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Research Article

Timber Portal Frames vs Timber Truss-Based Systems for Residential Buildings

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A large number of structures have been built during or after the construction of a house or residential-zoned building, which are not built at the same time and/or integrally with the structural integrity of the residential dwelling. These include carports, pergolas, sheds, and barns. The typical method of constructing these structures is a general timber truss and column system. The aim of this study is to look at the feasibility and economic incentive that may be gained from using a timber portal frame system, similar to the steel or timber portal frames used for larger industrial constructions, over the traditional timber truss and column arrangement. In this study, designs for three cases of timber truss and timber portals were carried out using industry appropriate methods and standards. Using the design information and data gathered through talks with industry professionals, both methods of construction were compared on cost and overall time duration. From the comparison of the truss and portal designs, the use of timber portal frames over timber truss systems proved to have advantage in relation to overall cost and man power involved. This could certainly affect the current attitude towards the construction of small residential buildings in the future.

1. Introduction

Portal frames (Figure 1) have been in use since the 1960s and are typically used in larger more industrial type construction with spans usually larger that 15–20 m [1, 2]. A portal frame does not have the inner or web members that a truss has and relies on rigid connection of the columns to the rafters [3]. In addition to the benefit of more space due to the elimination of web members, portal frames tend to be less labour intensive and cheaper to construct and up until now have only really been used is larger industrial style construction [4]. In construction of timber portal frames, material properties and characteristics significantly influence the behaviour and performance of structures similar to concrete building structures [5] and hot-rolled steel buildings [6].

There is a large demand for fast economical construction of smaller structures such as garages and carports [7] as well as industrial storage racks [8]. Therefore, a comparison of current available methods of designing and constructing both traditional timber truss-based systems and residential sized timber portal frames is made. The idea of using timber portal frames for small-scale residential structures does not seem to be popular. With a great deal of large-scale steel and timber portals around for decades, the idea of this study was to determine if there is a viable reason that these portal constructions have not made their way into the residential construction market. In doing that, this study looks at the current available methods of design and construction of the mentioned systems from the very beginning of the design and planning stage until the final stage of the project. Three cases have been designed for both systems of construction, with the goal being, to compare apples with apples and create a legitimate comparison between the two methods. All three studied cases (Figure 2) have been designed for a column height of 2.6 m, a roof pitch of 10°, and a length of 6 m with a total of 3 bays of 2 m spacing between columns and the location is assumed to be suburban Melbourne, Australia.

Ensuring continuity in the comparison of these two construction methods is an essential step which has been done to the best means as possible. Comparing apples with

Figure 1: Typical timber portal frames.

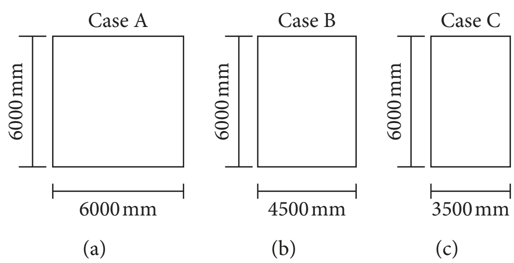

Figure 2: The three cases to be designed. (a) Case A. (b) Case B. (c) Case C.

apples is essential as any deviation in what is being compared will give a skewed result. It is for this reason a standard column spacing of 2 m has been determined for both truss and portal, with a lintel on top of the truss arrangements which the trusses sit on, as it would be possible to reduce this spacing.

2. Portal Frames

2.1. Design of Portal Frames. The portal frames have been designed based on each element at a time approach. The overall design guide for the portal system has been based on Timber Portal Frames Design Guide [9]. This book referenced exact design procedures and arrangements. In addition to the mentioned design guide, the design procedure is carried out using Standards Australia [10–12]. Portal frame layout and section for Case A are illustrated in Figure 3.

For transparency, a wide variety of timbers were designed for in the portal frame design. Each timber was then checked in relation to price as to whether it was chosen for the application. All of the timber cases were made from radiata pine and included laminated veneer lumber (LVL), glued laminated timber (glulam), and machine graded pine (MGP). Each timber case was designed using its relevant standard. In the case of portal frames, the order of design starts at the first element under stress to the last. This means first the purlins are designed then the girts, rafters, columns, and then gussets. The elements within the portal are purlins, girts, rafters, mullions, columns, and gussets. The purlins are secondary members spanning between the main portal frames to support cladding, roofing, etc. [13]. In this study, the purlins are designed as simply supported beams; however, it is rare but possible to have continuous spanning purlins. Purlins can contribute to a large proportion of cost in portal frame construction of larger systems [14]. Therefore, there is a large emphasis on the economical design. However, for these small-scale structures with the proposed arrangements, the purlins should have minimal effect of the total cost.

It is assumed to be three purlins per rafter, one at the ridge, one in the centre, and one at the end. This is due to simplicity and the options of timber to be used, i.e., glulam and LVL do not have significantly small enough sections for it to be feasible to have more than three members per span. Girts are much the same as what the purlins are for the roof, although they span between columns/mullions. The rafters are the overhead span between the columns connected at the centre ridge. To create a portal system, there must be a ridged moment transferring connection between the columns and the rafters. In this study, a "two pin" portal is designed in which there is moment transferring connections at the column-rafter connection as well as at the rafter-rafter ridge. Mullions are the vertical members supporting the girts in the walls of portal frame buildings. They act as simply supported beam columns carrying wind pressures perpendicular to the wall as well as loads due to the cladding in the plane of the wall. They are not intended to carry a significant lateral load as those of the columns and are typically a lot smaller in cross section than that of the buildings columns. The portal frames columns keep the structure standing, taking axial forces from the rafters and roof as well as pressures due to the girts from wind, cladding, etc. The gussets are the moment transferring element that creates the portal system. There is a large number of different ways to achieve this, but in this study, a double plywood gusset nailed to the rafters and columns is implemented. For the lateral load resisting system of the portal frames, simple steel bands are used across all end bays in an *X* system connected by bolts. All wind loads are determined by Australian and New Zealand Standard [11] and applied to the portal frames. The final design sections for the portal frame elements are tabulated in Table 1 for Cases A, B, and C, respectively.

2.2. Portal Frame Labour. The labour cost of a job is usually the main factor in the total cost of a project. The time it takes to manufacture the elements off-site and construct the total structure will determine the cost due to labour for the project. $70 per hour for a labour cost is assumed based on an average hourly rate of $30/hour full time rate plus allowances for annual leave, sick pay, and consumables including safety. A standard working day of 8 hours is assumed. This is working 6 am to 3 : 30 pm with a half-hour lunch. The cost of construction is split into off-site and on-site construction. The off-site construction of the portals consists of the cutting of lengths and angles of the purlins, rafters, columns, mullions, and girts. These lengths are then packed and transported to site. As the predelivery materials of portals are only lengths of timber and are not large in more than one dimension, they are more easily transported and delivered. For this reason, it is assumed that a standard rate of $100 delivery fee applied to all portals. The on-site

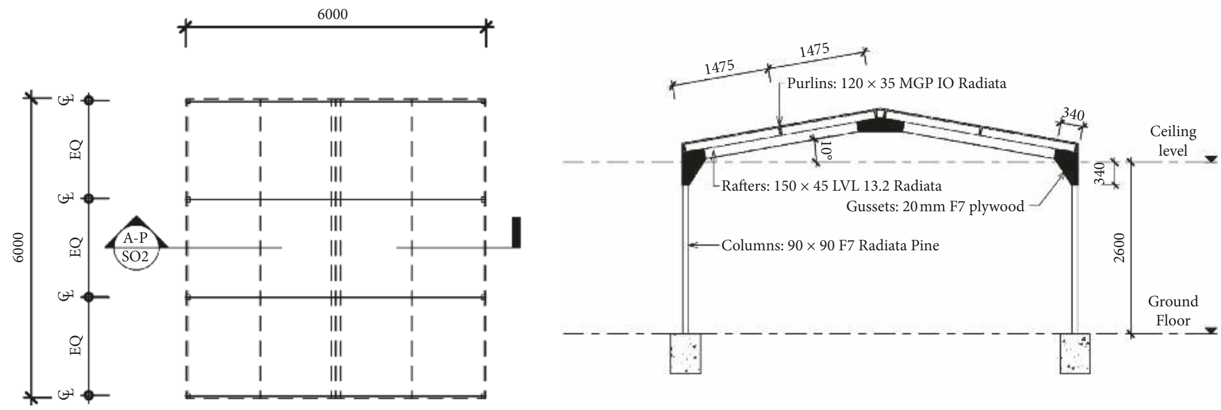

Figure 3: Portal frame case A. (a) Layout. (b) Cross section.

Table 1: Summary of designed portal elements.

	Case A	Case B	Case C
Purlins			
LVL	130 × 36 mm LVL 13.2	130 × 36 mm LVL 13.2	95 × 36 mm LVL 13.2
Glulam	120 × 65 mm Glulam GL8	120 × 65 mm Glulam GL8	120 × 65 mm Glulam GL8
MGP	120 × 35 mm MGP 10	120 × 35 mm MGP 10	120 × 35 mm MGP 10
Girts			
LVL	130 × 36 mm LVL 13.2	130 × 36 mm LVL 13.2	130 × 36 mm LVL 13.2
Glulam	120 × 65 mm Glulam GL8	120 × 65 mm Glulam GL8	120 × 65 mm Glulam GL8
MGP	120 × 35 mm MGP 10	120 × 35 mm MGP 10	120 × 35 mm MGP 10
Rafters			
LVL	150 × 45 mm LVL 13.2	150 × 45 mm LVL 13.2	150 × 45 mm LVL 13.2
Glulam	126 × 65 mm LVL 13.2	126 × 65 mm LVL 13.2	126 × 65 mm LVL 13.2
MGP	170 × 35 mm seasoned MGP	170 × 35 mm seasoned MGP	170 × 35 mm seasoned MGP

method of construction for portal frames consists of the following steps:

(i) The column holes and connections are dug and concreted in

(ii) The portals themselves, being the rafters and columns, are constructed on the ground, connected by the plywood gussets

(iii) After construction, the portals are then tilted up and connected by the purlins and girts

(iv) All mullions, lateral load resisting, and other structural elements are connected

(v) The finishing elements such as cladding and roofing are added

2.3. Total Cost of Portal Frames. The total cost of the portal frames consists of two parts, namely, the material costs and the labour/construction costs. The material costs have been determined from taking averages of several timber suppliers. Prices are per lineal metre for each section. The chosen sections and their prices are tabulated in Table 2.

The LVL is chosen for the rafters, even though it is slightly more expensive than the MGP as it has a much smaller section size, which will benefit the overall transportation and construction. The labour cost is difficult to estimate; therefore, for consistency, it is assumed that two cuts and one joint to be one "Point." Each "Point" is assumed to take 15 minutes in duration. This allows an easy approximate determination of time spent on each structure throughout both truss and portal arrangements. It is assumed that half of one-man hour is taken to dig concrete and attach the column anchor to in order for the columns to be attached. As stated earlier, these are simple pinned anchors commercially available, and a more fixed solution may be derived at in further studies. Based on the full analysis of the project schedules, cost calculations have been carried out and the results are summarised in Table 3 for the total labour costs.

Delivery of the portals is standard but assumed less than that of truss systems, as they are not as big of a total area due to not being fully constructed yet. Assume half an hour labour for each column hole, concrete, and attachment of column anchor. The design and cost of these are not considered and the design or testing of available anchorages for small timber portals could be cause for further study. The cost is calculated by the number of columns multiplied by the time allowed for anchorages multiplied by the hourly rate. The hoisting and joining of each portal is assumed to take 0.5 hours per portal for two men. Up until now, the

Table 2: Summary of portal element costs.

Element/Case	Type	Length (m)	Price/lineal metre	Contingency	Price
Purlins					
A	120 × 35 mm MGP 10	35.19	$2.96	20%	$124.99
B	120 × 35 mm MGP 10	35.19	$2.96	20%	$122.12
C	120 × 35 mm MGP 10	35.19	$2.96	20%	$124.99
Girts					
A	120 × 35 mm MGP 10	19.44	$2.96	20%	$69.05
B	120 × 35 mm MGP 10	19.44	$2.96	20%	$69.05
C	120 × 35 mm MGP 10	19.44	$2.96	20%	$69.05
Rafters					
A	150 × 45 mm LVL 13.2	24.37	$7.37	20%	$215.53
B	150 × 45 mm LVL 13.2	18.28	$7.37	20%	$161.65
C	150 × 45 mm LVL 13.2	14.21	$7.37	20%	$125.73
Columns A, B, and C	90 × 90 mm F7	15.6	$13.00	20%	$243.36
Mullions A, B, and C	90 × 90 mm F7	9.1	$13.00	20%	$141.96
Gussets A, B, and C	20 mm plywood				$162.00
Consumables A, B, and C	Assume $100 for consumables				$100.00
				Total cost	
				A	$1,056.90
				B	$1,000.14
				C	$967.09

Table 3: Summary of portal labour costs.

	Case A	Case B	Case C
Total cuts/rafter	2	2	2
Total rafters	8	8	8
Total cuts/purlin	2	2	2
Total purlins	18	18	18
Total cuts/gusset	3	3	3
Total gusset	12	12	12
Total cuts/mullion	2	2	2
Total mullion	18	18	18
Total joints	80	80	80
Total cuts	124	124	124
Total points	62	62	62
Column cuts	12	12	12
Column points	6	6	6
Total construction time for all	17	17	17
Total	$1,190.00	$1,190.00	$1,190.00

portals have been assembled and the columns in place. The time and cost of putting all elements together have been provided in the preerection stage. The final stages involve attaching the roof cladding and all other finishing elements. It is assumed this will take 2 men for one day. Determining the material costs and construction/labour costs for each case, respectively, the total portal frames costs (excluding mark-up GST) have been summarised in Table 4.

Table 4: Summary of total portal frames cost.

	Case A	Case B	Case C
Total	$4,059.00	$3,914.00	$3,864.00

3. Truss Systems

3.1. Design of the Truss Systems. There are several computer-aided design software packages to greatly reduce the amount of time and effort that is required in the design of truss systems. These computer-aided design packages are becoming more available for portal construction; however, this is an upcoming market and it is hard to get hands on. The design times and costs have not been considered in this study. The package used for the truss design is called Cornerstone. The Cornerstone software designs and produces plans for the most economical structure. Parameters entered are the size, location, height, roof slope, etc. The program then produces plans that include member sizes, lengths, angles, and forces in each member, connections and spacing's although, and most of the truss parameters can be selected previously if so desired. The structure location, height, and roof pitch are selected based on the mentioned building attributes in Section 1. The program then produces plans in according to all relevant Australian Standards. An example of truss design in Cornerstone software is illustrated in Figure 4.

The Cornerstone software also produces a quote for each structure. In this study, these quotes are not used in order to create continuity between the comparisons. Cornerstone only produces the truss systems, but it does not design the lintels and columns. Therefore, these have been designed manually, resulting in Case A having 140 × 35 mm MGP 10 radiata pine while, cases B and C having 120 × 45 mm MGP 10 radiata pine. The adopted columns are 90 × 90 mm F7 radiata pine designed in the same method as those in portal frames. Utilised truss system layout and cross section for Case A are shown in Figure 5.

3.2. Materials. As mentioned earlier, the cornerstone software produces the most economical design possible based on available Australian Standard section sizes and timber types.

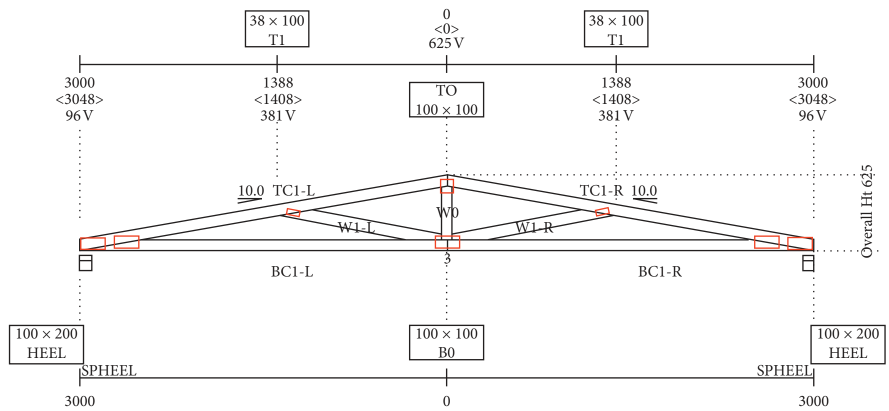

Figure 4: Truss design in Cornerstone software.

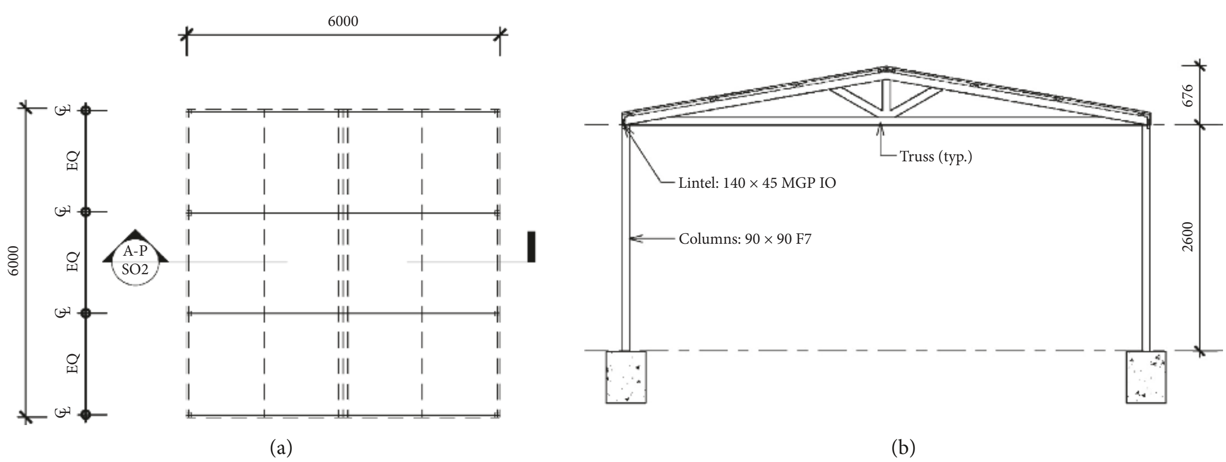

Figure 5: Truss system Case A. (a) Layout. (b) Cross section.

The same timber price list has been used for truss systems as that for portals for continuity. From the list produced by Cornerstone, Case B has an F-17 bottom chord. Case C has a small enough span to use two less chords than Cases A and B. Material costs for truss systems Cases A, B, and C are determined and summarised in Table 5.

3.3. Labour and Costs. The labour for the truss systems has been calculated in the same way as for portals, where two cuts and a join account for one "Point" with each point having a time a monetary value. Based on the full analysis of the project schedules, the predelivery labour times and costs have been calculated and summarised in Table 6. The number of trusses, cuts, joints, and truss points are determined from the cornerstone print out. The column cuts and points are also added and used for the total predelivery labour.

After this, the standard cost of $200 (approximate figure from industry professionals) is added for the delivery of the truss systems from the off-site initial construction to be used for the on-site construction. The insulation of columns is again, done as and charged at, in the same vein as with portal systems, where the number of columns multiplied the time allowed for each columns (0.5 hours) and then multiplied by the hourly rate for the total cost of column insulation. This is standard throughout all truss systems as $210.00 and 3 hours

Table 5: Summary of truss material costs.

Element	Type	Case A	Case B	Case C
Truss	90 × 35MGP 10	$264.67	$243.85	$126.35
Purlins	120 × 35 mm MGP 10	$106.56	$106.56	$106.56
Lintel	140 × 35 mm MGP 10	$49.47	$49.47	$49.47
Columns	Try 90 × 90 mm F7	$324.48	$243.36	$243.36
Consumables	Assume $100 for consumables	$100.00	$100.00	$100.00
	Total	$845.18	$743.24	$625.74

Table 6: Summary of truss predelivery labour.

	Case A	Case B	Case C
No. of trusses	8	8	8
Total cuts/truss	17	15	9
Total joints/truss	6	6	6
Total truss points	68	60	36
Column cuts	12	12	12
Column points	6	6	6
Total construction time (hours)	18.5	16.5	10.5
Total	$1,295.00	$1,155.00	$735.00

Table 7: Summary of truss labour.

Erection	Case A		Case B		Case C	
	Money	Hours	Money	Hours	Money	Hours
Lintels	$280.00	4	$280.00	4	$280.00	4
Hoist/attach truss	$560.00	8	$560.00	8	$560.00	8
Attach purlins	$105.00	1.5	$105.00	1.5	$105.00	1.5
Attach roofing, cladding, and all finishing elements	$1,120.00	16	$1,120.00	16	$1,120.00	16
Total	$2,065.00	29.5	$2,065.00	29.5	$2,065.00	29.5

Table 8: Summary of truss labour.

	Case A	Case B	Case C
Total	$4,534.06	$4,373.24	$4,373.24

Table 9: Cost summary.

	Material	Preerection/delivery labour	Delivery	Column instillation	Erection	Total price
Case A truss	$764.06	$1,295.00	$200.00	$210.00	$2,065.00	$4,534.06
Case A portal	$1,054.02	$1,295.00	$100.00	$210.00	$1,400.00	$4,059.02
Case B truss	$743.24	$1,155.00	$100.00	$210.00	$2,065.00	$4,373.24
Case B portal	$1,014.10	$1,190.00	$100.00	$210.00	$1,400.00	$3,914.10
Case C truss	$625.74	$735.00	$200.00	$210.00	$2,065.00	$3,835.74
Case C portal	$964.22	$1,190.00	$100.00	$210.00	$1,400.00	$3,864.22

Table 10: Man hour summary.

	Preerection/delivery labour (hours)	Column (hours)	Erection (hours)	Total hours
Case A truss	18.5	3.0	29.50	51.00
Case A portal	18.5	3.0	20.00	41.50
Case B truss	16.5	3.0	29.50	49.00
Case B portal	17.0	3.0	20.00	40.00
Case C truss	10.5	3.0	29.50	43.00
Case C portal	17.0	3.0	20.00	40.00

labour. This makes that up until now in the estimation, the trusses have been made and the columns are installed in place. From here, the rest of the construction costs are determined from the production schedule as summarised in Table 7.

3.4. Total Costs. Based on the determined material costs (Table 5) and construction/labour costs (Tables 6 and 7), the total costs (excluding mark-up GST) for Cases A, B, and C have been calculated and tabulated in Table 8.

4. Discussions and Comparison

As shown in Table 9, comparing the total costs of portal frames and truss systems for Cases A, B, and C, respectively, gives an 89.5% costing of using portals over truss systems for both Cases A and B with a saving of $475 for Case A and $459 for Case B. Case C costs $28.45 more with 100.7%. Case C has less of a saving as the smaller span allows for less web members in the truss. The reduction of web members means there are less materials and less labour in the cutting and connection of members.

Table 11: Total man hours to complete.

	Total hours to complete
Case A truss	26.5
Case A portal	22.0
Case B truss	25.5
Case B portal	21.0
Case C truss	22.5
Case C portal	21.0

As summarise in Table 10, the man hours are less by 81.4%, 81.6%, and 93.0% in all respective cases, and again Case C is higher due to the decrease in web members in the truss. The total man hours are often the deciding factor in the choice of construction type in industry, as the total time a trade is on-site may affect another trades and the process of the complete job. Based on Table 11, Cases A, B, and C showed total time savings of 83.0%, 82.4%, and 93.3%, respectively, with an average time saving of 3.5 hours.

The results show a roughly 10% cost saving of using a portal frame arrangement for the equivalent sized structure. This is due to the amount of man hours that are accumulated in the cutting and joining to create the truss systems. The total man hours needed to complete each size of system was as much as 19% less when looking at portal frames. Case C threw off the results slightly as it was small enough in span to allow the use of a kingpost arrangement over a queen which was used in the other two cases. The use of the kingpost truss reduced the amount of cuts and joints, and therefore, having man-hours is required to build the system. This result showed the benefits and need for some sort of optimising in the design of the truss and portal arrangements.

The total timeframe needed to construct the portals compared to the trusses (the time duration from first cut until leaving the site) was around 17% less for the portal arrangements. This is excluding Case C which was 6.7% greater due to the aforementioned reasons. Reducing the time, effort, and overall cost of projects is obviously extremely important in any industry, let alone the construction industry. A saving of 10% in cost and or overall time may be the reason for a company bidding for a job to lose or win the contract.

5. Conclusions

The idea of using timber portal frames for small-scale residential structures does not seem to be popular. With a great deal of large-scale steel and timber portals around for decades, the idea of this study was to determine if there is a reason that these portal constructions have not made their way into the residential construction market. Three cases were designed: Case A, B, and C. Each case had a few nominal constraints, and all three cases were designed with both a truss and corresponding portal configuration. The truss systems were designed with a design package called Cornerstone, while the portal systems were all designed without a great deal of software. The wind and all other loadings were determined from Australian Standards in relation to the same location as the truss systems were designed for. All other elements of the portal including rafter, purlin, and gussets were designed using design limit state and deflection calculations from the Australian Standards. After this, there was a design for a portal and a truss system to be compared. Educated assumptions based on discussions with industry professionals were then used to determine approximate timeframes of man hours associated with both types of systems.

The final results of this study revealed a roughly 10% cost saving of using portal frames arrangement for the equivalent sized structure. From these results, it seems that using portals compared to truss systems would be a greater option for the time and cost conservative construction industry. This study is on three rectangular structures with average size and construction when looking at residential structures such as carports and pergolas. For these applications, looking at the results gathered a portal frame design would be a more feasible and economical option. The only problem that comes up when talking to industry professionals is that there is already a great amount of knowledge and experience in the construction and design of timber trusses. It is far easier to use the computer-aided design programs to firstly do the overall design and then change the design if need be while timber portals do not have many options in the design and optimisation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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