Ephemeral walls for natural, flexible living

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Abstract. This paper explores the feasibility of developing flexible engineered timber partitions using digital tools for adaptable and flexible housing. For the past decades, a shift in gender roles, an ageing population, new ways of forming families, globalisation and a population in constant motion, a rigid construction sector, and the way we design our cities are necessitating a change toward spaces that are adaptable to our changing needs. In order to address this need in part through flexible engineered timber partitions, extensive testing was undertaken to study the flexibility of timber through kerf patterns. These partitions folded through kerf hinges are modular, easy to fabricate, affordable, and can be placed anywhere within an apartment. Even more, as the partitions are considered a kit of parts designed to be disassembled, they can be reused in the future, promoting a circular economy. All the materials are natural. In the 21st century, with such technological advancements, the climate emergency, and citizens in constant motion, flexibility and customisation should be at the forefront of housing design.

Keywords: flexible housing, sustainable walls, engineered timber, flexible partitions

1. Introduction

This paper explores ways of increasing the design value of housing through the development of flexible interior spaces with engineered timber using digital design and manufacturing tools. This is realised through the design and fabrication of a series of flexible engineered timber partition prototypes with the aim of providing a greater autonomy for design changes to residents living in affordable housing rented apartments. Design value is a way of describing value in terms other than price through environmental, economic, and social value [1]. Social value in this context is considered in terms of developing systems and spaces where residents feel “they have a degree of control over their housing environment” [2] and in terms of wellbeing, including participation, control, health, nature, movement and belonging [2, 3]. Environmental value is explored using engineered timber as it is considered one of the best materials to reduce embodied carbon in the built environment [4]. Economic value is explored through affordability by reducing construction costs [5]. By envisioning a future where housing is designed as a complete but unfinished product, residents can develop the spaces they inhabit, and these can be altered throughout a lifetime, enabling participation after design and construction [6].

1.1. *Social value*

To give residents agency in the design of their spaces, social value is explored through flexibility. Flexibility is considered in the private space of the home through materiality, by making engineered timber flexible for the development of partitions that are easy to manufacture using digital design and manufacturing tools. Participatory design research has shown a positive impact in giving residents agency in the design of their houses [7, 8].

The need for housing flexibility, which enables residents to change their spaces to different physical arrangements [9], became apparent during the COVID-19 pandemic, during which homes had to adapt on a short-term basis to an increased number of activities that they were not designed for [10, 11]. The need for flexibility is also necessary over the lifespan of a building, or a home on a long-term basis, to accommodate ageing populations, changing demographics or new working practices such as digitisation [12]. Studies have shown that limited flexibility can have negative effects on residents, reducing long-term diversity by forcing residents to move homes as their needs change, resulting in lost social bonds [13]. Flexibility enables residents to alter their spaces on a short-term basis to incorporate activities such as home-schooling or working and on a long-term basis to support changing family constellations. Long-term residents support community cohesion and improve the lifestyles and well-being of inhabitants [14]. In addition, housing flexibility improves environmental value as it promotes circular economies where lifespans of buildings last longer, avoiding premature demolitions [15] which have significant environmental, social, and economic costs [12].

1.2. *Environmental value*

Through improving environmental value with the use of digital timber, this research aims to promote and demonstrate ways of reducing the environmental impact of buildings. The built environment accounts for almost 40% of global carbon emissions [16]. The reason for choosing engineered timber is that it is a material that we can grow with excellent structural properties that stores carbon in its cells. Timber is the only mainstream structural material with these properties and is also one of the oldest building materials in the world [17]. A five-storey residential building with a cross-laminated timber structure can store up to 186 kg C m_{-2}, compared to 52kg C m_{-2} in the aboveground biomass of forests with the highest carbon density [18], suggesting that the storage of carbon in cities could be more than that of forests. Engineered timber has excellent properties of specific strength and stiffness compared to steel and concrete: it performs as well as steel and better than concrete. It is faster to build with, lighter, better for the environment and can be more affordable. Large solid timber has an inherent fire resistance, as the surface in contact with fire chars, protecting the wood [19]. However, unlike concrete or steel, timber burns. It is therefore essential, when using structural timber in buildings, to take adequate fire safety measures [20]. Off-site digital fabrication and fast on-site assembly can reduce construction time, emissions, cost, transport, and the weight of wooden buildings, and consequently the size of foundations. Architecturally, timber creates a more pleasant, relaxed, sociable, and creative urban experience [19].

Studies of the UK building sector have shown that novel modular timber structures can reduce 50% of the embodied carbon and 35% of the embodied energy when compared to conventional building methods and materials [21]. Europe's forests have increased by about 10^7 hectares since 1990, and there is a significant amount of timber from responsibly managed forests that could be used as an alternative to conventional materials [21]. Harvesting timber from mature forests gives space for new planting, leading to continued carbon uptake [22].

1.3. *Economic value*

This paper investigates economic value through the possibility of reducing the cost of construction using engineered timber and digital tools, and by providing a novel, less expensive, and more flexible approach to building interior walls.

2. **Methodology**

The methodology for this project involved several phases: design conceptualisation, material selection and testing, prototype fabrication and testing.

- Design conceptualisation: through literature review this phase investigated the existing research on flexible housing, the use of digital tools for developing engineered timber products, kerf patterns and existing flexible partitions. In addition, the design conceptualisation involved defining the objectives for the development of the flexible

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partitions including enhancing flexibility in housing, promoting sustainability and affordability and giving residents agency on the design of their spaces; and defining the design criteria based on modularity, ease of fabrication, affordability and environmental impact.

- Material selection and testing: this phase focused on investigating the performance of different materials and kerf patterns to develop the optimal flexibility for the design of the partition walls.
- Prototype fabrication and testing: the third phase involved creating the final design of the walls. Through an iterative process of gaining feedback, observation, design adjustments and digital fabrication, the first prototypes were developed. Further assembly and testing studied the assembly process, the different connections, the flexibility of the walls and the handling, and cost analysis.

The methodology outlined provided a structured approach to developing and testing flexible engineered timber partitions. Through iterative design, material testing, digital fabrication and full-scale prototyping, this research aims to demonstrate the feasibility and benefits of using flexible partitions to enhance housing adaptability, sustainability and affordability.

3. Design of flexible partitions

By creating flexible interiors, houses can adapt to residents' changing needs [15]. Flexible partitions have been common in Japan for centuries. Some Modernist examples took inspiration from this tradition [23], and they have recently been regaining momentum with the design of plugin walls with furniture incorporated. Here, the design of the flexible partitions with engineered timber takes a different approach, since they can be placed anywhere within the apartment, and kerfing allows the design to have several geometrical configurations.

The design and fabrication of these flexible partitions with engineered timber and digital tools aims to develop a proof of concept. The aim is not to design the "ultimate" interior partition but to bring a new approach to architecture and the design of interior spaces. Housing should be an organic process in which residents from middle to low incomes should have a say in how their homes are designed. In the 21st century, with technological advancements, the climate emergency and citizens in constant motion, flexibility and customisation should be at the forefront of housing design [12].

3.1. *Overall design of flexible partitions*

Extensive experimentation with different kerf patterns, scales and densities, and digital cutting tools [24] allowed diverse forms and foldability from which we could arrive at the optimal bending performance for the design of flexible partitions.

The partitions are made of plywood and can be placed anywhere within the apartment. With the use of flexible partitions, architects do not need to foresee how people will live in 20- or 30 years because residents can be free to design and adapt the way they live in an organic and flexible manner. Even more, as the partitions are considered as a kit of parts designed to be disassembled, they can be reused in the future (Figure 1).

Figure 1. Flexible partitions. London Design Biennale, 2023 Image by: Michael Ramage

The partitions have four types of panels: a panel that connects to the wall, a middle panel with or without kerfed hinges and an end panel (Figure 2). The panels are made of 6.5mm plywood with the kerfing fabricated with a CNC machine.

The design explorations have gone through an iterative process between design and modelling. They have been informed by design feedback from members of PLP Architecture and colleagues at the Centre for Natural Material Innovation at Cambridge University.

The panels are screwed to the wall through the wall connection and joined with a jigsaw puzzle connection and a timber key to lock them. The bottom of the panels is waxed with natural beeswax so it can slide easily. Additional modules in the future could provide sound insulation using felt between layers.

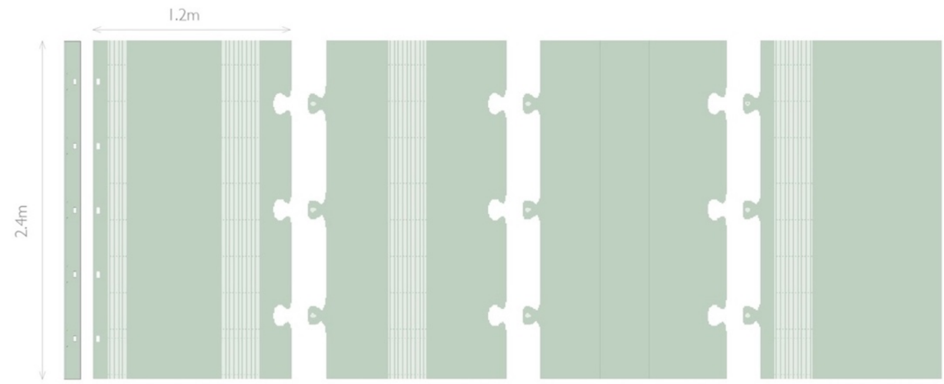

Figure 2. The flexible partitions. Drawing by: Ana Gatóo

3.2. *Flexible partitions with digital timber. Design and interactions*

The design of the partition wall went through an iterative process with various solutions for each of the problems. The final chosen solutions are explained below. The partition wall had five design problems to be solved:

- The material
- The kerf pattern
- The connection between panels
- The connection of the partition wall to the structural wall or columns
- The link to the floor
- The link to the ceiling

3.2.1. The material
The material selected for the walls is 6.5mm 5-ply FSC birch plywood. The approximate weight of the panel is 10kg, making it light and easy for one person to handle. They are the most affordable of the plywood panels with proper structural stability. The reason to use plywood is that it is sustainable, readily available, and low cost. Due to the Ukraine war (and significant amounts of Baltic birch coming from Russia), plywood is no longer as affordable as it was. However, this high cost is not expected to be a long-term price shift.

3.2.2. The kerf pattern
Previous to the design of the partition walls, extensive research into the flexibility of timber was conducted [24]. This research into kerf patterns led to the conclusion that the straight lattice pattern was the most consistent and easiest to fabricate (Figure 3). As the distance between lines remains constant throughout and tabs are the same, all stress points are uniformly stressed.

As per previous experimentation, a unit cell was created to provide consistency and replicability when creating a design. The unit cell can be arrayed on both the x-axis and the y-axis to extend the pattern as long and wide as needed. In addition, a Grasshopper [25] script was developed with the parameters required for designing the walls. These parameters were the line length, line width, the distance between lines and the number of unit cells in both the x and y axes (Figure 3).

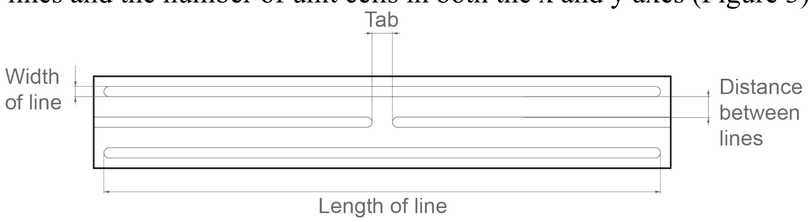

Figure 3. The unit cell of the kerf pattern. Drawing by: Ana Gatóo

The test results of previous research using plywood showed that the longer the cut line, the more flexible the material [24]. However, since the tabs and distance between lines provide structural integrity to the panel, it is essential to consider having as many tabs as possible. A balance between the length of the line and the number of tabs is needed to reduce the chance of breakage (Figure 3).

Regarding the distance between the lines, two distances were tested, 3mm and 6mm. The 3mm distance was more flexible since more material was removed; however, the material became quite fragile since the spacing was too narrow. For this reason, a tab length and distance between lines of 6mm were chosen for the design of the walls.

In terms of cut width, the 6mm cut provided more flexibility than the 3mm one, but since more material was removed, it proved to be more fragile. In addition, it required more width of pattern and so the 3mm was chosen for the design of the walls.

As per previous experimentation, a line length of 120mm was chosen throughout. This length provides optimal flexibility while maintaining a good balance between lines and tabs [24]. The partition wall is then composed of alternating columns of 18 tabs, 19 lines in its height and 19 tabs and 20 lines. This number of tabs gives sound structural integrity to the kerf pattern.

Regarding the width of the kerfing pattern, a total of eight-unit cells were chosen. This amount of unit cells makes eighteen lines. From previous testing, the results obtained showed that the material breaks at 120 degrees with four-unit cells. With six-unit cells, the material achieves the elastica curve [24]. Two more cells were added for safety to reduce stress and fatigue in the material and increase its flexibility. The total width of the pattern is 220mm.

Panel 1 has two hinges of the pattern (Figure 2). The first one relates to the first fold after the wall connection. This first fold just needs to curve 90 degrees and not 180, so the pattern's width is reduced to one-half or four-unit cells. All the other hinges are formed of eight-unit cells. Panel 1 is the only panel with two hinges; all the other panels comprise one hinge or none (Figures 4 and 5).

Figure 4. The flexible partition prototype. Image by: Ana Gatóo

Figure 5. Flexible partitions. London Design Biennale, 2023 Image by: Ron Bakker

3.2.3. Connection between panels

Several options were trialled to arrive at the optimal solution for connecting the walls. This consisted of a jigsaw connection between the panels and a key that would lock them in place. These connections were fabricated with the same plywood and a CNC machine and worked well when joining two adjacent panels. The key connection is made of two pieces that go into a hole in the ply from the two sides, interlock in between, and rotate, providing extra support to the puzzle connection at two points. This 2-point support avoids overturning. The concept was first fabricated with a laser cutter until the optimal design was accomplished.

In the second stage, it was manufactured with the Shaper Origin. Because of the tightness of the connection, the keys could not rotate. Two more samples were fabricated, allowing some tolerance so the system could work. The tolerance should be minimal, as more would make the keys turn too much and not provide the stability needed. One of the samples had a 1mm increase in the keyhole perimeter, and the second sample had a 0.5mm increase in the keyhole perimeter and a 0.5mm decrease in the edge of the key (Figure 6).

Figure 6. Key connection in 6mm plywood. Images by: Ana Gatóo

Figure 7. Wall connection to the 6mm panel. Image by: Ana Gatóo

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With these two options, a third possibility could be tested: introducing the original size keys into the keyhole that had increased the perimeter to 0.5mm. The optimal solution was the 1mm perimeter increase of the hole. No further tests were needed since this option performed optimally.

The key connection selected was the more cost-effective solution of the ones tested; it also used the waste produced when cutting the 6mm ply as the keys can be placed next to the puzzle connections. They do not need extra material; they reduce waste and increase efficiency, improving sustainability and being the most elegant solution.

3.2.4. Connection to the wall

The connection to the wall is an element that joins two systems: on the one hand, it needs to be connected to the wall, and on the other hand, it needs to be connected to the first panel. After several iterations, the design was developed with the use of 18mm plywood. The section would be similar to a double T but manufactured with plywood sheets. Different options were contemplated for the manufacturing. Finally, two L sections were designed, which would be fabricated with large holes where a "doughnut" piece was slid in and locked through a third piece that holds the connection in place (Figure 7).

The L sections are made of two pieces of plywood joined perpendicularly with pegs and glued. Since the L is a piece by itself, it is the one element that can be glued together without affecting the system's modularity, disassembly and reuse. The L connection was joined through a simple butt joint connection with pegs and glued together.

3.2.5. Connection to the floor

Two issues were to be solved when considering the floor and wall intersection. First, since it is a flexible partition, it must be able to slide. Different options were contemplated here. The selected option is to use beeswax. It is a natural material that can be applied easily to the bottom of the panels, allowing them to slide in any direction and protecting floors from scratches. It is also an optimal solution for disassembly and disposal since it is natural. Beeswax is readily available and has a low cost, and it can last for a long time, too.

3.2.6. Connection to ceiling

For single-panel walls, a connection to the ceiling did not seem necessary. Single panel walls are not soundproofed, as the plywood panels are 6.5mm in width and have holes throughout the kerfing. Since they are not soundproofed, there is no need to seal them to both the floor and ceiling to provide sound insulation.

3.3. Cost and fabrication

Prices of plywood sheets vary depending on quality, the number of sheets acquired and the manufacturer. The flexible walls had a total cost of £24/m^{2,} including machine rental, whereas the cost of plasterboard interior partitions in the UK is approximately £80/m^2.

The price for the flexible partition is less than half the price of the plasterboard wall. However, the plasterboard wall completely encloses a room and provides sound insulation. In contrast to plasterboard walls, the engineered timber flexible partitions can be disassembled and reused without creating waste and without needing to hire a skilled worker. A double-panel wall with cotton felt inside could be designed and fabricated for future developments. This could have a cost of around £60/m^2 from initial estimations.

3.4. Fireproof

Plywood must be fireproofed to comply with building regulations. This project used Flametect CWD. Clear Flame Retardant for Wood. Flametect CWD is applied to dry wood by spray. The absorption rate in the case of the 6.5mm panels was around 4m^2 per litre. The boards need to be left to dry for about 24hr in a covered space above 10ºC. According to the product specifications a BS476 Class 0 and 1 EN13501-1 2007+A1 - Euroclass B. BS /EN 13823 Type B classification is achieved [26].

There are other products in the market. Flametect provides the fireproofing protection needed for housing. The product is easy to handle, safe to use, non-toxic, non-corrosive, non-hazardous and completely odourless [26].

3.5. Prototyping

The first prototype was fabricated at scale with a Denford 6600 CNC with a bed of 1000mm by 600mm. The following prototypes were then fabricated at full scale with an AXYZ Infinite 4008 CNC router with a 1524mm x 2438mm bed.

The first full-scale prototype was fabricated to test how the wall system performed. Once built and tested, a consultation was undertaken with colleagues at the Centre for Natural Material Innovation, and another was conducted with colleagues at PLP Architecture, and several changes were introduced. A five-jigsaw connection system was introduced and trialled (Figure 8). The outside connections were moved closer to the edge, and the size of the jigsaws was reduced, so the key covered more surface between the two panels. A series of tolerances of 0.1mm, 0.2mm and 0.3mm were also trialled. The five-jigsaw connection was optimal, and the 0.1mm tolerance was the best option for keeping the connection tight whilst easing the assembly.

An additional change was introduced since, during transportation, the bottom kerf of one of the folds broke. It was then decided to remove a material section on the bottom of the folds. The removal took a curve shape, and several heights were trialled. The curvature with the lowest height was selected for the system (Figure 8).

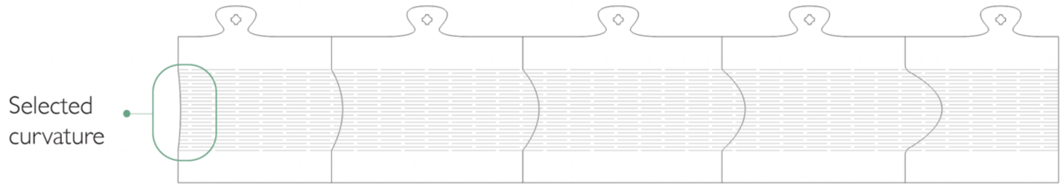

Figure 8. Curvature trials. Drawing by: Ana Gatóo

In 2023, a prototype, “Ephemeral: Natural flexible living”, was designed and built for the London Design Biennale as part of the “Eureka!” program (Figures 1 and 5). The aim of making the prototype was to understand, test, and analyse the system developed within an open building housing prototype of half a one-bedroom apartment for 2 people based on the London Plan’s spatial standards [5].

The prototype was composed of a structural kit of parts of glulam columns and beams and 27mm 3-ply panels based on the open building and with internal walls using the flexible partitions developed. The glulam beams and columns are connected with a Rothoblaas Lock T Mini 35mm x120mm, allowing a semi-concealed structural and demountable connection.

Three flexible walls were included in the prototype. Each wall was composed of three modules and was placed in different parts of the home with varying arrangements so people could appreciate the flexibility and functionality of the system.

The assembly was done in under two and a half hours by a team of five unskilled labourers. The disassembly was achieved in under thirty minutes. The material was then flat-packed into a pallet for transportation. The system demonstrated tremendous flexibility in terms of assembly and disassembly, showing that similar systems made with engineered timber and prefabrication can be used for long-term flexibility, where an apartment can change over the course of a lifetime. Apartments can increase or decrease depending on needs by buying neighbours’ space. Walls can be altered too, and rooms can be assembled depending on changing needs. Elements of the kits of parts of this system can be removed or reassembled into different configurations, there is no waste in the system, and spaces can be altered.

The assembly of each partition system was made of 3 modules, and the connection to the structure was conducted in fifteen minutes by two unskilled people. The partitions were connected on the floor, folded, and carried to the point of connection with the structure. The whole system weighs under 30 kg and is easily handled by two people. Once the interior location is decided, the system is screwed to the wall in less than five minutes. The fabrication of the first module on the CNC took around forty-five minutes, as it has the largest member of kerf lines, whilst the second and third took thirty minutes. One system can be fabricated fully in about two and a half hours, including cleaning and handling the panels.

The flexible partitions showed the possibility of having many design arrangements providing participation in the design of a space post-construction. The system provides privacy and a beneficial change in acoustics within the apartment, even if they are not soundproofed. The modules are robust and stable yet easy to handle. Further development is needed to provide soundproofing and to connect different systems.

4. **Results**

The results of this study show that flexible engineered timber partitions can be used to achieve social, environmental, and economic value. Each area is discussed below, supported by data and observations from the experimentation and testing phases.

4.1. *Social Value*

The primary objective of developing flexible timber partitions was to enhance the flexibility of interior spaces. The partitions are a kit of parts designed for being disassembled allowing residents to customise their living spaces. The partition walls can be assembled in fifteen minutes by two unskilled people. This ease of assembly facilitates frequent reconfiguration of living spaces. In addition, feedback from users who interacted with the system at the London Design Biennale was positive. Users appreciated the ability to reconfigure their spaces and noted the partitions' aesthetic appeal and functional benefits. The partitions provide a sense of control and personalisation, contributing to increased satisfaction and well-being among users.

4.2. Environmental Value

The use of engineered timber for the flexible partitions significantly reduces the environmental impact compared to traditional construction materials. Using engineered timber for partitions contributes positively to carbon sequestration, aligning with sustainability goals. The modular nature of the partitions promotes a circular economy. The partitions can be disassembled and reused in different settings, reducing waste and the need for new materials. Off-site digital fabrication minimised construction waste, as the precise cutting of panels reduced excess material.

4.3. Economic Value

The economic analysis of the flexible partitions reveals several advantages over traditional construction methods. The total cost (2023) of the flexible partitions was calculated to be £24 per square meter, including machine rental. In contrast, traditional plasterboard interior partitions in the UK cost approximately £80 per square meter.

Despite the lower cost, the partitions provide additional benefits, such as flexibility and ease of reconfiguration, which are not typically available with plasterboard walls. The affordability of the flexible partitions makes them accessible to a broader range of residents, including those in affordable housing. This accessibility promotes inclusivity and allows more people to benefit from flexible living spaces. Further developments, such as double-panel walls with soundproofing using felt, are estimated to cost around £60 per square meter, still offering a cost-effective solution compared to traditional methods.

5. **Discussion**

The development of flexible engineered timber partitions presents significant advancements in the field of flexible, affordable and sustainable housing. This section discusses the implications of the research findings, explores the broader context, and identifies areas for future research and development.

5.1. *Implications for housing design*
The results of this research demonstrate that flexible partitions made from engineered timber offer a viable solution for modern housing design, addressing the need for adaptability in living spaces. The key implications from this study show the benefits of enhanced flexibility and user control as the partitions give residents agency to modify their spaces based on their needs; environmental impact through the use of engineered timber; and economic benefits.

5.2. *Broader context and trends*
The findings of this research align with broader trends in architecture and urban design, where there is an increasing focus on flexibility, sustainability, and user-centric design. The COVID-19 pandemic underscored the need for flexivle living spaces as homes have become multifunctional environments [10, 11]. This research responds directly to such societal shifts by providing an elegant and practical solution for flexible interior design. As demographic trends continue to evolve, with aging populations and changing family structures, the demand for adaptable housing will likely increase [12]. Flexible partitions can address these needs, providing long-term benefits for diverse resident groups.

5.3. *Future research and development*
While the research demonstrates significant benefits, there are several areas for future investigation and improvement:

- Further research is needed to enhance the soundproofing capabilities of the flexible partitions. Incorporating materials such as felt between double-panel walls could improve acoustic performance without compromising flexibility.
- Ensuring that the partitions meet all fire safety regulations is critical. While Flametect CWD was used in this research, ongoing testing and validation are required to confirm compliance with evolving safety standards.
- Developing strategies for scaling the production and implementation of flexible partitions will be essential for their widespread adoption. This includes exploring partnerships with manufacturers, housing developers, and policymakers.
- Market integration efforts should focus on demonstrating the economic and environmental benefits of flexible partitions to stakeholders in the construction industry.
- Conducting long-term studies on user experience and satisfaction will provide valuable insights into the practical benefits and challenges of using flexible partitions. Engaging residents in the design and feedback process can further refine the product.

This discussion highlights the potential of flexible engineered timber partitions in modern housing design. By addressing the needs for flexibility, sustainability, and cost-effectiveness, these partitions offer a compelling solution for adaptable living spaces.

6. **Conclusion**
The results of this study show the successful development of flexible engineered timber partitions that enhance housing flexibility, reduce environmental impact, and provide economic benefits. These partitions offer a sustainable and affordable solution for modern housing needs, demonstrating the feasibility and advantages of using flexible partitions to create adaptable living spaces. This research has also shown that it is possible to develop participation without participants by providing flexibility for residents to adapt their spaces. Continued research and development will further enhance their functionality and integration into the housing market, contributing to more resilient and user-centered residential environments.

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Authors' contributions

Ana Gatóo: conceptualisation, methodology, data collection, analysis, writing – original draft
Michael H. Ramage: conceptualisation, methodology, writing – review and editing
Ron Bakker: conceptualisation, review and editing.

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