Elimination of Wastes in the Design of Buildings

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***Abstract*—Enormous amount of waste comes from construction works every year in various municipalities globally. Previous works has given much attention to wastes that are seen, such as excess materials that are not used on site, wastes from materials that are damaged during handling, wastes that are generated while trying to cut a material to fit the required size, etc. Meanwhile, wastes from the design may not be very obvious to the owners and to some site workers. This study reviews a design of a building using three different orientations of some of the wood components (roof panels, joists and beams). Using WoodWorks software, the volume of wood required for the construction of some building components were evaluated. A quality control of the result was done through a 'manual verification'. Where applicable, manual calculations override the results of the software. The study presents design results for roof panel, joists, beams and columns. The result showed that the orientation of wood sections affects the volume of wood that will be required for a building. The volume of wood used in construction is dependent on the design of the building. Designers need to check various orientation and support conditions to evaluate opportunities for savings/optimization of materials.**

***Index Terms*—hidden waste, design waste, sustainable construction, waste reduction, material specification**

I. Introduction

THE construction industry has a significant contribution to the national economy of a country [1]. Meanwhile, construction is known to have a high level of waste. Recent studies have identified material waste from construction projects as a serious economic and environmental problem [2]. This means that waste reduction in construction can be translated to improvement in national economy. Waste from construction processes has a significant impact on the economy and the environment [3]. The largest portion of waste in landfills is from the construction industry [4]. A high proportion of municipal waste is construction related [5]. Hence, its reduction is important. Construction waste has become a big problem in many countries [6]. The increase in the amount of waste that is generated by construction activities has caused major concern for the construction industry [7]. In reference to the UK where construction produces 100 million tonnes of waste in a year, of which more than 60 million tones goes straight to the landfill, increased pressure on landfill sites and growing awareness of the environmental impact of the construction industry has made the minimization of construction waste absolutely necessary [8]. More than 50% of total waste that was reported for the United Kingdom is from construction. It is important to note that huge amount of construction waste is not peculiar to the United Kingdom alone. Other countries produce enormous waste from construction too. Developing countries in Asia produce a great amount of construction waste [1]. Construction and demolition wastes generates thousands of tonnes of solid waste every year in Hong Kong [9]. The minimization of construction waste has become a pressing issue in Hong Kong. Managing waste responsibly is an essential aspect of sustainable building. As regards construction waste, waste management means minimizing waste where feasible, reusing materials that may otherwise become waste, and eliminating waste where possible [10]. The image of the construction industry has been badly affected by increasing quantities of waste [11]. Hence, construction professionals need to step up on the effort to minimize waste, incorporate sustainability measure into every stage of the design and construction, and rebuild the image of the industry to that which avoids waste through, recovery, recycling, reuse, and total waste elimination. By re-using what already exist, we save the material, cost, and energy input that would have been required to make a completely new facility [12].

Over the years, material wastage has been a problem that has heightened the cost of building work [13]. Waste reduction in construction can bring significant savings for end users. Minimizing material waste will improve project performance, enhance value for individual customers and have a positive impact on the national economy [14]. Many construction industries have not learned the act of minimization of material wastage on the construction site [13]. In addition to production of huge quantity of solid wastes, the construction industry consumes a large part of raw material and global energy [3]. Construction wastes are construction materials that are lost in transit on or offsite, or discarded without adding value to the project that it is meant for. This includes leftovers from newly constructed facility and overproduction [11]. Cited by [7], [15] defined waste as that which can be eliminated without reducing value to the customer. This can be activities, resources or rule. The definition of waste by [15] (though short), is a little more comprehensive, as waste can also include excess materials that are included in the project but are not

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needed. Materials resources on building construction projects have to be managed to minimize waste, enhance value, and ensure that cost and time related goals are achieved [16]. Waste management is an important aspect of cost control in production and construction industries [17]. The concept of waste management is a field that is evolving. The end goal will be to reach a stage where nothing will be regarded as waste. i.e., a stage where all output of a process can be converted to a beneficial material for use, and for the environment. However, in the meantime, adequate efforts should be made to ensure that unnecessary use of materials (design wastes) are avoided in the design of buildings. A designer may have to show a documentation that material input that will be required for various orientations/patterns for the building are considered before selection of the design that guarantees safety of the end users whilst having minimal material input. This study hopes to illustrate how excess (but unnecessary) material can be avoided in the design of a project. The focus for this study is wood structures. To address the issue about wastage in construction, there is need for incorporation of sustainable construction principles. Efforts should be made to eliminate waste not only at the construction site. Waste reduction principles ought to be incorporated into planning, design and material specification of buildings. Unnecessary use of materials (hidden wastes) should be avoided in design.

II. Methodology

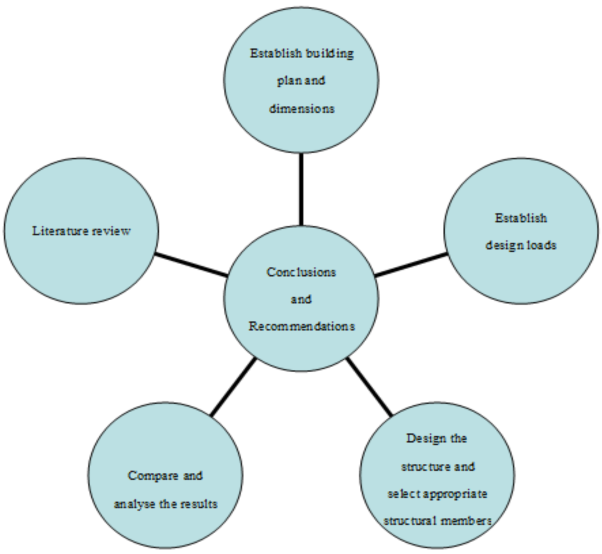

Figure 1. Project methodology.

The study performed design evaluations on some sections of a building plan. The volume of wood that will be required for four members (roof panels, roof joists, beams and columns), while considering three different patterns/orientation for the building was considered. WoodWorks® software was used in the design analysis. A ‘manual design check’ was done on the selected materials as a quality control to verify the accuracy of the design. This check also includes the use of excel spreadsheet that has been previously made to verify the accuracy of the output of the design software. WoodWorks® is a design tool that structural engineers can use for a quick design of heavy timber or light frame construction based on latest codes and standards [18]. It is recommended that a manual verification be always done as a quality check for software results. Wherever the result from manual check conflicts with the software, manual verification overrules. Fig. 1, shows the project methodology, Fig. 2 shows the design process for the project while Fig. 3 shows the building plan for evaluation.

The results were evaluated to see the magnitude of the impact of hidden waste in design and also evaluate potential areas for material efficiency. Cross-laminated timber, CLT was specified for roof panels, lumber was specified for roof joist, and glulam was specified for the beams and columns

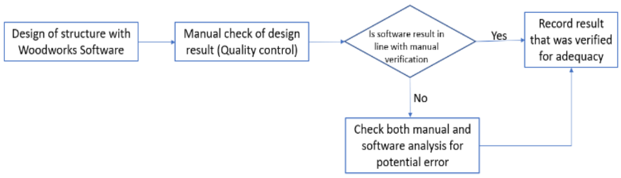

Figure 2. Design process for the project.

Fig. 3 presents some sections of a multi-family residence that is used for evaluation of avoidable hidden waste from various patterns for the roof panel, joists and beams. Note that for this design, it is assumed that the loads from the beams are carried by the columns (and not shared with the studs).

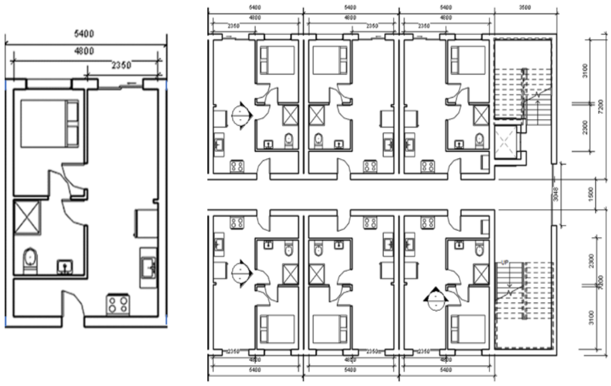

Figure 3. Some sections of the layout of the building unit.

A. Load Inputs

In any building design, loads are primary considerations because they present the magnitude and nature of the external forces or hazards that a building will be required to resist to provide reasonable performance in terms of safety and serviceability throughout the useful life of the structure. The type and magnitude of design loads affects important decisions like material selection, architectural configuration and construction details [19]. It is important to note that buildings with different design loads may have different material specifications. The following loads were used as the starting loads for this design.

Snow load on roof: In a report on a survey of roof snow loads on arena-type buildings in Canada, a snow load of 2.9 KPa was reported for Lethbridge Alberta, and 1.5 KPa for Edmonton Alberta [20]. For these designs, snow load of 3.0 KPa was used.

Live load on roof: R 301.6 (from international residential code) indicates that the minimum roof live loads (pounds per square foot) of horizontal projections shall be 20 for flat or rise less than 4 inches per foot (1:3) and tributary loaded area of 0 to 200 square foot [21] ($\approx$ 1 KPa). The minimum roof design live load for Alberta infrastructures is 1.5 KPa or 1.5 KN concentrated (whichever produces the more critical effect) [22]. Live load used in the design for the roof area is 1.5 KPa.

Wind load on roof: Design wind velocity for Edmonton (q50) is 0.45 KPa [23].

Dead load on roof: Dead load for common residential construction for single light-frame wood roof with wood structural panel sheathing and ½-inch gypsum board ceiling (2psf) and asphalt shingle roofing (3 psf.) is 15 psf. $\approx$ 0.7 KN/m^2. If the roof is with conventional clay/tile roofing, the dead load is 27 psf. $\approx$1.3KN/m^2, [19]. For this design, the dead load for the roof is rounded up to 1.5 KN/m^2. The density of Glulam used in the calculation of self-weight is structural members is 560.6 Kg/m^3 [24]. The density of Sawn lumber used for calculation of self-weight is 530Kg/m^3 [25]. Density of CLT used in self-weight calculations is 500Kg/m3 [26].

B. Orientations for the Roof Panels

Each unit of the building is 5.4m x 7.2m. Three different orientations considered for the roof panels are as shown in Fig. 4 below.

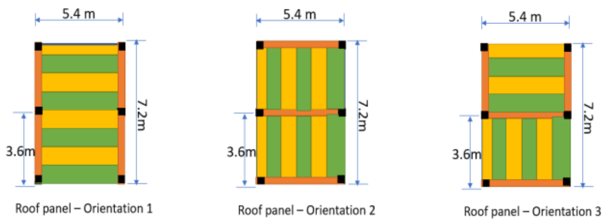

Figure 4. Orientations/patterns for the roof panels.

III. Results and Discussion

A. Roof Panels

Table I and Table II shows the design results from WoodWorks software for the roof panel design for orientations 1 and 2 using the same loading type. Orientation 3 is a combination of the panel patterns in orientations 1 and 2. The design output from WoodWorks® software showed that there are various material choices. The two orientations also showed different material input requirements.

TABLE I. Design Result Showing Suggested Material Selections [Orientation-1] (from WoodWorks Software

```
                          DESIGN RESULTS  -  CSA-O86-19
: Roof Panel Design- Orientation 1
=================================================================================
DESIGN DATA:
       Material:        CLT
       Total length:    5.40   [m ]
=================================================================================
LOADS: (force=kN, pressure=kN/m2, udl=kN/m, location=m )
             >>Self-weight automatically included<<
=================================================================================
Load          | Type          |Distribution|Pat-|  Location     |   Magnitude   |Unit
              |               |            |tern| Start   End   | Start    End  |
--------------|---------------|------------|----|---------------|---------------|-----
Dead load      Dead            Full Area                          1.50(1.00m)   kN/m2
Snow load      Snow            Full Area                          3.00(1.00m)   kN/m2
Wind load      Wind            Full Area                          0.45(1.00m)   kN/m2
Live load      Live            Full Area                          1.50(1.00m)   kN/m2
Load magnitude does not include Normal Importance factor from NBC Tables 4.1.6.2,
4.1.7.3, 4.1.8.2 which is applied during analysis.

=================================================================================
SUGGESTED SECTIONS that PASSED the CODE CHECK:
=================================================================================
   | Species      |    bxd     | Bending| Shear | Disp./  | Volume
   |   Grade      |    mm      | Mf/Mr  | Vf/Vr | Allow.  |  m^3
   |--------------|------------|--------|-------|---------|--------
     S-P-F
 1      E1          1000x175     0.36     0.42    0.78      0.945
 2      V2          1000x175     0.87     0.42    0.94      0.945
     D.Fir-L
 3      E2          1000x175     0.44     0.34    0.89      0.945
 4      V1          1000x191     0.84     0.31    0.62      1.031
     Northern
 5      E3          1000x191     0.46     0.44    0.77      1.031
>>For more detailed output, select a Suggested Section from the Data Bar.<<
=================================================================================
DESIGN NOTES:
=================================================================================
 1. WoodWorks analysis and design are in accordance with the 2015 National Building
    Code of Canada (NBC), Division B, Part 4, and the CSA O86 - 19 Engineering Design
    in Wood standard.
 2. Please verify that the default deflection limits are appropriate
    for your application.
```

TABLE II. Design Result Showing Suggested Material Selections [Orientation-2] (from WoodWorks® Software

```
                          DESIGN RESULTS  -  CSA-O86-19
: Roof Panel Design - Orientation 2
=================================================================================
DESIGN DATA:
       Material:        CLT
       Total length:    3.60   [m ]
=================================================================================
LOADS: (force=kN, pressure=kN/m2, udl=kN/m, location=m )
             >>Self-weight automatically included<<
=================================================================================
Load          | Type          |Distribution|Pat-|  Location     |   Magnitude   |Unit
              |               |            |tern| Start   End   | Start    End  |
--------------|---------------|------------|----|---------------|---------------|-----
Dead load      Dead            Full Area                          1.50(1.00m)   kN/m2
Snow load      Snow            Full Area                          3.00(1.00m)   kN/m2
Wind load      Wind            Full Area                          0.45(1.00m)   kN/m2
Live load      Live            Full Area                          1.50(1.00m)   kN/m2
Load magnitude does not include Normal Importance factor from NBC Tables 4.1.6.2,
4.1.7.3, 4.1.8.2 which is applied during analysis.

=================================================================================
SUGGESTED SECTIONS that PASSED the CODE CHECK:
=================================================================================
   | Species      |    bxd     | Bending| Shear | Disp./  | Volume
   |   Grade      |    mm      | Mf/Mr  | Vf/Vr | Allow.  |  m^3
   |--------------|------------|--------|-------|---------|--------
     S-P-F
 1      E1          1000x105     0.36     0.45    0.83      0.378
 2      V2          1000x139     0.53     0.34    0.48      0.500
     D.Fir-L
 3      E2          1000x105     0.43     0.36    0.94      0.378
 4      V1          1000x139     0.64     0.27    0.43      0.500
     Northern
 5      E3          1000x139     0.36     0.39    0.55      0.500
>>For more detailed output, select a Suggested Section from the Data Bar.<<
=================================================================================
```

With a choice of CLT: Douglas Fir L. E2, for the roof panels, Table 3 showed that there is a difference in material requirement. For example, for orientation 1, given that the dimension of the panel is 1000 x 175mm, and the length is 5.4m, the volume of each panel is 1m x 0.175m x 5.4m = 0.945m3. This is presented in Table 1. The length of the building unit is 7.2m. Without consideration of material requirement for overhang portion of the roof, for a 7.2m long unit, volume of CLT required is 7.2 x 0.945 = 6.804m^3. For 10 units, this will be 68.04m^3. As seen in Table 3. The material selection for orientation 2 is 1000 x 105 D. Fir-L E2.

TABLE III. VOLUME OF WOOD INPUT REQUIRED FOR THE ROOF PANELS USING CLT: DOUGLAS FIR L. E2 FOR THE THREE ORIENTATIONS

Building section (Roof panels)	**Orientation-1**	**Orientation-2**	**Orientation-3**
Volume of wood for roof panels (10 building units), m^3	68.04	40.82	54.43

The design for orientation 1 will use 66.7% more material in roof panels than orientation 2, while the design for orientation 3 will use 33.3% more material than the design for orientation-2.

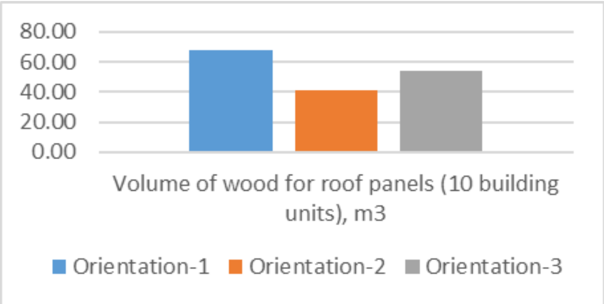

Figure 5. Comparison of volume of wood for roof panels with varied orientations of the panels.

B. *Orientation for the Roof Joists*

Three different orientations considered for the roof joists are as shown in Fig. 6 below

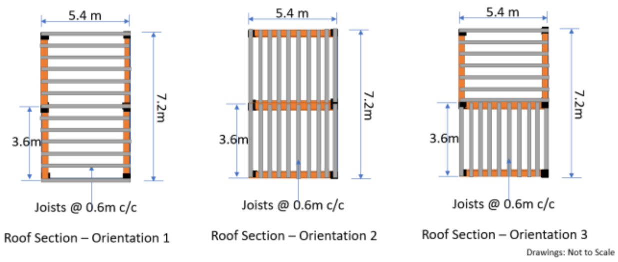

Figure 6. Orientation for roof joists.

Given the orientation of the joists, the number and orientation of the beams are also different. Orientation 1 has four beams, with each beam supporting the joists at each end of the joist. Orientation 2 has 3 beams as shown in Fig. 6, while orientation 3 also has 4 beams as shown in Fig. 6. The column positions are the same. Load selection for the joists includes dead load of $3.0KN/m^2$, live load of $1.5KN/m^2$, snow load of $3.0KN/m^2$, and wind load of $0.45KN/m^2$. Tables 4 and 5 show the design output from WoodWorks software for the joists.

TABLE IV. DESIGN RESULT SHOWING SUGGESTED MATERIAL SELECTIONS [JOISTS: ORIENTATION-1] (FROM WOODWORKS SOFTWARE).

```
          W o o d W o r k s   S I Z E R -  Software for Wood Design
Joist2_Shared load from R     Sizer 2020 (Update 2)             17 Dec,2021 20:36
________________________________________________________________________________
                COMPANY                 |                PROJECT
                                        | Type 1 Building - Project 1
                                        | One level building - Wall
________________________________________________________________________________
                     DESIGN RESULTS  -  CSA-O86-19
Joist: Joist Design - Orientation 1
================================================================================
DESIGN DATA:
       Material:        Lumber @ 600 [mm] spacing
       Load sharing:    Case 2;
       Lateral support: top = continuous,  bottom = at supports;
       Total length:    5.40   [m ]
================================================================================
LOADS: (force=kN, pressure=kN/m2, udl=kN/m, location=m )
             >>Self-weight automatically included<<
================================================================================
Load          | Type          |Distribution|Pat-| Location      |  Magnitude    |Unit
              |               |            |tern| Start   End   | Start    End  |
--------------|---------------|------------|----|---------------|---------------|-----
Dead Load      Dead            Full Area                          3.00(600mm)   kN/m2
Live load      Live            Full Area                          1.50(600mm)   kN/m2
Wind load      Wind            Full Area                          0.45(600mm)   kN/m2
Snow load      Snow            Full Area                          3.00(600mm)   kN/m2
Load magnitude does not include Normal Importance factor from NBC Tables 4.1.6.2,
4.1.7.3, 4.1.8.2 which is applied during analysis.

================================================================================
SUGGESTED SECTIONS that PASSED the CODE CHECK:
================================================================================
   | Species       |    bxd     | Bending| Shear | Disp./   | Volume
   |   Grade       |    mm      | Mf/Mr  | Vf/Vr | Allow.   |  m^3
   |---------------|------------|--------|-------|----------|--------
     S-P-F
 1      SS              89x286     0.79    0.41    0.81      0.137
     D.Fir-L
 2      SS              89x286     0.79    0.32    0.68      0.137
     Hem-Fir
 3      SS              89x286     0.81    0.38    0.71      0.137
>>For more detailed output, select a Suggested Section from the Data Bar.<<
================================================================================
```

Material selection for joist in orientation 1 is lumber, Douglas Fir Larch, SS, 89 x 286mm.

TABLE V. DESIGN RESULT SHOWING SUGGESTED MATERIAL SELECTIONS [JOISTS: ORIENTATION-2] (FROM WOODWORKS® SOFTWARE)

```
________________________________________________________________________________
                     DESIGN RESULTS  -  CSA-O86-19
Joist: Joist - Orinetation 2
================================================================================
DESIGN DATA:
       Material:        Lumber @ 600 [mm] spacing
       Load sharing:    Case 2;
       Lateral support: top = continuous,  bottom = at supports;
       Total length:    3.60   [m ]
================================================================================
LOADS: (force=kN, pressure=kN/m2, udl=kN/m, location=m )
             >>Self-weight automatically included<<
================================================================================
Load          | Type          |Distribution|Pat-| Location      |  Magnitude    |Unit
              |               |            |tern| Start   End   | Start    End  |
--------------|---------------|------------|----|---------------|---------------|-----
Dead Load      Dead            Full Area                          3.00(600mm)   kN/m2
Live load      Live            Full Area                          1.50(600mm)   kN/m2
Wind load      Wind            Full Area                          0.45(600mm)   kN/m2
Snow load      Snow            Full Area                          3.00(600mm)   kN/m2
Load magnitude does not include Normal Importance factor from NBC Tables 4.1.6.2,
4.1.7.3, 4.1.8.2 which is applied during analysis.

================================================================================
SUGGESTED SECTIONS that PASSED the CODE CHECK:
================================================================================
   | Species       |    bxd     | Bending| Shear | Disp./   | Volume
   |   Grade       |    mm      | Mf/Mr  | Vf/Vr | Allow.   |  m^3
   |---------------|------------|--------|-------|----------|--------
     S-P-F
 1      No.1/No.2       64x235     1.00    0.44    0.65      0.054
 2      No.1/No.2       89x184     0.99    0.35    0.98      0.059
 3      SS              38x286     0.89    0.64    0.55      0.039
 4      SS              64x235     0.71    0.44    0.59      0.054
 5      SS              89x184     0.71    0.35    0.89      0.059
     D.Fir-L
 6      No.1/No.2       64x286     0.88    0.31    0.32      0.066
 7      No.1/No.2       89x235     0.78    0.23    0.41      0.075
 8      SS              38x286     0.89    0.51    0.46      0.039
 9      SS              64x235     0.71    0.35    0.50      0.054
10      SS              89x184     0.71    0.28    0.75      0.059
     Hem-Fir
11      No.1/No.2       64x286     0.80    0.36    0.31      0.066
12      No.1/No.2       89x235     0.71    0.27    0.41      0.075
13      SS              38x286     0.92    0.60    0.48      0.039
14      SS              64x235     0.74    0.41    0.52      0.054
15      SS              89x184     0.73    0.33    0.78      0.059
     Northern
16      No.1/No.2       89x286     0.76    0.29    0.36      0.092
17      SS              64x286     0.83    0.44    0.46      0.066
18      SS              89x235     0.74    0.34    0.60      0.075
>>For more detailed output, select a Suggested Section from the Data Bar.<<
================================================================================
```

S-P-F SS 38 x 286mm and D.Fir-L SS, 38 x 286mm yielded the minimum wood volume input among the result output from WoodWorks® software for orientation 2. Material selection for the roof joists for orientation 2 is lumber, D.Fir-L SS, 38 x 286mm. Material selection for roof joist for orientation 1 is lumber, D.Fir-L SS, 89 x 286mm.

TABLE VI. VOLUME OF WOOD INPUT REQUIRED FOR THE ROOF JOISTS FOR ORIENTATIONS 1 - 3

Building section (Roof Joists)	**Orientation-1**	**Orientation-2**	**Orientation-3**
Volume of wood used for roof joists (10 units), m^3	17.81	7.8	13.49

Figure 7. Comparison of material use for varied orientation of roof joists.

Table 6 and Fig. 7 also confirms that considerable material savings can be achieved just by exploring a different orientation for the design of roof joist. For the roof joist, a design with orientation 3 will use 72.9% more wood than orientation 2, while a design with orientation 1 will use 128.3% more wood in the roof joists than a design with orientation 2.

The results presented for the beams and columns were manually derived. For the beams, material selection for the beams in orientation 1 is Glulam 20f-Ex D. Fir. L 175mm x 494mm. Material selection for the beams in orientation 2 is Glulam 20f-Ex D. Fir. L 175mm x 456mm. Orientation 3 is a mix of patterns for orientation 1 and orientation 2. Table 7 shows that the volume of wood requirement for beams in orientation 3 is higher than that of orientation 1 and 2. Volume of wood requirement for the beam is least in Orientation 1. CSA 086:19 [27] provides a guide for engineering design in wood. A guide for the calculation of moment resistance for glulam beams is provided in CSA-086-19 (Clause 7.5.6.5). For this design, the adequacy of the beams was checked for bending moment, shear, bearing at supports and deflection. Where applicable, adequacy of structures should be checked for resilience against other natural disasters like earthquakes, etc.

TABLE VII. VOLUME OF WOOD INPUT REQUIRED FOR THE BEAMS FOR ORIENTATIONS 1 - 3

Building section (Beams)	**Orientation-1**	**Orientation-2**	**Orientation-3**
Volume of wood used for beams (10 building units), m^3	12.45	12.93	14.84

Material selection for the columns in the three designs is Glulam-16c-E (D.Fir. L.): 175 x 152mm. For orientations 1 and 3, the middle columns are increased to 175 x 190mm to create enough bearing at supports for the two beams resting on the columns.

TABLE VIII. VOLUME OF WOOD INPUT REQUIRED FOR COLUMNS FOR ORIENTATIONS 1 - 3

Building section (Roof columns)	**Orientation-1**	**Orientation-2**	**Orientation-3**
Volume of wood used for columns (10 units), m3	6.92	6.38	6.92

In the effort to minimize waste, conserve and optimize the use of natural resources, it is important to avoid unnecessary use of resources. This study showed that material waste can be hidden in the design works. Although this material wastage is not very obvious, the goal of the project can still be achieved without the use of excess and unnecessary materials.

IV. CONCLUSSION AND RECOMMENDATIONS

The research question aims to see if there are places for hidden waste in design. This study showed that hidden waste can be in design. This can be through various means such as selection of unnecessary patterns that will result in the utilization of more materials when other patterns that will provide the same function are available. Design waste can also include selection of materials that will use more natural resources when other materials that can achieve the same purpose (with less use of natural resources) are available. The study showed that by changing the patterns of the roof panels, joists and beams, there is a considerable change in the amount of wood materials that will go into such project. It is recommended that designers pay a good attention to evaluating how alternative designs can help with conservation of natural resources whilst minimizing wastes. In addition to structural safety, minimization of waste and sustainable culture should always be part of the major guiding principles in design of buildings. Further study is recommended on the cost savings that variations of the orientations of the building structures will give to the end users.

CONFLICT OF INTEREST

There is no conflict of interest for this article.

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