ENVIRONMENTAL UTILITY OF WOOD SUBSTITUTION IN COMMERCIAL BUILDINGS USING LIFE-CYCLE ANALYSIS

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Abstract. Wood is the predominant construction material in the US residential sector. In commercial and midrise construction, the use of wood is limited compared with reinforced concrete and steel. Wood, being a natural, renewable material that sequesters carbon, is a natural fit for newer construction with enhanced sustainability goals. The objective of this study is to evaluate and identify the environmental utility (avoided emissions) of using wood in place of steel and concrete in the commercial construction and renovation sectors in Oregon, United States. The study used comparative, cradle-to-grave, life-cycle analysis, with Athena Impact Estimator for Buildings. Six case studies that represent different building functionalities, material systems, and construction techniques were modeled via the user interface input option, and the results were evaluated for global warming potential (GWP) and impacts on energy sources, such as fossil fuel consumption, when structural materials are substituted using wood. Out of the six case studies, one building was completely redesigned as per current codes using wood as the major structural material. Bills of materials for both wood redesigns and the as-built designs were used as input in the software and subsequently analyzed. Results showed that the average reduction in GWP due to wood substitution was about 60% across the six case studies. These findings reinforce the perception of wood as a green building material having potential for commercial construction.

Keywords: Life-cycle analysis, wood, commercial buildings, Athena Impact Estimator for Buildings, global warming potential.

INTRODUCTION

There are multiple factors influencing a choice of building materials: knowledge and experience, common practice in the industry, building type, building codes, reference buildings, technological solutions, economic issues, environmental properties, cost, performance, and the infrastructure in the design and construction industry (Roos et al 2010). Although initial cost and material properties are of primary concern in

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material selection, it is becoming increasingly important to consider the environmental impacts when making such decisions (Sinha et al 2013).

Building construction and use contributes almost 40% of US carbon dioxide (CO_2) emissions and about 41% of total US energy consumption (DOE 2010). Building materials and construction practices are major contributors to this impact (Dixit et al 2010). Wood is the primary building material in single-family, residential construction; however, there is limited application in midrise and commercial buildings. Wood utilization accounts for as low as 4% of the non residential construction in North America, compared with more than 70% of residential construction and remodeling (Robichaud et al 2009). Wood, being a natural, renewable material that sequesters carbon, is a good fit for new construction with enhanced sustainability goals. Although the environmental performance of wood as a building material is well documented (Buchanan 2006, 2010; Bowyer 2008; Sinha et al 2013), a consequence of its limited use in commercial structures is that there is little information available regarding life-cycle costs and long-term performance; this is a limitation that limits its choice as a construction material. Forests and forest soils absorb about 14.4% of CO2 emissions from fossil fuel use in the United States (EPA 2017), and have the potential to increase carbon storage through expanded management and greater use of harvested material in durable products. Therefore, a recommendation to sequester more carbon from the atmosphere is through the increased use of wood products in commercial construction, and as an energy source to replace fossil fuel consumption (FFC) (McKinley et al 2011).

Buyle et al (2013) present an overview of current research on life-cycle analysis (LCA) for the building construction sector. Comparisons between case studies are difficult due to regional influences in electricity production, manufacturing processes, and transportation as well as the choice of the functional unit (FU); therefore, only general trends were identified. Robertson et al (2012) compared cross-laminated timber (CLT) or glue-laminated timber building to a traditional reinforced concrete building using LCA, finding that wood was advantageous in 11 out of 12 impact categories, with a global warming potential (GWP) reduction of 71%. Wallhagen et al (2011) showed that substituting reinforced concrete slabs with laminated wood reduced the impact from materials by 25%. Energy consumption and CO_2 emissions from building materials were compared for a single building designed with various materials (reinforced concrete, steel, and wood) in Taiwan. CO_2 emissions for the concrete and steel buildings were found to be 3.1 and 2.2 times higher than for wood, with embodied energy 2600, 2100, and 1100 MJ for concrete, steel, and wood, respectively (Li and Altan 2012). Many studies such as Börjesson and Gustavsson (2000), Nässén et al (2012), Gustavsson and Sathre (2006) study the differences in CO_2 emissions when using concrete or wood for a building. All the referenced studies found wood to be favorable in terms of environmental impact. These studies however considered functional equivalence of the building when deciding their FU rather than structural as well as functional equivalency (as presented in this study). Wood utilization for nonresidential and multihousing buildings is dwarfed in comparison with reinforced concrete and steel. However, there are a number of pioneering projects around the world that have demonstrated successful implementation of wood in large, tall structures. More than a dozen buildings, 6-14 stories high, were built between 2006 and 2015 using wood as the primary material for the structural system (Gosselin et al 2015). Many suggest that this may be just the beginning of this type of construction (Dezeen Daily 2015).

An important aspect of wood acceptance in nonresidential construction is better communication between forest product firms and the stakeholders. A study of the perception of wood for application in nonresidential construction showed that architects considered it to be the most environmentally friendly and authentic material, but that wood was not thought to be innovative. Architects also rated steel and concrete higher on other attributes, such as durability, fire resistance, and structural performance (Robichaud et al 2009).

The dynamics in the US construction sector are rapidly changing and so are the attitudes, perceptions, and knowledge level of specifiers and developers with regard to use of wood in construction (Mallo and Espinoza 2015; Dezeen Daily 2015). Material choice is a matter of experience and perception on the part of the designer. To enhance the perception of wood as a green building material, an objective study can help to quantify the environmental utility of wood as opposed to other construction materials. One way to quantify environmental utility is to consider case studies in which the predominant building materials were steel, reinforced concrete, masonry, or a combination of these materials, and to reassess using a life-cycle approach after virtual substitution of main structural elements with wood.

The overarching goal of this work was to evaluate environmental impacts and changes in energy consumption resulting from use of wood in place of steel and reinforced concrete for the structural systems of commercial buildings. Comparative, cradle-to-grave, LCA methodology was implemented using the Athena Impact Estimator for Buildings (IE4B). The above goal was accomplished with the following approach:

- Determine through development of case studies, the environmental impacts and embodied energy of conventional structural materials in existing buildings using architectural and structural drawings of six selected commercial buildings, state and privately owned, obtained from structural engineers and facility managers, and using Athena IE4B to generate the bill of materials (BOMs).
- Quantify and compare the environmental impacts due to direct wood substitution for the structural materials of the gravity load systems in these existing commercial buildings using Athena IE4B to select wood components.
- Use basic structural engineering principles to redesign one case study building with conventional wood products and generate the BOMs.
- Quantify and compare material choice-driven environmental impacts for the redesigned building with Athena IE4B, both the existing building's BOMs and the wood redesign BOMs.

MATERIALS AND METHODS

Six existing buildings were identified in the state of Oregon. These buildings were located in three different cities. The buildings were chosen for two distinct reasons. First, their material of choice was either steel or concrete. Second, across the six buildings chosen they covered a wide range of functionality. The case studies are described in detail in subsequent sections. These six case studies were examined in Athena IE4B to determine environmental impacts using the original structural plans for loads, spans, and material/structural systems. Subsequently, the original materials were substituted using Athena IE4B (ASMI 2015) with wood structural counterparts. This substitution was only done on the gravity load structural systems, keeping the lateral force–resisting system (LFRS) and foundations the same. The bills of materials were generated by Athena IE4B for each case study with original materials and then with the direct wood substitution materials with results analyzed and compared. Next, one case study was completely structurally redesigned, including both gravity and lateral load systems, using conventional wood products in accordance with current codes. A BOM was calculated for each wood redesign options and the as-built structural drawings. Finally, the analysis to quantify environmental impacts from alternative BOMs was conducted in Athena IE4B, and results were compared among each other and with results from the Athena-generated BOM.

Life-Cycle Analysis

Environmental impacts of different building materials were assessed with LCA using the Athena IE4B software. LCA is an analytical method widely used to assess environmental effects of the inputs and outputs that relate to a product or process. The International Standards Organization (ISO) LCA framework, which is divided into four iterative stages goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040 2006), was followed. Athena IE4B is an LCA-based tool that provides access to comprehensive life-cycle inventory data and reports results consistent with the US EPA TRACI v2.1 (Tools for Reduction and Assessment of Chemical and Other Environmental Impacts) methodology (ASMI 2014). The goal of this study is to compare the environmental effects of substituting wood for other structural building materials in commercial construction. The scope consisted of performing comparative, cradle-to-grave LCA for the structural systems of commercial buildings via two approaches—direct material substitution using Athena IEB4 and a total redesign using current codes.

In the first approach, six case studies were modeled in Athena IE4B via the user input interface, and then equivalent wood materials were substituted in the structural system using the software. In the second approach, one of the six case studies was selected and analyzed using the BOMs import option in Athena IE4B for the original materials, and then also a wood redesign using conventional wood materials and current codes.

To capture life-cycle environmental impacts of structural building materials, a modified cradle-to-grave analysis was conducted, excluding the Use stage results. Cradle-to-grave LCA system boundaries include five stages (Product, Construction, Use, End of Life, and Beyond Building Life), starting with the raw material supply (cradle) and ending with disposal, recycling, reuse, or recovery of the material (grave). The Product and the Construction life-cycle stages, defined in the EN 15978 standard (CEN 2011) account for the effects of all activities related to raw material supply, transportation, manufacturing, transport of materials to the construction site, disposal of construction waste materials, and energy use associated with construction-installation processes. The Use stage of the LCA is omitted from the scope of this study because the goal was to capture the impact change due to the material selection for the structural system of a building. Therefore, the environmental impacts of the building use would be the same in both cases if we assume that the operational energy is not affected by the structural system, but rather the building envelope, and the maintenance and replacement effects are the same over the building's structural system life cycle. The End of Life stage refers to the building's end of life instead of the material's end of life, and accounts for deconstruction, demolition, transportation, waste processing, and disposal of materials. Even though this is the end of the building's life cycle, it may not be the end of the life cycle for the material itself. Therefore, the last life-cycle stage of the structural building materials, known in Athena IE4B as Beyond Building Life, accounts for the benefits and burdens due to reuse, recycling, or recovery potentials of the materials, such as carbon sequestration of wood products and carbonation of concrete (ASMI 2014). On the other hand, Athena IE4B models steel recycling using "closed loop recycling" methodology, with the benefits of using scrap steel in the fabrication captured in the Product stage of the LCA as opposed to Beyond Building Life. However, carbon sequestration and concrete carbonation avoided environmental burdens are only accounted for in the Beyond Building Life stage. Therefore, it is important to include this stage when comparing entire life-cycle *environmental* impacts of structural building materials. Therefore, the LCA system boundaries include all cradle-to-grave life-cycle stages, except for the Use stage of the building materials. The FU is defined as the function of the object or system being analyzed, and for this research the FU is the building's structural system whose function is to safely support the loads in the building.

Data Inventory and Impact Assessment

Life-cycle inventory analysis accounts for upstream energy and material inputs and outputs for all the materials and processes included within the system boundaries. This step can be done by collecting primary data or using secondary data. Athena IE4B performs the inventory analysis using its proprietary database; hence, secondary data were used. Even though users do not have direct access to the database, the Athena Institute provides transparent information and various publications on its website. Regionalized data were collected, and then aggregated and peer reviewed. The oldest data point is less than 10 years old. Parts of the data developed by the Athena Institute are included in the US Life-Cycle Inventory database at the discretion of the manufacturer/plant (ASMI 2014). The database contains the majority of structural, enclosure, and partition materials commonly used in North America, and these can be combined into more than 1500 different assemblies. The Athena IE4B database contains region-specific data for energy consumption, transportation, construction, and demolition processes. However, the Athena Institute warns that results should be viewed with a 15% margin of error due to the nature of LCA assumptions and uncertainties (ASMI 2014). Inventory results include an extensive list of material and energy flows from and to nature, including emissions to air, water, and land. The impact assessment step of the LCA translates results from the inventory analysis step into environmental impact measures. This step is also carried out by Athena IE4B in accordance with the US EPA TRACI v2.1 methodology (Ryberg et al 2014). It reports the impact measures for the following categories in standardized units for ease of comparison:

- GWP: CO_2 equivalent mass (100-year time horizon)
- Acidification (air) potential (AP): sulfur dioxide equivalent mass
- Human health particulate (HHP): particulate matter 2.5 μm or less (PM 2.5) equivalent mass
- Eutrophication (air and water) potential (EP): nitrogen (N) equivalent mass
- Smog (air) potential (SP): trioxygen (O_3) equivalent mass
- Ozone depletion (air) potential (ODP): trichlorofluoromethane (CFC 11) equivalent mass
- Total primary energy (TPE) consumption: megajoules (MJ)
- Nonrenewable energy consumption (NRE): megajoules (MJ)
- FFC: megajoules (MJ)

In this study, the focus was on carbon footprint, best represented by the GWP category. Other impacts, such as FFC, were analyzed and discussed in less detail than GWP. The interpretation step is applied throughout LCA, and includes observations such as identifying problems, considering limitations, and drawing conclusions.

Approach. Steps were taken to simplify analyses by excluding from consideration some nonstructural elements common to various building types. First, windows, window frames, doors, and partitions were not included since they are nonstructural and have different factors affecting the life span. Second, stairs, entrances, and some building irregularities were disregarded in the analysis, because they would be the same for both models of each case study and; therefore, would not have a significant impact on the final comparisons. Third, insulation and cladding materials were outside the scope of this work as they are solely specified by the architect and not the structural engineer, and would require special expertise to specify materials that comply with the energy code and meet acoustic requirements. Insulation has, arguably, the highest environmental impact within nonstructural building materials and the different insulation types vary widely in their environmental performance. Cladding materials have a shorter life span than the structural materials, which would result in additional inconsistencies between the case studies. Consequently, to capture the sole effect of structural building material substitution within a building system, insulation and cladding materials were not included in either the original buildings or the wood substitution scenarios. Only structural sheathing (oriented strand board [OSB] and plywood) was included in the analysis, as opposed to surface finishes and membrane materials. Fourth, foundations and LFRSs were kept the same as for the original model in the different wood substitution models. Athena IE4B is not capable of estimating material quantities for the lateral force (wind and seismic) systems. Member dimensions, such as joist and beam depths, were not considered a constraint for the selection of wood substitution materials, although in reality architects would limit them. Finish materials, such as carpets, acoustic tiles, and door and window materials, were not included.

All buildings considered in the study were identified for study purposes as being located in Portland, OR. In reality, they were located in the state of Oregon but in different cities. Portland is assumed representative of the Pacific Northwest region. The main environmental impact measure for this project was the GWP, expressed in kg of CO_2 equivalency, and FFC, measured in MJ (megajoules of energy). End of Life and Beyond Building Life stages have been analyzed, conservatively assuming the final destination of these materials and processes will still be repurposed for the same function. This ensures a more complete and fair comparison among different building materials. In addition, for the wood redesign case, it is assumed that the environmental impact of the connections is minor compared with that of the members; therefore, connection design was not performed.

Direct Material Substitution Approach

Two approaches were used to analyze the environmental impacts of wood substitution in commercial construction. Figure 1 shows the Athena IE4B process flow for the wood substitution approach and the BOMs approach. The first approach used direct material substitution via the

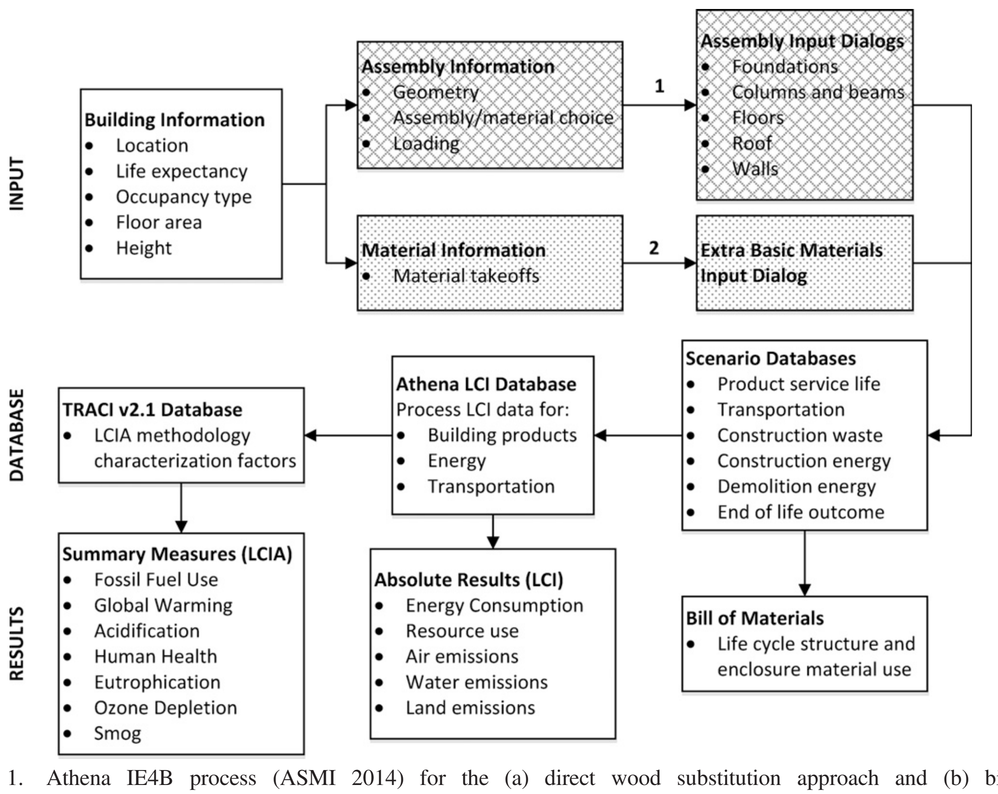

Figure 1. Athena IE4B process (ASMI 2014) for the (a) direct wood substitution approach and (b) bill of material approach.

Athena IE4B assembly input dialog for six case studies, whereas the second approach used the BOMs input option for an actual wood redesign using current codes for one of the case studies. In using Athena software for each of the approaches, the user provides building information, such as location, life expectancy, occupancy type, floor area, and height. Location determines the energy sources and average transportation distances for the region; life expectancy and occupancy type determine operational energy and water use, as well as maintenance and replacement schedules; floor area information is used to show results per m^2; and height is used to estimate the on-site construction energy uses. Architectural and structural drawings of six selected commercial buildings, state and privately owned, were obtained from structural engineers and facility managers. Building location, type, floor area, and height were extracted from design documents. Case study buildings were located in Oregon, and assumed in Portland, OR, for the purposes of Athena IE4B modeling. These case studies were chosen to represent different conventional construction systems such as steel studs, cast-in-place concrete, concrete masonry units (CMUs), and open-web steel joists. Buildings vary in height from one story (5 m) to five stories (19 m) and in floor areas from 1470 to 6220 m^2. The direct material substitution approach uses the Athena IE4B assembly input dialog to estimate the material quantities. Foundations, floors, roofs, walls, and beams and columns were included by specifying the material type, span or tributary area, live loads, etc., based on the design drawings and Athena capabilities. Models only included structural materials. If a structural system or material could not be modeled automatically in Athena IE4B, then its quantity was hand calculated and inserted via the BOMs feature for both the original model and the comparison wood substitution model.

Case Study Substitution Description

Table 1 shows assemblies in the direct wood substitution approach with an Athena-generated design. Case study buildings 5 and 6 were only one-story high, with wood replacement in the roof frame and beams and columns. However, the major difference was actually in the lateral system: tilt-up concrete shear walls vs a steel moment frame. Buildings examined in case studies 1-4 had three different combinations of beams/columns, floor, roof, and wall assemblies that were altered with wood substitution. Composite concrete and steel deck floors in case studies 1-3 and suspended (two-way spanning) concrete floors in case study 4 were substituted using a wood floor system, whereas case study buildings 5 and 6 were one-story, and thus did not have floors above grade to be substituted with wood.

Table 1. Summary of assemblies altered due to wood substitution for each case study.

	Case study					
Assemblies	1	2	3	4	5	6
Foundations	—	—	—	—	—	—
Beams and columns	—	1	1	1	1	1
Floors	1	1	1	1	—	—
Roofs	1	1	1	1	1	1
Walls	1	—	—	—	—	—
LFRS	—	—	—	—	—	—
Total	3	3	3	3	2	2

LFRS, lateral force–resisting system.

Case study 1. This two-story-plus-penthouse office building has the smallest floor area among the six buildings studied. The original floor system consists of open-web steel joists with corrugated metal deck and concrete topping, and was replaced with wood I-joists and plywood decking for a 2.4 kPa (50 psf) live load. This building had two roof systems: open-web steel joists with corrugated metal deck and steel I-joists with plywood decking. Both roof systems were replaced with wood I-joists and plywood decking. Wide flange (WF) beams and steel hollow structural section (HSS) columns were kept the same because the irregular plan layout made it difficult to model and obtain realistic material calculations from Athena IE4B. The beam and column material takeoff was calculated from the design drawings and input to both models via the extra materials input option. CMU shear walls

Table 2. Case study 1 summary of design scenarios via Athena for the original materials and wood substitution.

Case study 1	Original material	Wood substitution
Type	Office building	Office building
Location/year	Oregon/1990	Oregon/1990
Gross floor area	1466 m^2 (15,782 ft^2)	1466 m^2 (15,782 ft^2)
Height	10.8 m (35.5 ft)	10.8 m (35.5 ft)
Live load	2.4 kPa (50 psf)	2.4 kPa (50 psf)
	Penthouse = 4.8 kPa (100 psf)	Penthouse = 4.8 kPa (100 psf)
LFRS	CMU shear walls	CMU shear wall
Foundations	Slab on grade, strip footing, and spread footing	Slab on grade, strip footing, and spread footing
Floors	Open-web steel joist with corrugated metal deck and concrete topping	Wood I-joist with plywood decking
Roofs	Open-web steel I-joist with corrugated metal deck	Wood I-joist with plywood decking
	Steel joist with plywood decking	Wood I-joist with plywood decking
Beams/girders	WF	WF
Columns	HSS	HSS
Walls	CMU shear wall and elevator shaft wall	CMU shear wall and elevator shaft wall
	Steel stud wall	Wood stud wall

CSM, concrete masonry unit; LFRS, lateral force–resisting system; WF, wide flange; HSS, hollow structural section.

were also maintained as part of the LRFS. Steel stud walls were replaced with wood studs. Table 2 provides a summary of the original and wood scenarios modeled in Athena for case study 1.

Case study 2. The one-and-one-half-story exercise facility which was the subject of this case study has CMU shear walls on the perimeter and large open spaces supported on steel WF beams and HSS columns. In evaluating this building, the CMU shear walls were kept the same. WF beams were substituted by laminated veneer lumber (LVL), whereas the HSS columns were substituted with softwood lumber. The portion of the roof system with corrugated metal deck and concrete topping was replaced with wood I-joists and 16 mm (5/8 in) plywood decking. In addition, open-web steel roof joists were substituted using a light-frame, metal-plate-connected wood truss. Table 3 provides a description of original and wood scenarios modeled in Athena for case study 2.

Case study 3. The subject of this case study was a sports (basketball) facility with two

Table 3. Case Study 2 Summary of Design Scenarios via Athena for the Original Materials and Wood Substitution.

Case study 2	Original material	Wood substitution
Type	Exercise facility	Exercise facility
Location/year	Oregon/2007	Oregon/2007
Gross floor area	2997 m^2 (32259 ft^2)	2997 m^2 (32259 ft^2)
Height	11.6 m (38 ft)	11.6 m (38 ft)
Live load	Floor = 4.8 kPa (100 psf)	Floor = 4.8 kPa (100 psf)
	Roof = 2.4 kPa (50 psf)	Roof = 2.4 kPa (50 psf)
LFRS	CMU shear wall and braced frame	CMU shear wall and braced frame
Foundations	Slab on grade, strip footing, and spread footing	Slab on grade, strip footing, and spread footing
Floors	Composite metal floor with concrete topping	Wood I-joist with plywood decking
Roofs	Galvanized metal roof without concrete	Wood I-joist with plywood decking
	Open-web steel joist with galvanized metal deck	Light frame wood truss with plywood deck
Beams/girders	WF	LVL/PSL
Columns	HSS	Softwood lumber
Walls	CMU shear wall	CMU shear wall

CSM, concrete masonry unit; LFRS, lateral force–resisting system; WF, wide flange; HSS, hollow structural section; LVL, laminated veneer lumber; PSL, parallel strand lumber.

Table 4. Case study 3 summary of design scenarios via Athena for the original materials and wood substitution.

Case study 3	Original material	Wood substitution
Type	Sports center	Sports center
Location/year	Oregon/2013	Oregon/2013
Gross floor area	3455 m^2 (37192 ft^2)	3455 m^2 (37192 ft^2)
Height	18.9 m (62 ft)	18.9 m (62 ft)
Live load	Floor = 4.8 kPa (100 psf)	Floor = 4.8 kPa (100 psf)
	Roof = 2.4 kPa (50 psf)	Roof = 2.4 kPa (50 psf)
LFRS	CMU shear wall and braced frame	CMU shear wall and braced frame
Foundations	Slab on grade, strip footing, and spread footing	Slab on grade, strip footing, and spread footing
Floors	Composite metal deck with concrete topping.	Wood I-joist with plywood decking
Roofs	Galvanized metal roof without concrete	Wood I-joist with plywood decking
Beams/girders	WF	LVL/PSL
Columns	HSS	Softwood lumber
Walls	CMU shear wall	CMU shear wall
	Steel stud wall	Wood stud wall

CSM, concrete masonry unit; LFRS, lateral force–resisting system; WF, wide flange; HSS, hollow structural section; LVL, laminated veneer lumber, PSL Parallel Strand Lumber.

stories plus two mezzanines with a total height of 18.9 m. Materials are similar to case 2, with the exception of steel WF moment frames and some steel stud walls. The LFRS used CMU shear walls on two parallel exterior walls and steel-braced frames on the other two parallel exterior walls, and these were kept the same in the wood substitution scenario. Case 3 has a regular plan configuration that makes it easy to substitute for beams and columns, floors/mezzanines, and roof systems. The wood substitution model includes wood I-joists with plywood decking supported on LVL beams. Table 4 provides a description of the original and wood scenarios modeled in Athena for case study 3.

Case study 4. The building evaluated in this case was a residential structure constructed primarily of reinforced concrete, including suspended (two-way spanning) concrete slabs for the floors and roof, cast-in-place concrete shear walls, and concrete columns. For purpose of evaluating substitution effects, foundations and first floor of the building were kept the same in both models, whereas the other concrete floors were substituted with wood I-joists, plywood decking, and LVL floor beams. The roof was substituted using a light-frame wood truss and plywood sheathing. Reinforced concrete columns were substituted for with softwood lumber. Table 5 provides a summary of case study 4.

Table 5. Case study 4 summary of design scenarios via Athena for the original materials and wood substitution.

Case study 4	Original material	Wood substitution
Type	Residential building	Residential building
Location/year	Oregon/2013	Oregon/2013
Gross floor area	6220 m^2 (66900 ft^2)	6220 m^2 (66900 ft^2)
Height	16.2 m (53.0 ft)	16.2 m (53.0 ft)
Live load	1st floor = 4.79 kPa (100 psf)	1st floor = 4.79 kPa (100 psf)
	2nd-5th floor = 2.39 kPa (50.0 psf)	2nd-5th floor = 2.39 kPa (50.0 psf)
	Roof = 4.79 kPa (100 psf)	Roof = 4.79 kPa (100 psf)
LFRS	Cast-in-place concrete shear walls	Cast-in-place concrete shear walls
Foundations	Slab on grade	Slab on grade
Floors	Suspended concrete slabs	Wood I-joist with plywood decking
Roofs	Suspended concrete slabs	Light frame wood truss with plywood decking
Beams/girders	Not used in this system	LVL
Columns	Concrete	Softwood lumber
Walls	Concrete cast-in-place shear walls	Concrete cast-in-place shear walls

LFRS, lateral force–resisting system; LVL, laminated veneer lumber.

Table 6. Case study 5 summary of design scenarios via Athena for the original materials and wood substitution.

Case study 5	Original material	Wood substitution
Type	Medical building	Medical building
Location/year	Oregon/2012	Oregon/2012
Gross floor area	2230 m^2 (24,000 ft^2)	2230 m^2 (24,000 ft^2)
Height	5 m (16.5 ft)	5 m (16.5 ft)
Live load	Roof = 2.4 kPa (50 psf)	Roof = 2.4 kPa (50 psf)
LFRS	Moment frame	Moment frame
Foundations	Slab on grade and spread footing	Slab on grade and spread footing
Floors	Same as foundations	Same as foundations
Roofs	Open-web steel joist with metal deck	Wood I-joist with plywood decking
Beams/Girders	WF	Glulam
Columns	HSS	Softwood lumber

LFRS, lateral force–resisting system; WF, wide flange; HSS, hollow structural section.

Case study 5. Case study 5 involved evaluation of a one-story tall medical building with a regular rectangular layout. It has steel moment frames for the LFRS, which for purposes of assessment were kept the same, but all the other assemblies above ground were altered. The open-web steel joists with metal deck in the roof were substituted for using wood I-joists with plywood decking. In addition, steel beams and columns were replaced by glulam beams and softwood lumber columns. Table 6 provides a description of case study 5.

Case study 6. The focus of this study was a warehouse constructed of tilt-up reinforced concrete walls for the entire perimeter of the building as the LFRS. This design was kept the same in the wood substitution scenario. The only two assemblies that could be substituted using wood were the beams and columns and roof framing. Steel columns and beams were substituted for using softwood lumber columns and LVL beams. Open-web steel joists were replaced with a light-frame wood truss in the roof. Table 7 summarizes case 6.

Wood Building Redesign Approach

Overview. The wood building redesign involved the use of the Athena IE4B BOMs input method, which required that each of the building material types and quantities be known. The medical office building in case 5 was selected for this redesign. A structural system BOM per the existing building design drawings was created. The existing building used steel beams, columns,

Table 7. Case study 6 summary of design scenarios via Athena for the original materials and wood substitution.

Case study 6	Original material	Wood substitution
Type	Warehouse	Warehouse
Location/year	Oregon/2014	Oregon/2014
Gross floor area	2965 m^2 (31,920 ft^2)	2965 m^2 (31,920 ft^2)
Height	9.75 m (32 ft)	9.75 m (32 ft)
Live load	Roof = 2.4 kPa (50 psf)	Roof = 2.4 kPa (50 psf)
LFRS	Tilt-up concrete wall	Tilt-up concrete wall
Foundations	Slab on grade, spread footing	Slab on grade, spread footing
Floors	Same as foundation	Same as foundation
Roofs	Open-web steel joist with metal deck	Light frame wood truss with OSB decking
Beams/Girders	WF	LVL/PSL
Columns	HSS	Softwood lumber
Walls	Tilt-up concrete	Tilt-up concrete

LFRS, lateral force–resisting system; WF, wide flange; HSS, hollow structural section; LVL, laminated veneer lumber; OSB, oriented strand board.

open-web joists, and a steel moment frame. To create a BOM for the wood case, the structural members were redesigned using current codes with conventional wood products. The building was redesigned for both the gravity and LFRSs.

Redesign used the International Building Code (ICC 2009), Minimum Design Loads for Building and Other Structures (ASCE 2010), and the National Design Specifications for Wood Construction and Special Design Provisions for Wind and Seismic (AF&PA 2005a, 2005b), which are the codes used for the original design. Typical wood products used during the redesign included Truss Joist I-joists (TJI joists), diaphragm and shear wall plywood sheathing, glulam beams, headers, collectors, columns, sawn lumber studs, shear wall chords, and header supports. Some interior and exterior shear walls needed to be placed in the building to maintain the integrity and not compromise the functionality of the structure.

Building description. The medical office is an 87.2 m by 25.3 m (286 ft by 83 ft) rectangular, one-story building, with a height of 6.1 m (20 ft). The original building was designed predominantly with steel for its gravity system. Exterior walls and interior partitions are non-load bearing and were not included in the analysis. However, their general layout was kept the same when shear walls had to be added in the wood redesign. Windows, 7.6 m by 2.7 m (25 ft by 9 ft), along the length of the building and 10.7 m by 2.7 m (35 ft by 9 ft) along the width of the building, were separated by 1.5 m (5 ft) wide, wall segments. Beams and columns ran in three parallel rows along the length of the building, in addition to the steel moment frames at the ends of the building. All beams are WF sections, whereas columns are steel HSSs, except for the moment frame columns which were WF. Roof loads were transferred to the beams and columns through 12.2 m (40 ft) span open-web steel joists spaced 1.5 m (5 ft) on center. Metal roof decking was used, and reinforced concrete foundations consisted of slab on grade and spread footings.

The structural system of the medical office building was redesigned with conventional wood products while keeping the functionality of the building similar. The general layout of the building was kept the same, including the building's footprint, roof height, and column layout, as well as the exterior building appearance. Wall segments between the windows were increased from 1.5 m (5 ft) to 2.1 m (7 ft) wide to act as shear walls to comply with lateral force–resistance system requirements. Segments of the interior partition walls were designed to resist lateral forces in the north-south direction. Douglas fir-Larch Grade No. 2 or better was used for all sawn lumber. Exterior walls were 38 × 139 mm (1.5 × 5.5 in) studs, with 11.9 mm (15/32 in) plywood sheathing on one side. Interior shear wall segments were designed similarly. The central column row along the building's length was designed using glulam beams and sawn lumber columns. Beams and the columns along the length of the exterior walls were replaced with collector glulam beams and glulam headers above the windows. Collector beams were supported on 139 × 139 mm (nominal 6 × 6) columns at each side of the shear wall, whereas the window headers were supported on two 38 × 139 mm (nominal 2 × 6) studs on each side of the window opening. Wood I-joists were used to support the roof, keeping the other materials the same. Foundation design was retained from the original. Connection design was not conducted.

Design loads and member design. Building loads included dead, roof live, snow, wind, and seismic. Design criteria from the original general structural notes were applied to the wood redesign. Seismic design was performed using the Equivalent Lateral Force Procedure of ASCE 7-05 Section 12.8 (ASCE 2010) and the wind design using Method 1—Simplified Procedure, ASCE 7-05 Section 6.4 (ASCE 2010), as per the original building. Roof live load was determined in accordance with ASCE 7-05 Table 4-1, and exterior wall and window dead loads from ASCE 7-05 Table C3-1 (ASCE 2010). Table 8 summarizes the loads used for the wood redesign case. Figure 7 shows location and magnitudes of wind forces for the east-west wind direction. Member

Table 8. Wood building redesign loads.

Load Type	Application	Magnitude	Reference
Dead	Roof	0.96 kPa (20 psf)	General notes
	Wall (brick)	2.30 kPa (48 psf)	ASCE 7-05 Table C3-1 (ASCE 2010)
	Wall (stucco)	0.47 kPa (12 psf)	ASCE 7-05 Table C3-1 (ASCE 2010)
	Partitions	0.57 kPa (12 psf) of floor area	Breyer et al 2010
	Window glass	0.38 kPa (8 psf)	ASCE 7-05 Table C3-1 (ASCE 2010)
Live	Roof	0.96 kPa (20 psf)	ASCE 7-05 Table 4-1 (ASCE 2010)
Snow	Roof	1.20 kPa (25 psf)	General notes
Wind	Wall	Varies (Fig 7)	General notes ASCE 7-05 Section 4.6 (ASCE 2010)
Seismic	Wall	Varies (Cs = 0.11)	General notes ASCE 7-05 Section 12.8 (ASCE 2010)

design calculations due to wind uplift were not performed.

Allowable Stress Design methodology was used throughout the design process. Member design capacities were calculated in accordance with the National Design Specification (AF&PA 2005a). A summary of member dimensions is presented in Table 9.

Bill of materials. The estimated BOM for the original building is shown in Table 10. Table 11 presents the BOM for the conventional wood redesign. Total material takeoffs were calculated and converted to the FU used in Athena IE4B. A construction waste factor was applied, as a percentage of the quantity of material in use, for each material type, and added to the BOM. Original material takeoffs were determined from the structural plans, whereas wood redesign materials were from the code-based design. The BOM does not include the wall frame since it served only architectural purposes, but in the wood redesign, the LFRS includes shear wall segments, both exterior and interior. Roof wood I-joists were made of LVL flanges and OSB webs, and material quantities were accounted for and input separately.

RESULTS AND DISCUSSION

Direct Wood Substitution Approach Analysis

Global warming potential. Global warming has been attributed, in part, to the potential of greenhouse gases to absorb energy from escaping the Earth's atmosphere. GWP is a measure of greenhouse gases emitted to the atmosphere expressed in equivalent kg of CO_2 to allow for comparison of the GWPs of different gases. Development of six case studies, in which existing building structural systems were replaced via direct wood substitution, showed that substituting

Table 9. Summary of wood member design for Case 5.

Callout	Material	Dimensions	Length
Interior beam	Glulam 24F-1.7E-V5	222.2 × 762 mm (8.75 × 30 in)	9.1 m (30 ft)
Interior column	Sawn Lumber DF-Larch No. 1	235 × 235 mm (9.25 × 9.25 in)	5.8 m (19 ft)
Exterior beam (A)	Glulam 24F-1.7E-V5	171.5 × 723.9 mm (6.75 × 28.5 in)	10.1 m (33 ft)
Exterior beam (B)	Glulam 24F-1.7E-V5	171.5 × 533.4 mm (6.75 × 21 in)	7.1 m (23.25 ft)
Header (A)	Glulam 24F-1.7E-V5	139.7 × 228.6 mm (5.5 × 9 in)	7.1 m (23.25 ft)
Header (B)	Glulam 24F-1.7E-V5	171.5 × 304.8 mm (6.75 × 12 in)	10.1 m (33 ft)
Header support	Stud DF-Larch No. 2	38.1 × 139.7 mm (1.5 × 5.5 in)	3.7 m (12 ft)
Exterior posts	Sawn Lumber DF-Larch No. 1	139.7 × 139.7 mm (5.5 × 5.5 in)	5.8 m (19 ft)
Roof joist	TJI 560D 610 mm (24 in) deep	609.6 mm (24 in) deep	12.2 m (40 ft)
Roof sheathing	Plywood 12 mm (15/32 in) thick	11.9 mm (15/32 in)	Panel
Exterior stud	Stud DF-Larch No. 2	38.1 × 139.7 mm (1.5 × 5.5 in)	5.8 m (19 ft)
Shear wall sheathing	Plywood 12 mm (15/32 in) thick	11.9 mm (15/32 in)	Panel

Table 10. Bill of materials for the Case 5 original building.

Material name	Quantity in use (SI units)	Construction waste (%)	Total quantity (SI units)	Total quantity (US units)
Concrete	315 m^3	0.05	331 m^3	432 yd^3
Galvenized deck	20.7 Tonnes	0.01	20.9 Tonnes	23.0 Tons (short)
HHS	3.78 Tonnes	0.01	3.82 Tonnes	4.21 Tons (short)
OWSJ	19.7 Tonnes	0.01	19.9 Tonnes	21.9 Tons (short)
WF	20.2 Tonnes	0.01	20.4 Tonnes	22.5 Tons (short)

WF, wide flange; HHS, hollow dtructural section; OWSJ, open web steel joist.

Table 11. Bill of materials for the Case 5 conventional wood products redesigned building.

Material name	Quantity in use (SI units)	Construction waste (%)	Total quantity (SI units)	Total quantity (US units)
Concrete	315 m^3	0.05	331 m^3	432 yd^3
Glulam	44.9 m^3	0.01	45.4 m^3	1600 ft^3
LVL	36.8 m^3	0.01	37.1 m^3	1310 ft^3
Large dimension lumber	8.12 m^3	0.05	8.53 m^3	5.22 [1]MBFM
OSB	3380 m^2 (9 mm)	0.05	3546 m^2 (9 mm)	38.2 MSF (3/8″)
Small dimension lumber	270 m^3	0.08	291 m^3	188 [2]MBFM
Plywood	3900 m^2 (9 mm)	0.05	4100 m^2 (9 mm)	44.1 MSF (3/8″)

LVL, laminated veneer lumber; MBFM, 1000 board feet; MSF, 1000 square feet.

wood for the structural materials in commercial construction results in major reductions of GWP. Average reduction in GWP for all six buildings was 63%. All of the studies showed improvement in net environmental performance as shown in Fig 2. "Net" is the difference between the original and wood substitution scenarios in GWP from all the life-cycle stages within the boundary conditions. Values ranged from 46% for the one-story tilt-up concrete warehouse building to 99% for the five-story reinforced concrete residential building. The lowest (46%) reduction value for case 6 is due to wood substitution for the steel roof system, beams, and columns only. Intermediate reduction values were observed from other substitution arrangements in case studies 1-3 and 5. Cases 2 and 3 had similar constructions, with the materials for the floor, roof, and LFRS the same, but the building dimensions, layout, and function were different. Case 4 represents a 99% reduction value on the environmental savings due to wood substitution for the reinforced concrete floors, roof, beams, and columns. This suggests that there is a higher potential of environmental savings to be realized when reinforced concrete is replaced rather than steel. However, since this was the only case study where reinforced concrete (excluding the concrete cover on the composite metal deck floors) was replaced by wood, it is difficult to make a general conclusion.

Figure 3 shows that the Product and Beyond Building Life stages were the main contributors in GWP savings from wood substitution. Construction and the End of Life stages showed less environmental savings overall, and in some cases no savings, due to wood substitution, but the environmental impact values due to these stages are an order of magnitude less than the Product stage. This reinforces the fact that building materials, as delivered to the construction site, have significant GWP and are a major contributor to environmental impacts of the building system. Construction and End of Life processes do contribute toward increasing the embodied energy of the material; however, that contribution is much smaller in comparison with the manufacturing processes. This alludes to the potential that exists in achieving environmental savings by making sound decisions regarding building materials. In case 6 (Fig 3), there is no difference in GWP due to wood substitution for the Construction and End of Life stages. This is also observed in the End of Life stage in case

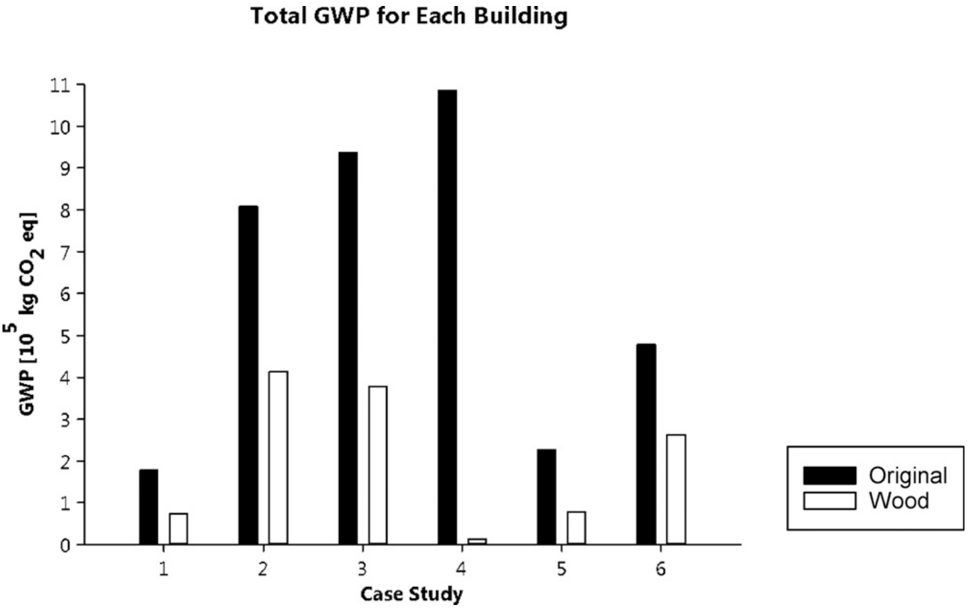

Figure 2. Total global warming potential output in kg of CO_2 equivalent for the original and the wood-substituted scenarios.

study 5. In both these cases, steel from the roof framing and beams and columns were replaced by wood. The small difference in GWP due to the Construction and End of Life stages between the two scenarios was expected since both steel and wood are manufactured off-site and have similar installation arrangements. However, the main difference in GWP was observed in the Product stage and, especially, in the Beyond Building Life stages due to wood substitution. A reason for this magnified difference in the Beyond Building Life stage is the way Athena

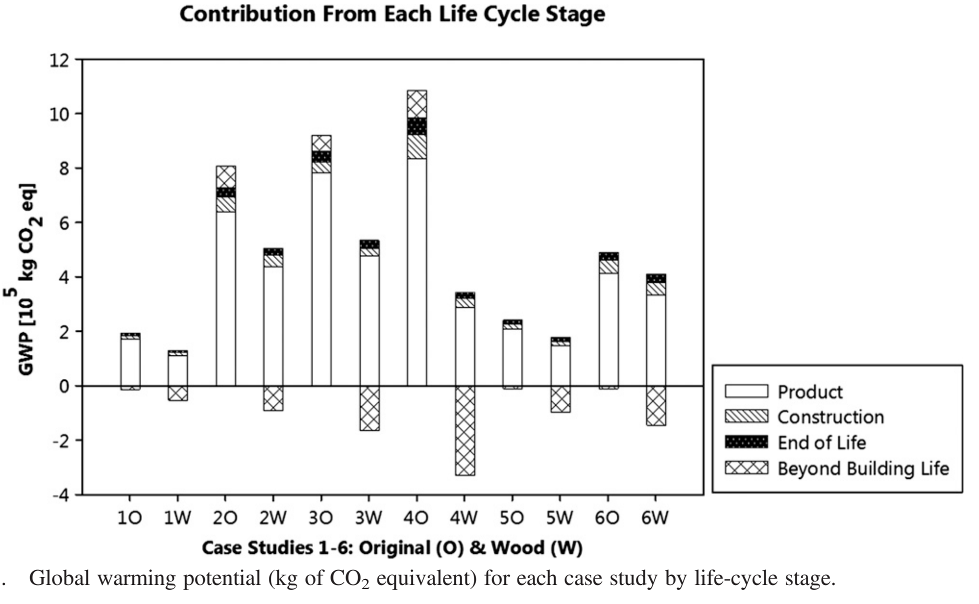

Figure 3. Global warming potential (kg of CO_2 equivalent) for each case study by life-cycle stage.

IE4B credits steel recycling vs biogenic carbon sequestration. Steel recycling is characterized with a "closed material loop recycling methodology" and accounts for the Production GWP savings due to the use of recycled steel instead of the no-recycled steel in the Product stage (ASMI 2014). On the contrary, the biogenic carbon sequestration for wood is only credited in the Beyond Building Life stage. Athena IE4B conservatively assumes that the current practices for the final disposition of the building materials will apply in the future. Steel recycling rates for 2013 are made available to Athena from the Steel Recycling Institute, and for structural products those rates reach as high as 98%, and 70% for reinforcing steel. The End of Life strategies for wood products are reported as 80% landfill, 10% combustion, and 10% recycling (ASMI 2014).

In examining the case studies, it is important to consider the amount of wood products being used as a substitute for other building materials. Table 12 presents the amount of concrete and steel replaced in each case study and the equivalent amount of wood products substituted. Total wood fiber resources used in each case are shown. In case 4, wood products are substituted mainly for reinforced concrete. In case studies 1-3, the concrete being replaced by wood was from the composite metal deck concrete floor assemblies, whereas the steel was from floor assemblies (metal deck, rebar, screws, beams) and in other assemblies being replaced. For cases 5 and 6, only steel members were substituted by wood. The largest amount of wood was used in case 4, which also corresponds to the greatest GWP savings. Case study 6 corresponds to the lowest GWP savings, even though it did not have the lowest wood substitution amount. The greatest savings in GWP were generally achieved when wood is substituted for concrete. Considerable savings can be achieved in floor and wall assemblies.

Energy consumption. The embodied energy is cumulative and expended by all processes within the given system boundaries, and is reported as TPE Consumption. In all case studies, less energy was consumed due to wood substitution. Case 4 showed a 56% reduction, case 6 a 14% reduction, and in cases 1-3 and 5 the energy use reduction varied from 21% to 32%. The percentage difference in TPE between the original and wood scenarios is smaller than for GWP, suggesting that GWP is impacted by many factors, including energy source. Subsets of TPE, such as renewable energy (RE), nuclear energy (NE), FFC, and wood-derived energy were examined. RE includes energy sources from hydro, nonhydro renewable, and wood. NRE includes two categories, FFC and NE. For the original buildings, the net RE is on average 1% of the TPE, whereas for the wood substitution scenarios, the net RE is on average 15% of the TPE. One contributor to this difference is the use of wood as an energy source within the wood product manufacturing facilities. Use of wood as an energy source is considered carbon neutral because the amount of carbon released is equal to the amount of carbon sequestered from the atmosphere during the life of the tree. The wood energy source counts for 77% of the RE used

Table 12. Amounts of concrete and steel material replaced in each case study and the equivalent amount of wood used in substitution.

Case study (metric ton)	1	2	3	4	5	6	Total
Total concrete	589	2026	2136	4934	748	2138	11,404
Concrete replaced	135	557	650	3660	0	0	4538
Percentage Replaced	*23*	*27*	*30*	*74*	*0*	*0*	*40*
Total steel	58	339	414	205	92	99	1095
Steel replaced	27	138	202	180	56	73	612
Percentage Replaced	*47*	*41*	*49*	*88*	*60*	*73*	*56*
Wood substituted	40	129	174	234	71	107	685
Total wood fiber used	87	417	555	765	172	221	2011

in the wood substitution scenarios. On the other hand, NE accounts for 25% of the NRE in the original building scenarios, whereas in the wood substitutions, NE accounts for 18% of the NRE.

FFC average reductions due to wood substitution for each of the case studies are presented in Fig 4. Major reductions in FFC resulted in all cases. Fossil fuel is the main energy source for all cases, in both original and wood substitution, accounting for 74% and 69% of the TPE for the original material and wood substitution scenarios, respectively. In addition, the Product stage accounts for about 85% of the energy consumption in terms of TPE and 80% in terms of FFC, whereas the Construction and the End of Life stages account for 10% and 8% of FFC, respectively. The FFC trend is similar to GWP in the Product stage, confirming that FFC is an important contributor to GWP. Average savings in FFC during the Product stage of the building life cycle due to wood substitution are 39% of the original scenarios. FFC for construction and End of Life stages were 32% and 20% less FFC, respectively, for the wood substitution scenarios as compared with the original material scenario, as expected due to the use of more heavy machinery for concrete and steel construction and demolition processes. On the contrary, the FFC due to the Beyond Building Life stage increased due to wood substitution, except for case study 4.

Wood substitution resulted in a 29% TPE reduction and a 33% FFC reduction, where 15% of the TPE is attributable to the use of renewable sources of energy in the wood substitution scenarios compared with only 1% in the original buildings. On average, 77% of the RE in the wood substitution scenarios is due to the utilization of wood as an energy source during the manufacturing stage. On the other hand, NE contributes to a larger percentage of the NRE in the original buildings compared with the wood substitutions.

Other impact measures. Using wood in the buildings investigated had mixed effects among the different case studies for the other TRACI impact category measures, including AP, HHP, EP, SP, ODP, TPE consumption, NRE consumption, and FFC. Improved performance for the different case studies varied due to differences among substitution levels, gross floor area, materials, and construction type. Wood

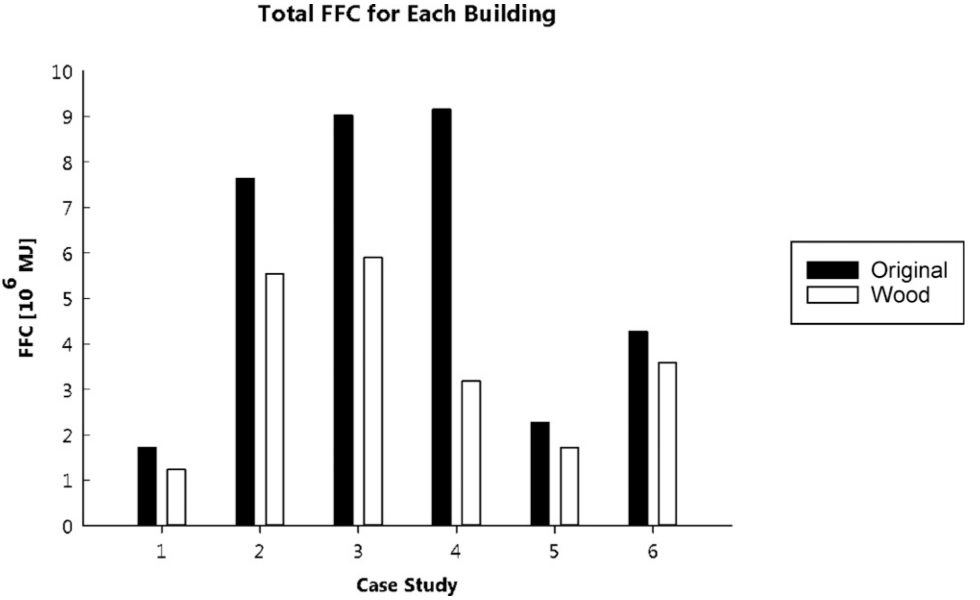

Figure 4. Total fossil fuel consumption (MJ) for each case study.

replacement levels vary in the type and amount of the material in the substitution. In general, all impact categories, except for EP and ODP, showed major reductions across the case study wood substitutions. On the other hand, wood substitution resulted in increased EP and ODP in case studies 5 and 6 and the lowest reductions among other categories for case studies 1-4. EP is “the fertilization of surface waters by nutrients that were previously scarce” and expressed in a nitrogen basis (ASMI 2014). The disadvantage of wood in this category may have to do with the fertilizers sometimes used in forest management. The exact cause of this observation is, however, unknown. ODPs are to the power of E-03 kg of CFC-11 equivalent; therefore, having an insignificant overall impact, even though there seems to be a considerable percentage increase. From all the TRACI impact category measures, wood substitution had the greatest effect in GWP for each of the case studies analyzed.

Analysis after Structural Redesign

Case study 5 was selected for a more detailed analysis and comparison. In addition to the direct wood substitution approach presented earlier, this case was analyzed after redesigning the entire building with wood using current codes and generating BOMs. The BOM thus obtained for the original and wood redesign were used as inputs in Athena. Comparisons were of two types. First, the BOM that was manually generated for the original design and the BOM for the code-based redesign for the building in case 5 were used in IE4B as inputs to conduct LCA and compare results. Next, these LCA results were compared with those from the direct wood substitution to see the differences between the design-based results (BOM approach) and software-generated results (direct wood substitution). To make the comparison as fair as possible, the Athena-generated BOM was modified to exclude materials that were not redesigned in the BOM approach such as rebar and welded wire mesh from the foundations, screws from the open-web steel joist with galvanized decking, and nails and galvanized sheet from the light-frame wood truss with plywood decking. This simplification resulted in a 4% difference for the original scenario and 13% difference for the wood substitution scenario.

Global warming potential. The terms in the following figures and tables represent four analysis scenarios for case study 5 and they are denoted as follows:

- *O-Athena: results for the original materials via the first approach (direct wood substitution or Athena-generated BOM).*
- *W-Athena: results for the substituted wood materials scenario via first approach (direct wood substitution or Athena-generated BOM).*
- *O-Design: results for the manually generated BOM for the original design via second approach (BOM approach).*
- *W-Redesign: results for code-based wood redesign generated BOM via second approach (BOM approach).*

The GWP for the four different scenarios are presented in Fig 5. GWP savings due to wood substitution via the Athena-direct substitution approach were about 69%, whereas the GWP savings due to wood redesign via the BOM approach were 166%. Additional GWP savings due to the BOM approach are attributed to the design of wood shear walls, which use less fossil fuel, more RE, and store CO_2, to replace the steel moment frame. It is difficult to compare these results with previous LCA studies, since there are not many that look at impacts of structural materials separately with the same boundary conditions. A recent study that compared the environmental savings due to substituting a concrete frame with a CLT frame found 75% GWP savings (Robertson et al 2012). The comparative savings in GWP were greater for the BOM approach as compared with the direct wood substitution approach. Comparisons from the BOM approach are assumed to be more accurate than the Athena-generated approach, because the material quantities are derived from engineering calculations for each member instead

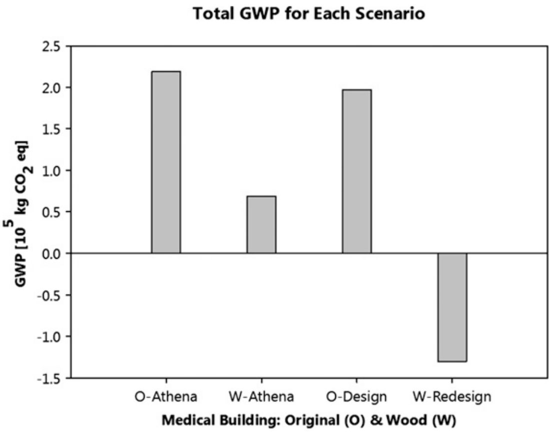

Figure 5. Total global warming potential for each of the scenarios of case study 5.

of algorithms for material sizing calculations used in the Athena IE4B software.

Figure 6 shows that GWP savings between the original and wood substitution materials were primarily achieved in the Product and Beyond Building Life stages for both approaches. GWP for the wood redesign scenario was reduced 23% in the Product stage and almost doubled the savings at the End of Life stage, whereas for the direct wood substitution approach these stages showed 31% and 86% reduction, respectively. GWP in Construction and End of Life stages showed an increase due to wood utilization in the BOM approach, but the opposite was true in the direct wood substitution approach. On-site GWP due to construction and the demolition of wood shear walls may be greater than for steel moment frames, and more energy intensive as well.

Results for Athena-generated design and BOM approaches were different as can be seen in Table 13. The Athena-generated design overestimated impacts for each assembly in the original material scenarios, whereas it underestimated impacts for the conventional wood materials in all assemblies except for the Beyond Building Life. Athena has no way to estimate the materials for the LFRS, and when the LFRS is combined with the gravity system, it is difficult to separate and accurately model the two without a detailed design, as in the redesign approach using BOM. In addition, the net difference for the wood material scenarios showed greater inconsistency. This is due, in

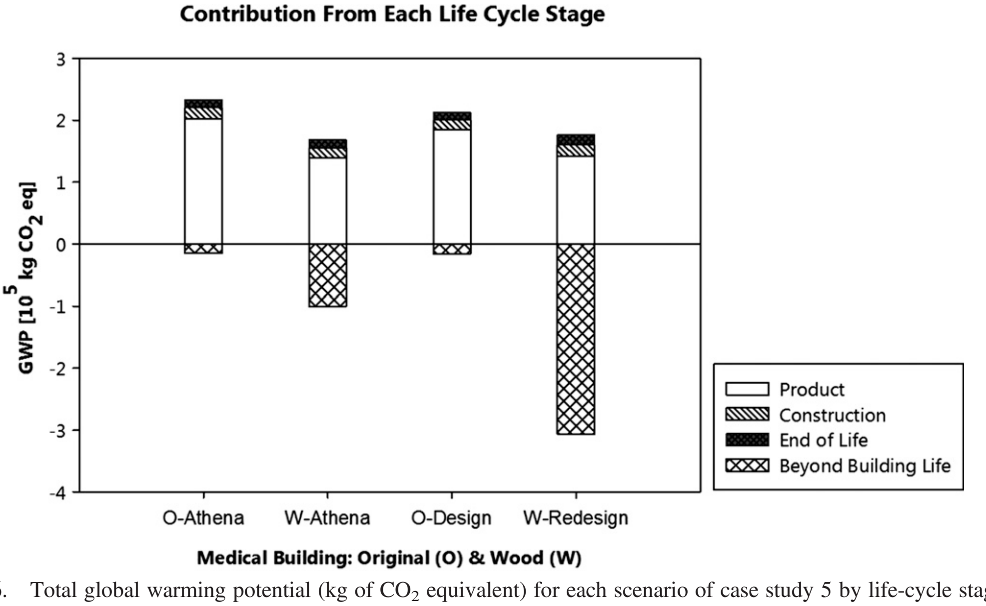

Figure 6. Total global warming potential (kg of CO_2 equivalent) for each scenario of case study 5 by life-cycle stage.

Table 13. GWP for each of the life-cycle stages for the original materials and wood substitution materials via direct wood substitution approach and BOM approach.

Life-cycle stage	O-Athena	O-Design	W-Athena	W-Redesign
Product	2.03E+05	1.84E+05	1.40E+05	1.42E+05
Construction process	1.76E+04	1.67E+04	1.62E+04	1.82E+04
End of life	1.27E+04	1.17E+04	1.25E+04	1.61E+04
Beyond building life	−1.42E+04	−1.59E+04	−9.97E+04	−3.07E+05
Total	2.19E+05	1.97E+05	6.87E+04	−1.30E+05

GWP, global warming potential; BOM, bill of material.

part, to the fact that shear walls not only altered the exterior wall layout but also had to be added in the interior of the building, and this was not considered in the first method.

Energy consumption. TPE differences between the two approaches for each material type resulted in a 22% consumption reduction for the direct wood substitution approach and a 9% increase for the BOM approach, meaning that a complete structural wood redesign of the building did not show major energy savings over the steel alternative. This is because of the high levels of recycled steel, and energy consumption reductions due to savings from raw material sourcing. The steel moment frame made more efficient use of material quantities than wood-frame shear walls, therefore contributing to energy savings. TPE consumption was 14% less due to the BOM approach as compared with the direct wood substitution approach for the original materials and 20% more for the wood redesign. The BOM approach for the wood redesign led to added shear walls in place of the moment frame, adding a greater amount of materials. Figure 7 presents the FFC results for the four scenarios. Similar trends to TPE are observed with FFC results, except that comparison between original and wood materials for the BOM approach resulted in 6% FFC savings. Although the total energy is 9% greater in the wood redesign, the FFC is 6% lower. FFC makes up about 70% of the energy source for the original materials, regardless of the method of analysis, whereas for the wood scenarios, FFC savings were 67% in the direct wood substitution and 62% in the BOM approach. Similar trends were observed by Börjesson and Gustavsson (2000) in their study, which concluded that FFC in building material production was 60-80% higher in case of concrete instead of wood. RE plays a much greater role in the wood utilization scenarios with more than 80% coming from wood sources. RE use increased as more wood was utilized in the redesign. NE accounted for 28% of the NRE in the original buildings and decreased as the wood material substitution increased with each method, suggesting that NE is used much more in steel production than in wood.

Other impact measures. Although GWP is the main impact measure used to compare the environmental effects of different building materials, other measures that quantify the impacts to

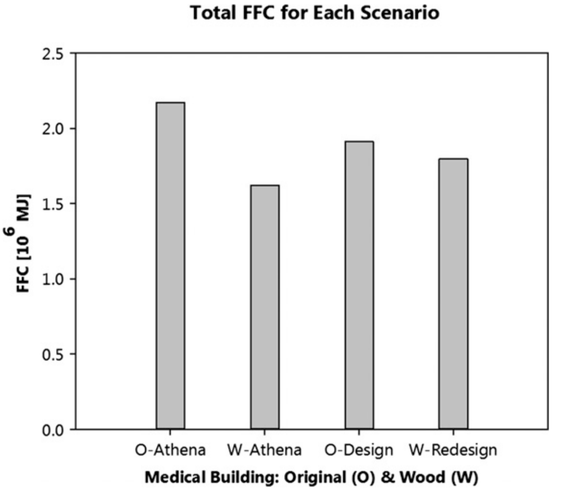

Figure 7. Fossil fuel consumption (MJ) for each scenario for case study 5.

human health, surface waters, protective ozone layer, etc., should be considered when making a material selection decision. The results from the direct wood substitution showed an impact decrease in all the other impact measures, except for the EP and ODP, due to the substitution of the original materials with wood products. EP and ODP showed a 16% and 66% increased impact, respectively, due to wood substitution. SP results were only 4% different, whereas the other categories ranged from 14% to 34% different.

The BOM approach showed that the conventional wood redesign performed unfavorably in all other impact measures, except for NRE and FFC. Wood redesign BOM vs original BOM showed an increase of 16% in AP, 8% in HHP, 66% in EP, 67% in ODP, and 31% in SP. With increased use of wood products there could be tradeoffs in other impact measures. Some of these measures have regional influence, such as AP, impacts on living organisms in water, such as EP, impacts on the human respiratory system, such as HHP, reduction of the ozone layer, such as the ODP, etc. For example, EP is related to fertilizers used, and HHP are a main concern in plywood production.

Potential for GWP savings when substituting wood for other material is substantial. However, the scope of this study was limited to the structural materials in buildings, which account for approximately 8-10% of the total cost of hospitals and 25-30% of the cost in office buildings (Taghavi and Miranda 2003). Therefore, an analysis of the different architectural materials could also be performed to put their contributions to the overall building impacts in better perspective. There are other economic drivers for choice of building materials; therefore, a cost-based analysis would qualify the results of this study.

CONCLUSIONS

Wood utilization for the structural systems of commercial buildings is low compared with other building materials, such as steel and reinforced concrete. The purpose of this study was to assess and compare the environmental impacts of using wood instead of other materials via a LCA methodology with the Athena IE4B. In a direct wood substitution approach, six case study buildings of various construction types were modeled in Athena IE4B using the original materials, and then the gravity system of each building was substituted by wood materials. A BOM approach was also used, and applied only to a one-story, medical office building. BOMs were obtained from the structural drawings of the original building; and for a current code-based conventional wood redesign of the building.

GWP, TPE, FFC, and other measures were examined. GWP savings were achieved across all the case studies using the direct wood substitution approach, with the largest savings occurring in the Product and Beyond Building Life stages. Substituting concrete with wood floor assemblies in high volume resulted in the highest GWP savings. Considerable energy savings were achieved via the direct wood substitution approach for all six buildings. Wood substitution resulted in FFC energy savings due to the reduced energy demand and the use of wood energy during the Product stage of the wood materials. The Product stage accounted for most of the energy used. As expected, utilization of wood products drives up the use of wood-based energy.

Code-based redesign in conventional wood products decreased the total impact on the environment, resulting in negative GWP from carbon sequestration. The conventional wood redesign scenario resulted in higher TPE consumption than the original design scenario, but the FFC was smaller for the wood case. Some other impact categories result in an increased impact due to wood utilization via the BOM approach, which means that with the current wood processing methods, there are trade-offs in achieving the GWP savings due to wood utilization.

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