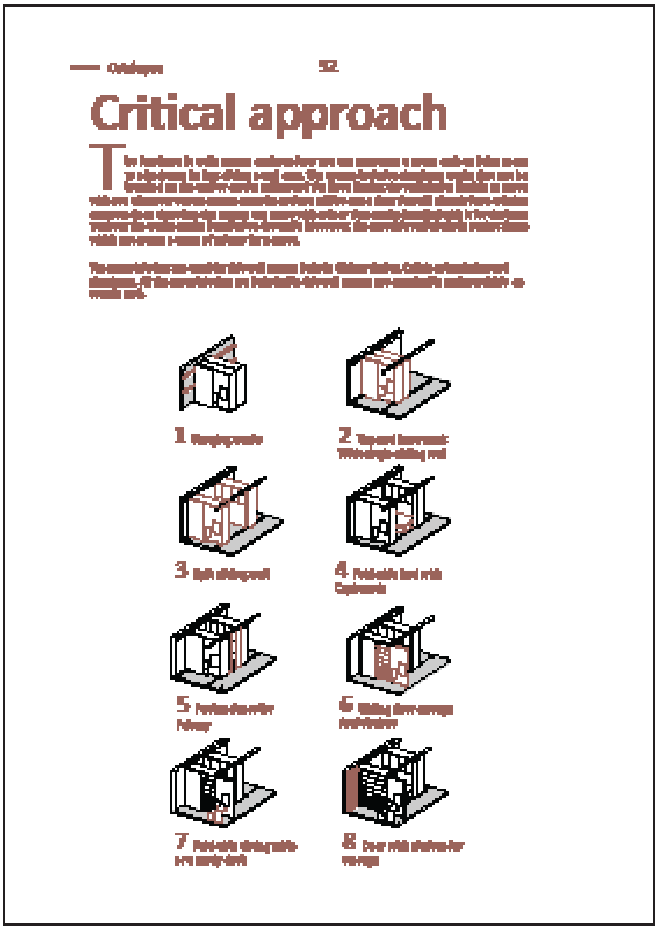
FURNITURE IN WALLS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Critical approach
1
2
3
4
5
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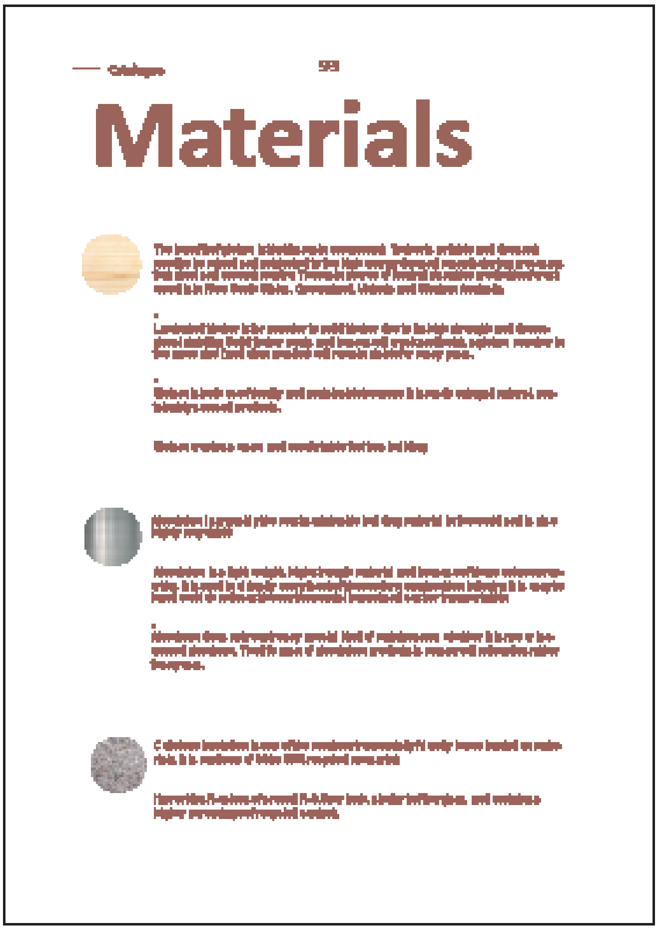
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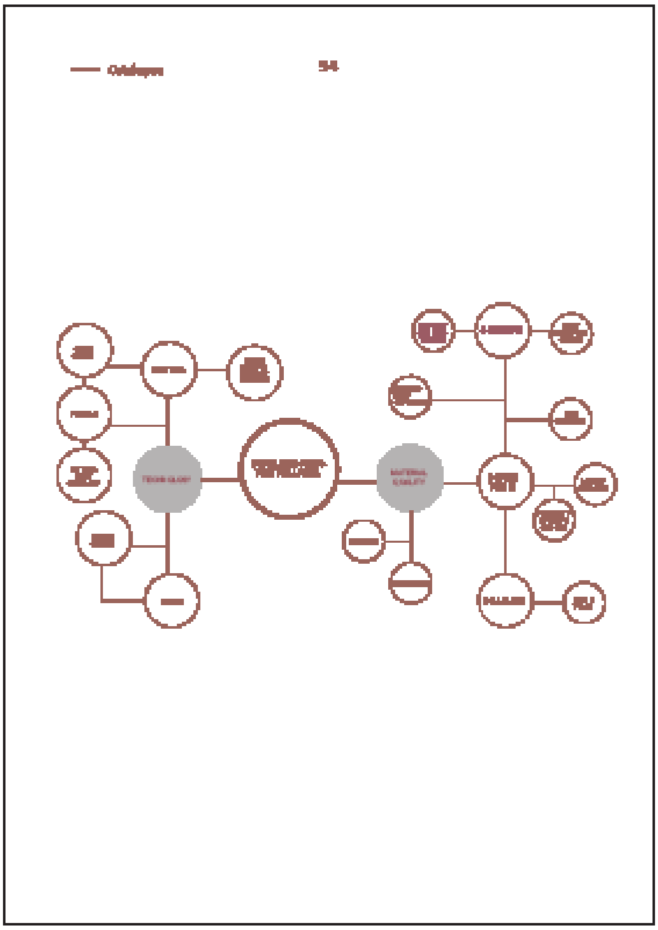
Materials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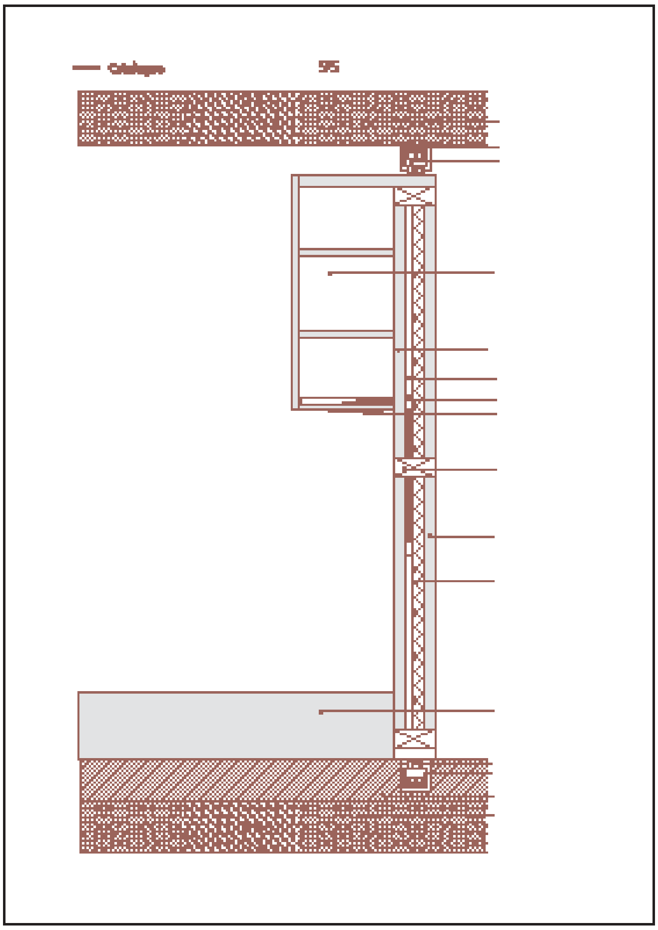

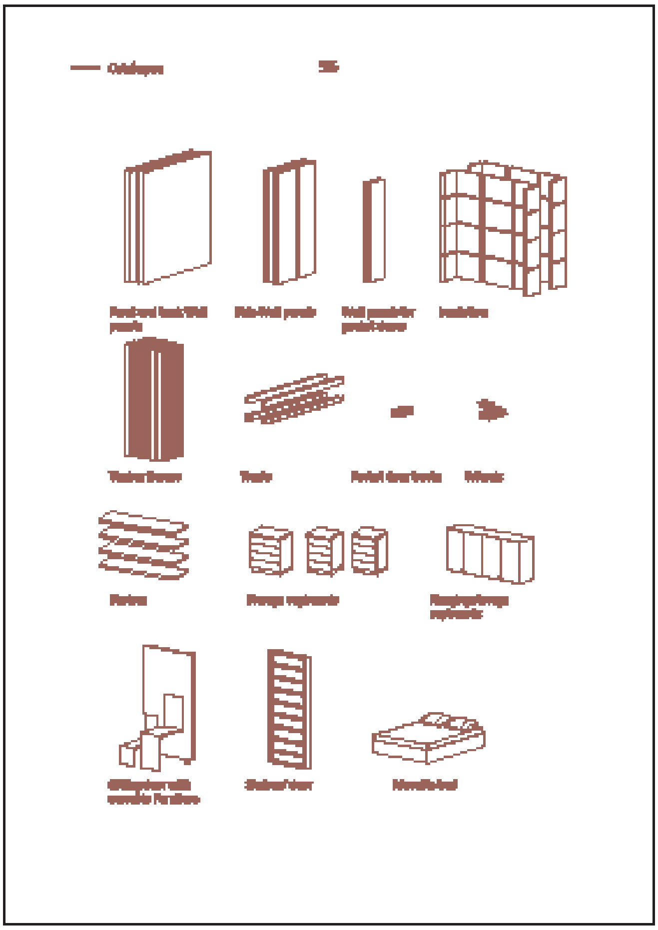

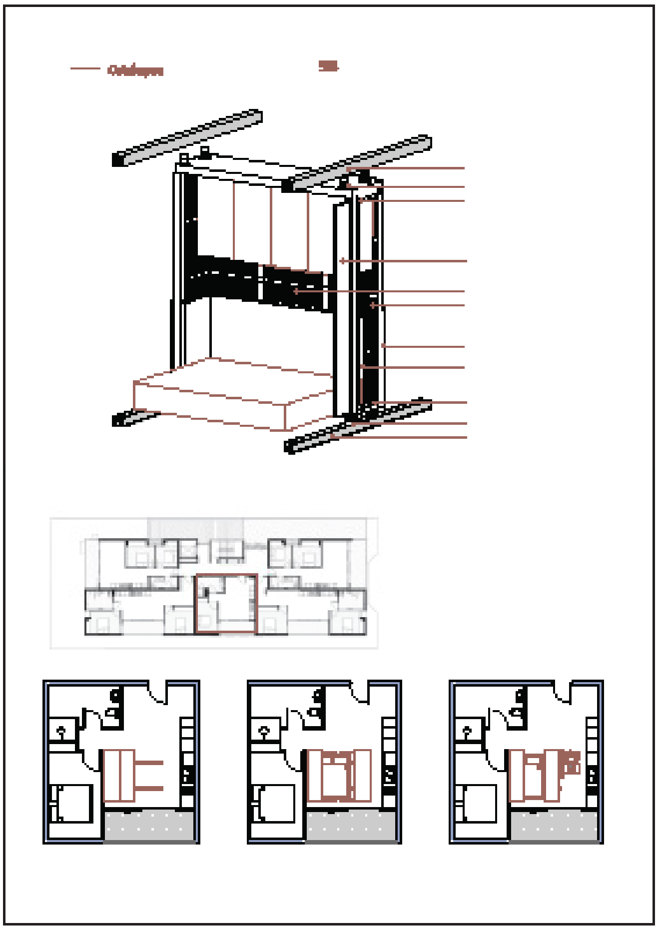

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