

Material efficiency in local timber construction: unlocking the potential of English timber

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Abstract

The rising demand for low-embodied carbon materials and supply chain disruptions, such as climate change impacts and global crises, necessitate a sustainable wood supply for building products. Supporting local capacity to grow, manufacture, and supply timber-building products can surmount international trade barriers. In the UK, the market is import-oriented, with forests in England primarily utilised for short-term purposes. This study explores material-efficient, optimisation-driven structural timber systems using local underutilised English timber for low to mid-rise buildings and retrofitting. Adding value to this timber offers long-term carbon sequestration, addresses the demand for low-embodied carbon materials, and provides socio-economic benefits through local education and employment. We present designs and simulations of structural prototypes using underutilised English timber and analyse timber-based truss system performance. Preliminary results show effective and scalable approaches for optimised truss, beam, and joist systems relevant to those interested in material-efficient timber structures with underutilised timber resources.

Keywords: nature-based solutions; harvested wood products; wood utilisation; topology-optimised structures; material-efficiency; underutilised timber; timber design; robotic construction

1. Introduction

The global built environment is projected to expand by 230 billion square meters by 2060, approximately double its current size [1]. By 2030, this increase is expected to reach 20%, with the majority of growth occurring in emerging and developing regions [2]. The materials used for constructing these buildings will profoundly impact the environment and how we live. Raw material consumption nearly doubled by 2016, and based on current trends, the global demand for natural, replenishable materials is anticipated to more than double to 190 billion tons [1], [3].

Traditional construction practices often rely on carbon-intensive resources such as steel and concrete. Nature-based solutions (NBS) offer alternatives such as timber, bamboo, hemp, or earth, which are both renewable and carbon-sequestering. By adopting NBS in construction and substituting high embodied carbon materials like steel and concrete with natural alternatives like wood, it is possible to reduce carbon emissions by 0.9 kilograms for each kilogram of carbon sequestered in the wood [4]. Thus, due to the urgent need to reduce greenhouse gas emissions and promote carbon sequestration strategies, there is a need for a rapid shift in practices across the construction industry.

Timber, the most advanced natural material in use, is processed for various purposes, from packaging and building products to fuel, food, and textiles. The demand for structural timber is significant, and the desire for an increase in engineered wood construction, such as mass timber, is substantial. The United Kingdom (UK), is the second-largest net importer of timber globally, with 82% of its timber imported [5]. However, the timber global trade is vulnerable to supply chain disruptions resulting from climate

events, forest disease and impacts, pandemics, invasions, and wars; therefore, ensuring the continuous and affordable supply of sustainably harvested wood for building products is a pressing issue. One way to meet demand and overcome international trade barriers is to support local and sovereign capacity to grow, manufacture, and supply timber-building products.

The UK, comprising roughly 3.24 million hectares of woodland, representing 13% of its total land area, boasts a vast array of forest types and management practices [6], [7]. These span from small private landowners and extensive monoculture plantations to progressively mixed, biodiversity conservation-focused forests. Conifer plantations, primarily situated in the North and West of England, Scotland, and Wales, supply the majority of domestically-produced structural softwood sawn boards utilised in building and construction.

In England specifically, forests account for 10% of land cover and exhibit a diverse assortment of species. Conifer plantations typically include Scots or Corsican Pine, Sitka or Norway Spruce, Larch, and Douglas Fir. Conversely, broadleaf stands may encompass Oak, Elm, Sycamore, Chestnut, Beech, and Ash species, which are particularly favoured by private small-lot landowners in the South. Conifer resources, particularly pines, are predominantly used for bio-energy, pallet and packaging production, and agricultural fencing [8]. Broadleaf species are preferred for specialised construction, boat building, and furniture markets; however, their value can be challenging to optimise for larger sawmills due to factors such as location, proximity, volume, and species diversity within each forest stand. Characteristics like log size, quality variance, and the extended processing time required for drying broadleaf species contribute to the limited adoption of structural broadleaf-sawn boards in building products. As a result, the majority of structural sawn board supplies for building products are imported, whilst locally-grown English timber remains underutilised and reserved for short-term applications.

In addition to supply chain challenges and lack of sovereign capacity to produce timber building products, like many regions worldwide, England and the UK are facing an increasing population, rising inflation and expenses, infrastructure and a building crisis, characterised by outdated and energy-intensive building stock, poor-performing public infrastructure, and an under-supply of housing [9]–[15]. There is an urgent need for new construction, retrofitting and renovation of existing buildings that incorporate NBS that are structurally capable and carbon-sequestering. Although the substitution of timber in structural building design is increasing and is heralded as the material of the future [16], [17], an increased demand requires greater material efficiency and lower-consuming timber products [18]. Focusing on residential buildings, material efficiency strategies can reduce emissions in the material cycle by over 80% by 2050 [4], [19].

This research adopts a material-efficient approach to investigate optimisation-driven structural systems using local underutilised English timber for low to mid-rise buildings to meet housing supply and retrofit existing poor-performing buildings. Adding value to local underutilised English timber through building products offers long-term carbon sequestration, supports the growing demand for low-embodied carbon construction material and brings a raft of socio-economic benefits to communities through local and regionalised education and employment. In the following sections, we present the structural performance of a timber-based truss system, looking at member utilisation, material volume and embodied carbon. The paper contains preliminary findings that inform a larger project looking to add value to English underutilised timber for use in construction.

2. Methods

This study aims to promote more efficient uses of homegrown local underutilised English timber, to provide opportunities to generate the local supply chains and industry and thus enable low-embodied carbon options for locally manufactured construction products through efficient structural design. The study was based on the properties of available materials, which are discussed in the following sections.

2.1 Material-efficient design development

A computational workflow has been developed using a parametric 3D modelling environment to design and analyse truss-like structures. Timber trusses are considered efficient structural typologies because they are primarily subject to axial stresses (tension and compression) rather than bending moments. The optimisation of these structural typologies to improve material efficiency has been extensively investigated, originating in the studies of A. G. M. Michell (1904) [20]. Recently, thanks to advances in computational power and software development that allow faster calculations [21], its potential is being explored further. For instance, Fairclough, Gilbert and Thirion [22] have demonstrated through a case study of a large transfer truss, industry-ready design solutions that enable reducing embodied carbon (EC) by customising the truss layout based on project-specific variables

Ching and Carstensen recently explored the optimisation of member layout in truss systems to reduce EC using the Ground Structure (GS) approach [21]. This approach consists of a dense structure populated with multiple potential elements, undergoing a sizing optimisation that allows the minimum bar area to approach zero. The GS method's first step is to define the design domain, load application, and boundary conditions. The domain is then populated with a grid of points, all connected to form potential truss elements. The optimisation criteria focus on minimising the weight and, in mono-material trusses, the volume of the employed resource. A material-agnostic method has recently been developed and made accessible to designers and engineers through a user-intuitive interactive design tool [23].

Using parametric modelling platforms, such as the Peregrine plugin [24] in the Rhino-Grasshopper environment, users can run a structural simulation that indicates the best truss layout given design boundary conditions and load cases. The contribution of a layout optimisation method in trusses for weight and volume savings can vary based on several variables, such as domain configuration, buckling of compressed members, load cases, allowed deflections, and manufacturing constraints. In some practical cases, this optimisation method can achieve up to a 40% volume reduction compared to a traditional Warren-truss layout with optimised cross-sections [22]. The primary trade-off for volume reduction lies in the layout complexity and related manufacturing constraints. The employed plugin (Peregrine in Rhino-Grasshopper) allows for post-processing rationalisation to simplify the design by reducing the number of joints and members.



Figure 1. Typical floor joists with open steel webs. The top and bottom chords are made of softwood-graded TR26.

This study leverages the Peregrine plugin in the Rhino-Grasshopper environment to design and analyse truss-based floor joists suitable for low- to mid-rise applications in multistorey residential, office, or school buildings, addressing the high demand for such structures in England and the UK [23]. Secondary structural elements, such as floor joists, are the primary focus and explore the potential of implementing English timber by replacing steel web joists with wooden alternatives. The industry benchmark for comparison is the conventional steel web joist with wooden top and bottom chords, a design widely employed in the UK construction market for timber-framed buildings (Fig. 1).

The workflow, developed within the Rhino-Grasshopper environment, integrates layout optimisation with Peregrine and structural analysis in Karamba 3D[25]. The process can be summarised in four main steps: i) defining the domain and boundary conditions (joist dimensions, material properties, load cases) and performing layout optimisation using Peregrine; ii) selecting the minimum cross-section according to maximum utilisation values for members and manufacturing constraints (e.g., joint typology); iii) optimising the cross-section and conducting structural analysis with Karamba 3D; and iv) comparing the results with the industry benchmark in terms of embodied carbon and timber volume through an A1-A4 life-cycle assessment.

2.2.1 Material properties

The primary factor influencing the design of structural timber is the grading system. The top and bottom chords in steel web joists typically comprise TR26-graded softwood, often imported from Scandinavia. Compared to the C-grading system, TR26 characteristic values closely resemble C27[26]. Utilising high-grade timber versus low-grade timber can significantly impact structural performance.

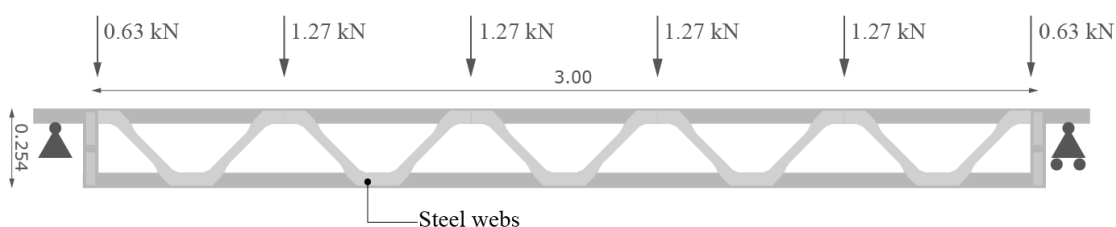


Figure 2. Typical floor joists are used as an industry benchmark for prototype design analysis. Chords cross-section 47x72mm softwood graded TR26, with open steel webs.

Earlier research on English timber has found potential for structural yield of strength classes around C16 [27], [28]. Thus, the study constrains availability to C16-graded softwood timber as the primary resource and considers underutilised and out-of-grade softwood sawn boards [29], [30], looking to existing agriculture and pallet and packaging markets to evaluate their potential structural performance. In England, more than 70% of sawn softwood processed goes to pallets, packaging, and fencing [7]. Additionally, broadleaf stands account for approximately 70% of English woodland, and therein lies potential for how more significant volumes can be value-added to long-lasting timber-building products.

By examining alternative timber sources and grading systems, this research aims to promote sustainable and locally sourced materials in the construction industry, fostering a more material-efficient approach to designing timber building products.

2.2.2 Prototype design

The prototypes are 3-metre-long joists with 20 cm supports at both ends of the top chord and a 25 cm distance between the chord axes. These dimensions were established based on examples of timber-framed three and four-bedroom houses featuring open-web floor joists, where 3 metres is a typical small span, while also considering the ease of manufacturing and manoeuvrability within a testing laboratory. The design optimisation objective is to reduce volume, with the minimum cross-sections of each member determined primarily by two parameters: a numerical factor, the utilisation of members in tension and compression (capped at 85%), and an empirical factor, manufacturing constraints such as joints.

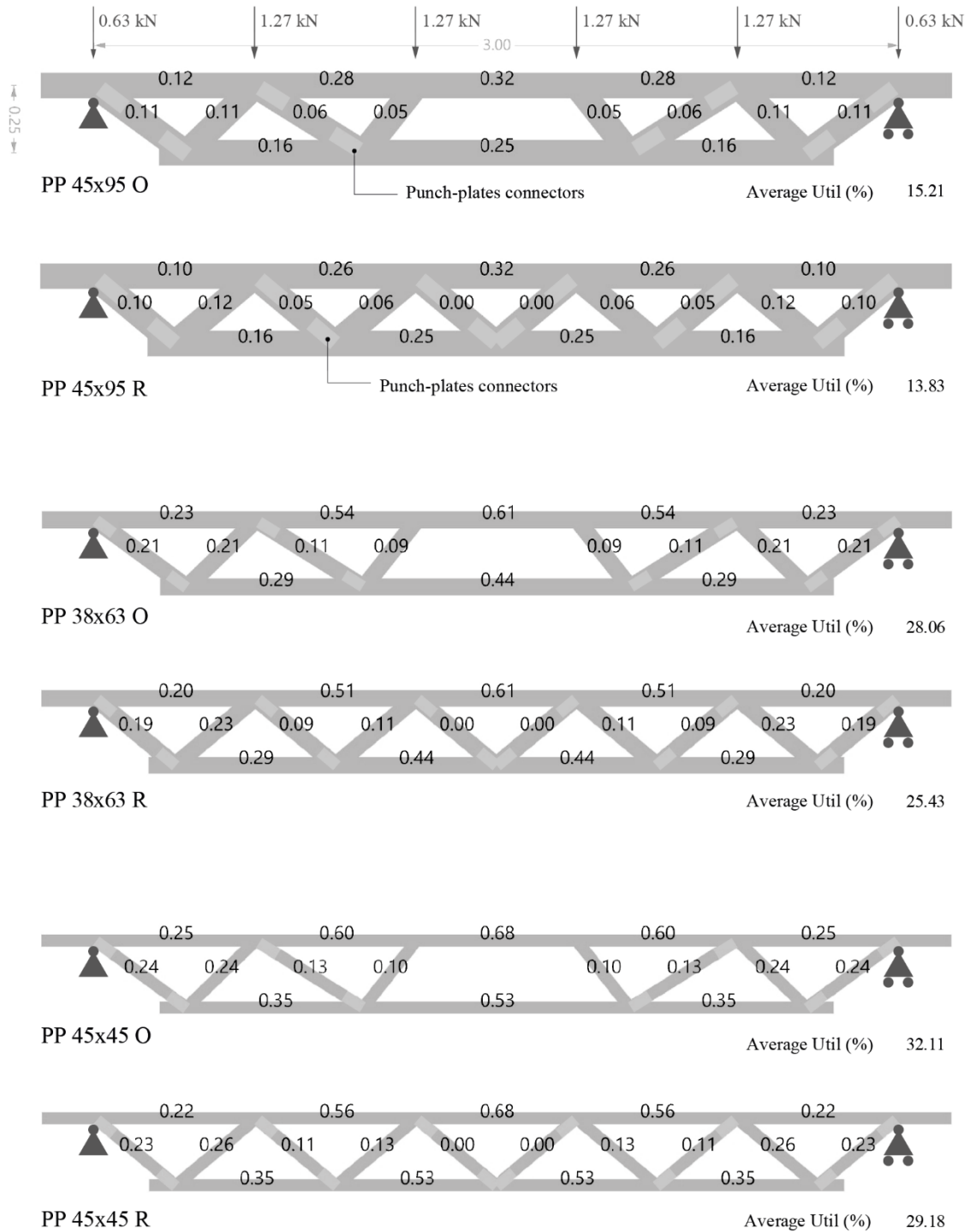


Figure 3. Prototype design proposals joined with steel punch-plates to assess the effects of cross-section variations according to commercially available industry standards (45x95mm treated wood, 38x63mm untreated wood).

Due to the limited truss domain height (25 cm), the grid division for layout optimisation has points only at the top and bottom chords to prevent the generation of complex nodes in between. The applied loads include 1.5 kN/m² for live loads, 0.6 kN/m² for top chord dead loads (timber floor and framed walls),

and 0.25 kN/m² for bottom chord dead loads (ceiling), each multiplied by a safety factor of 1.5. A single 3-metre joist with 60 cm centre spacing is designed to support 6.34 kN or 3.52 kN/m². The loads are applied at nodes of the top chord spaced every 60 cm along the chord for consistency with the industry benchmark (steel web joist) and to maintain the same setup for mechanical testing to be conducted in subsequent research phases.

Regarding potential applications in the construction industry, the cross-section specification for C16 carcassing timber is typical for industrial softwood producers in the UK. A series of design tests have been developed for both currently available commercial cross-section sizes and speculative future sizes, which could be more diverse and vary in scale. For the 3-metre prototype, the minimum cross-sections tested in the simulation are 45x95 mm and 38x63 mm for the graded ones and 45x45 mm for the ungraded ones. In the examples presented in Figure 3, the chords and webs are designed with the same width for each case (45 or 38 mm). The connections of tension webs to the chords are intended as steel punch plates. This impacts the EC calculation, with 63x152 mm plates for the 45x95 mm case and 38x76 mm plates for the other two cases (38x63 and 45x45 mm). Connection details can significantly influence structural performance, embodied carbon, or volume data, leading to the proposal and implementation of two alternative joining systems in distinct prototypes.

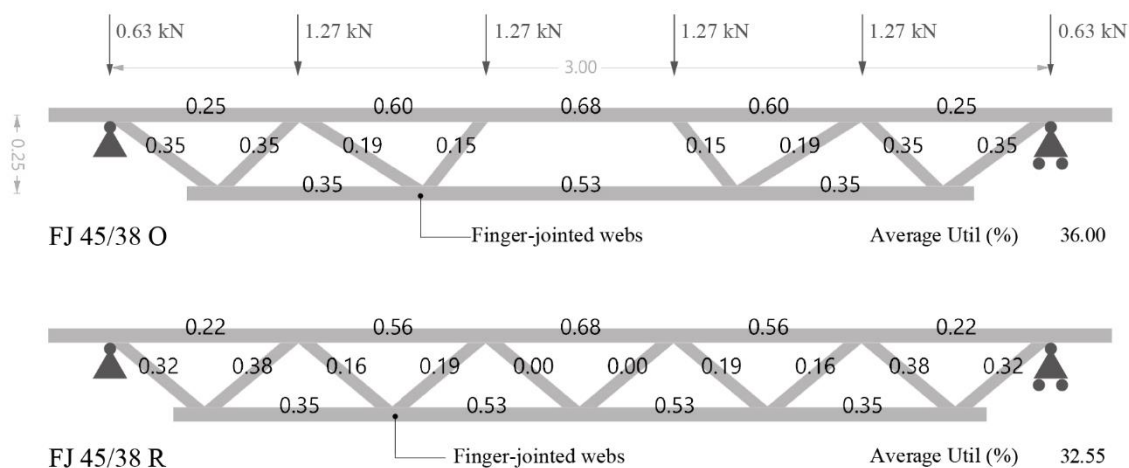


Figure 4. Prototype design proposal for finger-joint floor joist to assess steel-free connections' contribution to embodied carbon. In this case, an adaptation of the commercially available cross-sections is considered for the webs (38x38mm).

Prototype 1 – Steel punch-plates

The first prototype, depicted in Figure 3, features chords and webs connected through steel punch plates, a method currently prevalent in the construction industry. To minimise EC, the punch plates are strategically employed only for joining the tension chords. This selective application of punch plates serves to contain both the EC and volume when compared to industry benchmarks, showcasing an innovative approach to balance material use and environmental impact in the construction process. By refining traditional methods in this manner, the first prototype demonstrates the potential for improving the efficiency of widely used construction techniques.

Prototype 2 – Finger-joint

The second prototype features a truss system with finger-jointed webs and chords, a method commonly employed in the North American construction industry [31]. This design permits using more minor webs

than chords, potentially leading to additional material savings. Although the absence of steel connectors significantly reduces EC values (as shown in Table 1), industry-based examples often utilise resorcinol resin containing formaldehyde for gluing, raising health concerns. As an alternative, polyurethane-based glue will be used for assembling this prototype in future investigations.

For both prototypes, two alternative member layouts have been considered: an optimised layout, in which member distribution is derived from the Peregrine method and each diagonal has a different angle, and a regular layout, in which all diagonal webs maintain the same angle, similar to a Warren truss.

Since the prototypes are relatively small and subject to minor loads as secondary structural elements, the primary distinction between the two layouts is the absence of two central tension webs in the optimised version, which are omitted due to their near 0% utilisation factor. However, for ease of manufacturing and considering the potential improvement in overall stability during truss handling, the initial prototypes to be tested will be based on a regular layout.

Table 1. Overview of the design proposals compared with the industry benchmark. PP stands for Punch-plates connected, FJ stands for Finger-joint, R is the Regular layout of webs, and O is the Optimised layout of webs.

	Standard joist	PP 45x95 O	PP 45x95 R	PP 38x63 O	PP 38x63 R	PP 45x45 O	PP 45x45 R	FJ 45/38 O	FJ 45/38 R
Volume Δ (%)	-	65.70	77.05	-2.58	5.02	-15.30	-8.32	-18.59	-12.39
EC Δ (%)	-	-35.74	-17.73	-67.99	-60.11	-73.76	-67.63	-74.57	-72.80
EC + Seq Δ (%)	-	270.26	252.83	135.84	137.32	110.03	114.87	101.65	117.57
Volume (m3)	0.0203	0.0336	0.0359	0.0198	0.0213	0.0172	0.0186	0.0165	0.0178
EC (kgCO ₂ eq)	11.21	7.21	9.23	3.59	4.47	2.94	3.63	2.85	3.05
EC+Seq (kgCO ₂ eq)	-3.56	-13.21	-12.58	-8.41	-8.46	-7.49	-7.66	-7.18	-7.75
Average Util. (%)	-	15.21	13.83	28.06	25.43	32.11	29.18	36.00	32.55
Ratio (V/Av Util.)	-	2.21	2.60	0.70	0.84	0.54	0.64	0.46	0.55

2.2.3 Life-cycle assessment

To evaluate the carbon impact of the design, a Life-Cycle Assessment (LCA) calculation has been performed considering the stages A1-A4, which are from cradle (A1: raw material supply) to gate (A3), and then adding the transportation to the construction site (A4). In this context, there is no information on the emissions during the construction phase (A5). The comparison between a typical floor joist with metal webs and the proposed prototypes would not affect the comparison since the installation procedure should be the same.

For timber, the LCA is performed using the Inventory of Carbon & Energy (ICE) database [32]. The calculations are based on the weight of the timber, and the EC values refer to "Timber, Softwood, No Carbon Storage", where the EC for the modules A1-A3 is 0.263 (kgCO₂e/kg); this value has been used for both the prototype and the industry benchmark. The A4 module is calculated using the table of transport emission factors for the UK [33], which identifies "European manufactured" 1500km by road, 0.160 (kgCO₂e/kg), and "nationally manufactured" 300km by road, 0.032 (kgCO₂e/kg). The biogenic carbon as the contribution of timber to sequester atmospheric carbon is -1.64 (kgCO₂e/kg). Two EC values are analysed, with and without biogenic carbon, EC+Seq (kgCO₂eq) and EC (kgCO₂eq).

A ratio (V/Av Util.) was developed, as shown in Table 1, normalising the volume against material utilisation, showing the importance of considering both aspects of biogenic carbon and material utilisation to maximise material efficiency.

For the steel components, the webs and punch plates, the EPD data are derived from one of the available manufacturers on the market. For the selected manufacturer, the embodied carbon (A1-A4) for both is 2.297 (kgCO₂e/kg). The carbon impact of the polyurethane glue for the considered LCA modules is 0.876 (kgCO₂e/kg), and the average amount considered is 0.3 kg of glue per finger-jointed joist. To give a reference value, the glue accounts for an increase of about 2% in the EC calculation.

3. Results

This research adopts a material-efficient approach to investigate optimisation-driven structural systems using local underutilised English timber for low to mid-rise buildings, to address housing supply challenges and retrofit existing poor-performing buildings. The study focuses on the structural performance of optimised truss systems, analysing various parameters for comparison, including member utilisation, timber volume, and embodied carbon, both with and without sequestration. All data are expressed as increased or decreased percentages relative to an industry benchmark for the same span load case (Table 1). The developed algorithm will serve as a fundamental basis for studying and designing larger building products, such as truss beams employed as primary structural elements. The simulation results show promising outcomes, with expected structural performance according to initial inputs such as geometry, loads, and material properties.

For the design of floor joists, the research analyses several combinations of member cross-sections and joining techniques. All proposed solutions demonstrate a lower EC compared to standard systems. The reductions in EC range from approximately -17% to -74% without accounting for carbon sequestration. This reduction can be attributed to substituting steel webs with timber and the lower impact of the LCA A4 module for local timber transportation. Concurrently, the use of steel in the designed prototypes is minimised and restricted to tension webs.

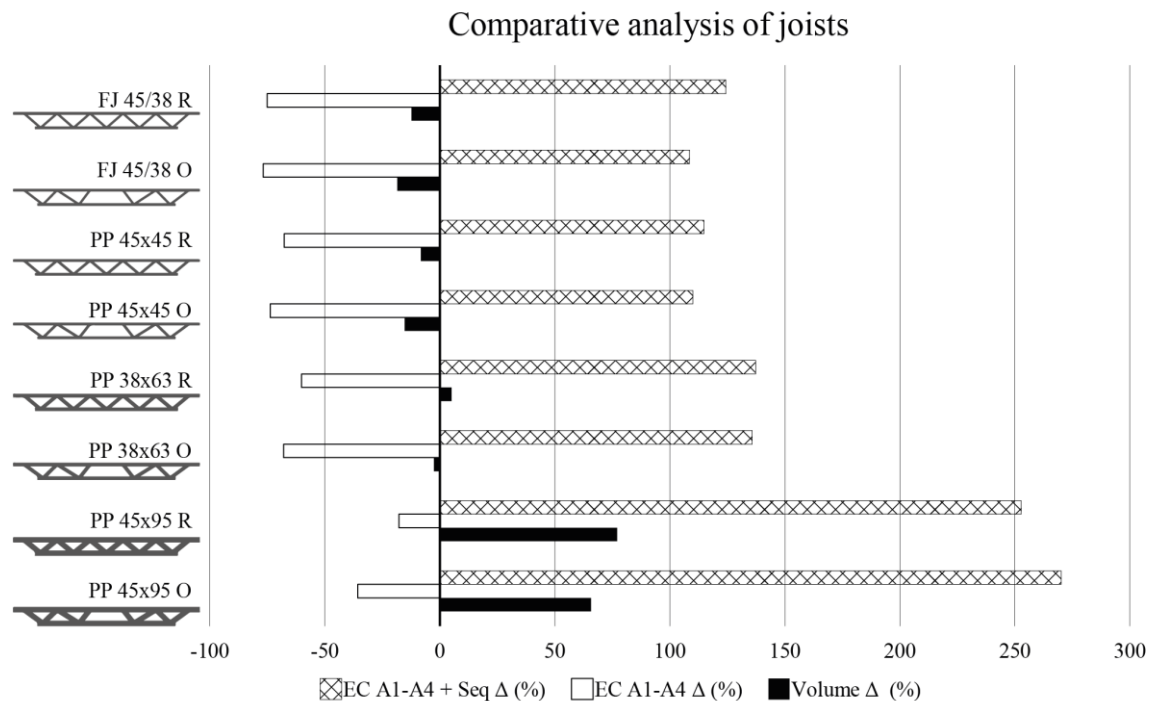


Figure 4. Overview of the design proposals compared with the industry benchmark. PP stands for Punch-plates connected, FJ stands for Finger-joint, R is the Regular layout of webs, and O is the Optimised layout of webs.

In contrast, the volume of timber employed in the prototypes varies between approximately +77%, with an average member utilisation of 14% and a maximum of 32%, to -18.5%, with an average member utilisation of 36% and a maximum of 68%.

In the comparative analysis of joists (Figure 4), the EC+Seq (kgCO₂eq) reveals a significant rise in the sequestered carbon within each joist. Compared to the industry benchmark joist (-3.56 kgCO₂eq), PP 45x95 O showed the highest level of carbon sequestration (-13.21 kgCO₂eq) due to larger dimensions in the chords, and the use of timber rather than steel in the webbing.

4. Discussion and conclusion

This study employed an optimisation-driven approach to develop material-efficient structural systems that utilise locally underutilised English timber for low to mid-rise buildings. The aim was to address housing supply issues and retrofit existing poorly-performing structures employing local resources. The research analysed optimised truss systems, considering parameters such as member utilisation, timber volume, and embodied carbon. The developed workflow can potentially design more significant building components, such as truss beams used as primary structural elements.

The findings revealed that the proposed solutions exhibited lower embodied carbon than standard systems, which can be attributed to substituting steel webs with timber and reducing the impact of local timber transportation. However, timber volume and member utilisation demonstrated broader values among the prototypes. The prototypes represent viable alternatives to current practices. Future structural testing is required to evaluate their potential for application in real-life scenarios. As the larger project, which this study is a part of, evolves, these promising alternatives will be assessed through manufacturing and structural testing, examining real-world applicability. Following the testing results, subsequent phases of the research will focus on larger primary structural elements such as beams, walls, and columns, as well as the supply of local resources.

In summary, this study establishes the foundation for the development of material-efficient timber structural systems for low to mid-rise buildings, employing locally grown and manufactured English timber. These systems have the potential to contribute to addressing housing demand and the retrofit of poorly performing and outdated existing buildings. The material-efficient design workflow is transferable and relevant to audiences interested in material-efficient topology-optimised timber structures, which can apply the insights to regions where stocks of underutilised timber resources exist. The research findings present a promising avenue for promoting sustainable and regionally-sourced solutions within the construction industry.

Acknowledgments

This research forms work from the Timber in Construction (TIC) project funded by the Forestry Commission, and the Growing the Future Project funded by the Laudes Foundation. The authors would also like to thank and acknowledge TIC partners Timber Frame Management, Smith and Wallwork Engineers, Rothoblaas, and Ecosystems Technologies for their insights and constructive feedback on this work.

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