Evaluating Sustainability of Buildings Using Multi-Attribute Decision Tools

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Abstract

Developing tools and methodologies for the evaluation of sustainable buildings is essential to promote transparency in the building design community. Building sustainability includes attributes from the built, natural, and social systems and inherently requires a series of trade-offs. These complex and often competing priorities require consideration at each stage of a building's life cycle.

A total of 24 environmental, social, and economic indicators were developed and applied to three alternative building systems: cross-laminated timber (CLT), steel and glass, and reinforced concrete.

The goal of this study was to demonstrate the use of a multi-attribute decision support system (MADSS) that uses a series of indicators, assigns numerical values to these indicators, and then allows for systematic evaluation and ranking of alternatives. A case study approach was used to demonstrate the utility of the MADSS approach in identifying ''hot spots'' and trade-offs for the three building systems. Portland, Oregon, was selected as the location for the alternative buildings. The functional unit for this study was a mixed-use nine-story building with an area of 19,000 ft^2. All processes from extraction of raw materials to end-of-life operations were considered in this study. The CLT building was found to have a higher rank compared with concrete and steel in all three attributes of environmental, economic, and social sustainability.

The results of this study are intended to serve as a demonstration of the MADSS tool for building systems and to identify hot spots in the various indicators utilized for sustainability evaluation. The ranking of environmental, social, and economic attributes of building materials on specific indicators will vary with the interests of stakeholders and the building's location, type, design, and other factors.

For long-term investors, property is typically expected to perform two functions in a portfolio: provide diversification benefits and long-term sustainable income. For this reason, long-term investors should be aware of the environmental and social global trends that are increasingly affecting the property industry, with potentially significant impacts to a portfolio in the years to come. The world needs more energy and housing to enable continued economic development and population migration. By 2035, the International Energy Agency (2007) estimates that energy demand could increase more than 30 percent. This is due predominantly to global trends, such as the growing global population, the expanding economies of developing countries, and urbanization (Pivo and McNamara 2005). Producing more energy will generate a host of environmental, social, and economic costs. Anticipating these costs, we need to evaluate property development alternatives with the goal of minimizing energy consumption in the construction and occupation of buildings.

The construction and operation of buildings is responsible for the consumption of up to 40 percent of global energy use, causing at least one-third of greenhouse gas emissions due to construction-related activities (Pérez-Lombard et al. 2008, Robertson et al. 2012). Meeting the demand for more energy while avoiding the environmental, economic, and social threats posed by growing fossil fuel use is a challenge for the sustainable development of buildings.

Sustainably managed forests sequester carbon in the near and long term and also provide durable wood products for housing, offices, and public buildings. Traditional dimension lumber and panel production used in ''stick-built'' construction has limitations for multistory commercial housing designs. In contrast, cross-laminated timber (CLT) has been used in midrise construction (6- to 12-story buildings) and offer an option for lowering the economic and environmental costs associated with midrise buildings (Lehmann 2013).

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Building sustainability involves various relations between built, natural, and social systems and an associated series of trade-offs at each stage of a building's life cycle (Conte and Monno 2012). To cope with this complexity, systematic, holistic, and practical approaches to sustainable building design need to be developed (Vilcekova et al. 2015).

No clear criteria exist for evaluating building sustainability that include environmental, social, and economic attributes, and measuring and weighting potential criteria remains unresolved (Yang et al. 2008). However, several tools and methodologies have been developed for the analysis of complex systems and trade-offs. Multi-criteria decision analysis (MCDA) can be described as ''a collection of approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter'' (Belton and Stewart 2002). According to Scott et al. (2012), the purpose of a decision support system is not to replace the decision maker but rather to aid the decision-making process by presenting complex, interlinked data in a way that allows the impacts of different choices to be more clearly understood.

MCDA is a practical tool and has useful features for evaluating complex problems, such as dealing with mixed sets of quantitative and qualitative data, including expert opinions and public input. The structure of MCDA enables a collaborative environment for decision making and accommodates the participation of multiple stakeholders (Belton and Stewart 2002, Mendoza and Prabhu 2009). Group decision making in MCDA involves identification of participants, providing information to decision-making participants to enable contributions, and aggregation of information provided by the participants (Mendoza and Martins 2006).

The multi-attribute decision support system (MADSS) tool and methodology has been previously used to evaluate environmental, social, and economic attributes for agricultural management systems and for bioenergy case studies (Pelzer et al. 2012, Vasileiadis et al. 2013, Radics et al. 2015, Parish et al. 2016). Pelzer et al. (2012) and Vasileiadis et al. (2013) developed DEXi Pest Management for ex ante assessment of sustainability of cropping systems. The studies combined expert surveys with the multi-criteria assessment tool (DEXi Pest management) to evaluate the environmental, economic, and social sustainability of maize systems. Radics et al. (2015) and Parish et al. (2016) developed and applied a suite of 35 indicators, including environmental, economic, and social attributes, using a MADSS framework to compare the sustainability of bioenergy production systems across different feedstock types.

Based on the lack of holistic criteria and the availability of a variety of tools used for decision making, the goal of this study was to demonstrate the use of a specific MADSS tool and methodology. The MADSS tool allows for the development of a set of 24 sustainability indicators, 8 subcategories, and 3 sustainability attributes useful for buildings. The MADSS tool is also used for the combination of these indicators into subcategories and then attributes, ranking of attributes (environmental, economic, and social sustainability), and group decision making through an iterative process for alternative building systems. A midrise CLT building and comparable reinforced concrete construction (RCC) frames and steel frames (SF) are used as alternative construction materials for the comparison buildings. RCC and SF are commonly used materials in midrise building construction, while CLT is attracting growing interest in the US building community for midrise building construction.

Materials and Methods

Developing the MADSS structure

In this study, we used a commercial software package to conduct the MADSS analysis. The DEXi software is designed for complex decision problems and allows for both expert judgment and group decision making. It can also use a combination of quantitative or qualitative data and can accommodate incomplete or missing data (Bohanec 2011).

In this work, the MADSS approach was based on six steps. Each step can be conducted with input from both ''expert'' and ''nonexpert'' stakeholders. This model uses a hierarchical tree structure to measure attributes that are the highest branch in hierarchy. These attributes are measured through subcategories (second branch in hierarchy) and indicators (lowest branch in the hierarchical tree structure). The structure of the MADSS analysis conducted in this work is shown in Figure 1.

The six steps of the MADSS approach include the following:

1. Definition of the goals of the case study and agreement on the features of interest, such as all three sustainability attributes (environmental, economic, and social) or a narrower subset of interest to a particular aspect of the case study.
2. Identification of the indicators used to characterize the case study. Ideally, these indicators should draw on prior work or analytical structures relevant to the case study, but they may also include features of unique interest to the group.
3. Structuring the indicators into subcategories that are balanced and that represent the features of interest for the case study. The subcategories are then combined to inform the attributes of interest.
4. Assignment of a ''scale'' for each indicator. The scale may be quantitative (e.g., dollars, mass, temperatures, Btu) or qualitative (e.g., visual appearance, biodiversity). Because DEXi is best suited as a screening tool, the ranking scale can be a simple 3-point scale.
5. Creation of a utility table that defines the impact of different combinations of indicators on the subcategory (e.g., determining the ranking of two indictors with high marks combined with one low mark). The utility may also be ''weighted'' to emphasize specific subcategories or attributes to make some feature ''more important'' than other features.
6. Review of the DEXi output to verify the internal consistency and then analysis and discussion on the trade-offs and ''hot spots.''

The structure of the MADSS analysis conducted in this work is shown in Figure 1. The building system of interest is a CLT building and was compared with two more traditional building systems: an RCC and an SF. Advocates of CLT have identified a series of potential environmental and social values (Falk 2013) associated with this type of building construction. Potential environmental values include the use of renewable materials and low water use during product manufacturing, while social values might include local

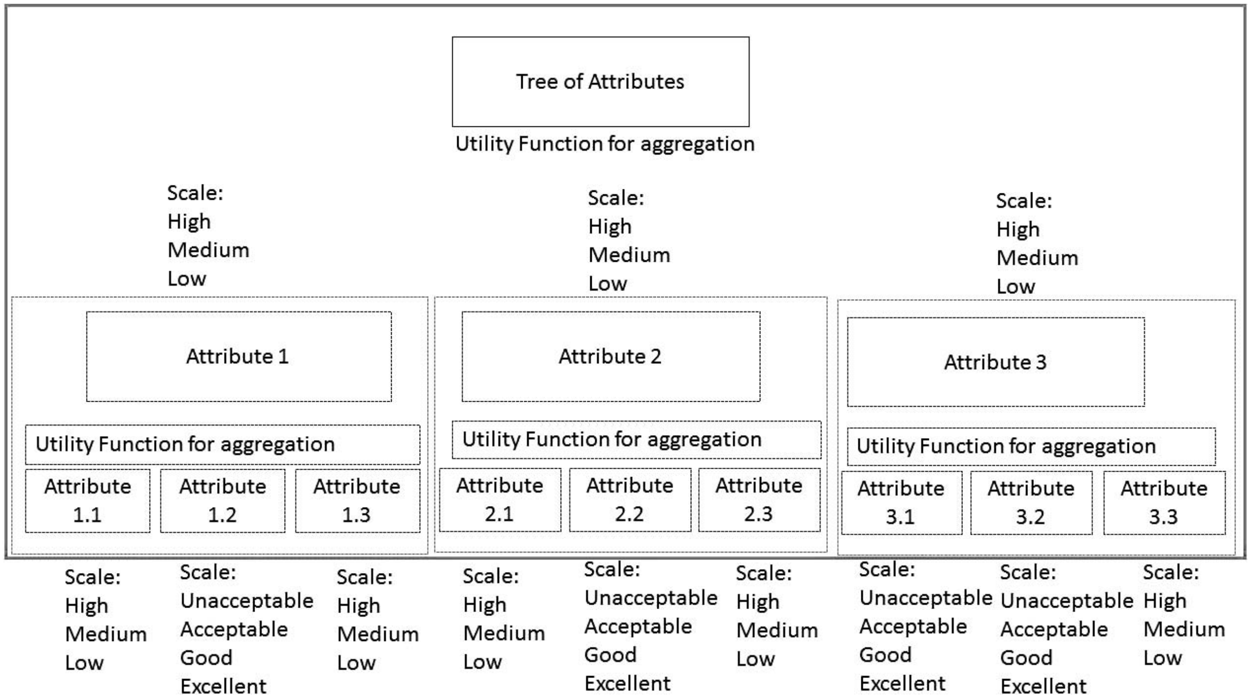

Figure 1.—Graphical representation of the DEXi multiattribute decision support system (MADSS) tool used in the study. The scales provided in this figure are examples of ratings that can be used in the tool.

manufacturing jobs in rural communities and the improved mental health of the building's occupants (Fell 2010, Nyrud and Bringslimark 2010, Burnard and Kutnar 2015). This case study included all three sustainability attributes (environmental, economic, and social) and weighted all three attributes equally. The indicators are the foundation of the MADSS. The indicators feed information into the subcategories, which are then combined into attributes that provide a complete view of the system. For example, in this case study, the environmental attribute includes three subcategories: (1) water use, (2) energy use, and (3) materials use and disposal. The water use subcategory has indicators including use (1) in the production of raw materials, (2) during construction, and (3) during occupancy. The hierarchy used for this work is shown in Figure 2. These indicators need a common definition across all the cases being studied, but the specific ranking of each of these indicators can be defined as needed to meet the goals of the analysis and features of interest. The definitions for all the indicators used in this work are shown in Appendix A.

The indicator scale used in this work was a mixture of quantitative and qualitative features, but all of the indicators were reduced to a 3-point scale with 3 indicating the best feature and 1 the lowest score. This work did not use a rank ordering, which forces differentiation between the cases (Reeb et al. 2016). Rather, this work used an ''absolute'' scale, which allows all three cases to simultaneously be low or high (Bohanec et al. 2007).

The utility table (shown in Appendix B) connects the indicators and their scores with the relative ranking of the subcategories and attributes for the three cases studied here: CLT, RCC, and SF building systems. Creation of the utility table requires key decisions by stakeholders on how to balance trade-offs between indicators. For example, if the water use subcategory has indicators including use (1) in the production of raw materials, (2) during construction, and (3) during occupancy, and if a specific case is ''good'' or ''high'' on all three indicators, then the resulting subcategory is also ''good'' or ''high.'' If all three indicators are ''low'' or ''bad,'' then the subcategory would also be ''low'' or ''bad.'' The complexity arises when two indicators are ''high'' and one is ''low.'' The stakeholders will need to define the subcategory score for the utility table in this type of situation. Because the DEXi tool is most useful as a screening tool to identify hot spots, this assignment is likely to be based on a consensus opinion rather than some analytical tool. Finally, the results need to be reviewed for internal consistency. One of the main benefits to using a tool such as DEXi is the ability to involve stakeholders at all levels of decision making. The stakeholders can help define the indicators, help with the evaluation of a specific case, or participate in the analysis of hot spots and trade-offs.

With this introduction to the MADSS concepts and the DEXi tool, in the next section we discuss the application of the DEXi tool in a case study evaluating the overall sustainability of three different building materials.

Developing the attributes, subcategories, and indicators used in this case study

The sustainability of three buildings with frames made of different materials was evaluated for their environmental, economic, and social attributes. The functional unit for this study is a mixed-use nine-story building with an area of 19,000 ft^2 in Portland, Oregon. The location was chosen because of the state's interest in developing CLT buildings as an environmentally preferred material and at the same time its interest in deriving social benefits by creating jobs in timber-dependent communities in Oregon (OregonBest 2016).

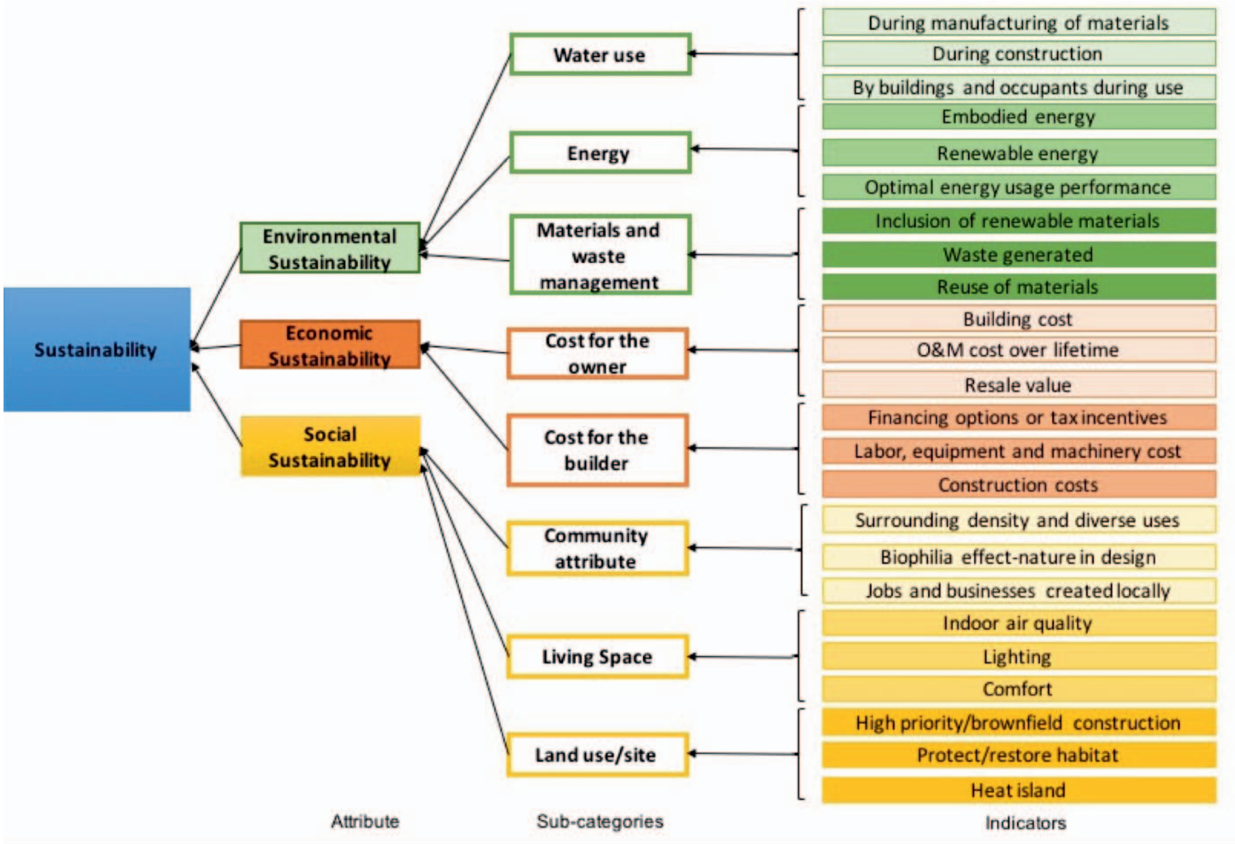

Figure 2.—Building sustainability tree framework where environmental, economic, and social sustainability are measured through indicators. (Color version is available online.)

Comparative buildings made from CLT, RCC, and SF are considered for this study. To allow for side-by-side comparisons of the three buildings, all three buildings were based on a common mixed-use design, with about 50 percent of the space designated for commercial use and 50 percent for housing use. The core and shell structures had similar floor plans; interiors; furnishings; material-specific insulation; heating, cooling, and ventilation; and glazing. Critical for this case study, the energy use by occupants was assumed to be equal for all three designs. All processes—extraction of raw materials, transport of raw materials, manufacturing units and materials, construction site, construction of buildings, operation and use, and deconstruction and end-of-life operations—were considered in this study.

The economic, environmental, and social attributes of the buildings were based on a series of 24 indicators. The environmental indicators were based on the long-standing criteria included in building rating systems, such as Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM). These criteria are well developed and use a prescriptive set of criteria focused on neighborhood, environment, materials, and the interior fixtures of buildings (Baldwin et al. 1998, US Green Building Council 2005). These rating systems award points based on the prescribed criteria with a heavy emphasis on environmental impacts and little or no emphasis on social and economic impacts. Grouping the LEED rating system checklist broadly into environmental, social, and economic attributes helped identify the lack of economic indicators available in LEED (Table 1). Pivo (2008) noted this lack of social and economic criteria in LEED when he compiled 66 criteria on sustainability and social responsibility in property and included topics such as location, public facilities and services, design and environment, operations and maintenance, and occupant behaviors. However, this work also neglected economic attributes. A combination of the LEED criteria with the criteria provided by Pivo (2008) was used to create environmental and social indicators used in this work. Pivo (2008) condensed the list of 66 criteria into 10 dimensions of environmental and social categories. Table 1 shows the comparison between the 10 dimensions from the Pivo (2008) study, LEED 4.1 ratings, and the new indicators created in this study for environmental, social, and economic categories. As much as possible, this work built on the LEED and Pivo criteria, although some dimensions, such as worker well-being and local citizenship, do not have corresponding unambiguous comparisons with the LEED 4.1 categories.

The use of this prior work is one example of Step 2 in the MADSS process, where we drew on the well-established LEED criteria and prior work; for example, Pivo is developing indicators for this case study. In addition, this work included economic indicators that included financial and investment considerations. Based on this prior work, a set of 24 environmental, social, and economic indicators were identified for this case study.

Table 1.—Pivo's (2008) dimensions and LEED 4.1 ratings for new construction checklist grouped into environmental and social attributes with the new indicator list created in this study.[a]

Category	Pivo's (2008) 66 indicators combined into 10 dimensions	LEED 4.1 scales combined into environmental and social categories	Indicators created in this study	
Environmental	Energy conservation	Optimize energy performance, renewable energy production + green power, sourcing + material ingredients + C&D waste, interior lighting and daylight, thermal comfort + acoustic performance	Water use	During manufacture, during construction, by buildings and occupants during use
	Urban revitalization	High-priority (brownfield), surrounding density and use, site development—protect or restore habitat	Energy	Embodied energy, renewable energy, optimal energy usage performance
	Environmental protection	Indoor + outdoor + cooling tower water use, rainwater management, heat island	Materials and waste management	Inclusion of renewable materials, waste generated, reuse of materials
	Health and safety	Enhance IAQ + low-emitting materials + IAQ assessment		
Social	Corporate citizenship	Enhanced commissioning	Community attribute	Surrounding density and diverse uses, biophilia effect: nature in design, jobs and businesses created locally
	Credentialing	LCA + EPD		
	Worker well-being		Living space	Indoor air quality, lighting, comfort
	Local citizenship			
	Social equity and community development		Land use/site	High-priority/brownfield construction, protect/restore habitat, heat island
	Less automobile dependent	Access to quality transit		
Economic	NA	NA	Cost for the owner	Building cost, O&M cost over lifetime, resale value
			Cost for the builder	Financing options and tax incentives, labor, equipment and machinery cost, construction cost

[a] C&D = construction and demolition; IAQ = indoor air quality; LCA = life-cycle assessment; EPD = environmental product declarations; NA = not applicable; O&M = operations and maintenance.

Once the indicators were developed in MADSS, they were rated on a 3-point scale (with 1 meaning low performance in the attribute, 2 being intermediate performance, and 3 being high performance) based on consensus among authors and building professionals with knowledge of building materials and construction, sustainability supply chain and logistics, literature survey, and expert opinions. The experts were identified through participation in bio-based materials sustainability conferences and life-cycle assessment (LCA) seminars and included industry professionals, experts from not-for-profit agencies, and academics. The experts identified had overall knowledge of the construction industry and building materials studied here in addition to sustainability principles and LCA topics. The experts rated the 24 indicators on a scale provided and also rated the subcategories and attributes to measure sustainability. A modified Delphi approach was used to achieve consensus among the expert panels (Clayton 1997, MacMillan and Marshall 2006).

Results and Discussion

This section shows the results of comparing RCC and SF buildings using the MADSS approach described in ''Materials and Methods.'' The indicator rating scale was developed on the basis of a compilation of expert opinions and scientific literature. The utility function, which defines the relationship between the indicators and the subcategory level of the hierarchical tree to the higher level (e.g., indicator level to subcategory level), was also developed as follows:

1. If the indicator ratings were either all low or mixed with a majority of low values, then a low value was assigned to the aggregate indicator or the subcategory. For example, for the water use indicator, if the subcategories of during manufacture, during construction, and by buildings and occupants during use were all assigned low values, the water use indicator was assigned a low value for the CLT building type.
2. If the indicator ratings were all high or mixed with a majority of high values, then a high value was assigned to the subcategory. For example, for the water use indicator, if the subcategories of during manufacture, during construction, and by buildings and occupants during use were all assigned high values or a mix of high and medium values, the water use indicator was assigned a high value for the RCC building type.
3. If the indicator ratings were mixed low values or intermediate, then an intermediate value was assigned

to the subcategory. For example, for the community attribute indicator, the subcategory surrounding density and diverse uses was given an intermediate rating, the biophilia subcategory was given a low rating, and jobs and businesses created was given a low rating for the RCC building type. This created an overall intermediate rating in the community attribute indicator for the building type.

4. If the indicator ratings were all intermediate, then an intermediate value was assigned to the subcategory. For example, in the SF building type, for the indicator cost for the builder, the subcategories of financing options, labor and equipment cost, and construction cost were all assigned medium values, leading to an aggregated rating of intermediate.

We also validated the ranking provided by experts with a survey of the available literature on the three building materials and synthesized it to a 3-point scale in MADSS. Available environmental product declarations for CLT, concrete, and reinforced steel and structural steel were utilized for validating the ranking the indicators of water use during manufacture and construction, embodied energy, renewable energy, waste generated, and inclusion of renewable materials (Institut Bauen und Umwelt 2012, Cementos Argos 2014). Operational energy and water use for CLT, RCC, and SF buildings was obtained from studies that analyzed life-cycle energy consumption (Xing et al. 2008, Chen 2012).

In the economic sustainability attribute, the building cost, operations and maintenance costs, and resale value are given high ratings based on data from Zumbrunnen and Fovargue (2012). In this case, new market tax credits, a federal tax benefit that encourages private investment in communities with high poverty and unemployment, were applied to the local production of CLT. New market tax credits have been secured for several wood building projects in Oregon (Ecotrust 2014), and these credits will enhance the financial return of the CLT building while providing jobs and income in low-income rural communities. CLT has the potential to spur investment in local wood but also to bring about more passive-design, zero-net-energy homes (Foster et al. 2010). The labor, equipment, machinery, and construction costs were rated based on conversations with construction professionals (US Forest Service 2015).

Because all three buildings were modeled as having the same basic features in terms of landscape, site, transportation availability, and recreational facilities, a majority of indicators under social sustainability were modeled similarly for all three buildings. CLT buildings scored higher on indicators such as comfort, biophilia effect, and protecting or restoring habitat. This is owing to the inherent renewable nature of CLT. Natural environments have been shown to have positive effects on psychological well-being (Hartig et al. 1997, Tyrväinen et al. 2014).

The authors assigned indicator ratings for all three building comparisons by collecting expert opinions and, based on the rules described in this section, developed the utility table. Appendix B provides the utility function table for the comparison of the three types of buildings.

The results of the MADSS evaluation using the DEXi tool are shown in Table 2. The overall sustainability and the environmental, economic, and social attributes are all provided. The scale for the rankings, as indicated above, ranged from 1 to 3 (bad to good) for all of the attributes measured. Table 2 shows the rankings provided for all the subcategories and the attributes in this study. Overall sustainability is a measure of the rankings from all three attributes (environment, economic, and social), and the eight subcategories add up to the attributes. The indicator level rankings are shown in Appendix B. These rankings are graphically represented in Figures 3a through 3d.

Figure 3a shows the overall sustainability rankings for each of the three building systems. The building system made of CLT had the highest rating (3, represented by the largest triangle) for the environmental and social attributes and the lowest (1, represented by the smallest triangle) for the economic attribute of the three buildings evaluated. This is because of the overall high ranking in environmental and social sustainability subcategories, such as water use, energy, materials, and waste management, and the social subcategories, where the performance of CLT buildings is higher. Figures 3b through 3d show the performance of the three building systems for the more detailed subcategories for the environmental, economic, and social attributes.

Figure 3b shows that the CLT building has the best environmental performance compared with the other two buildings. This is owing to the assumption that a sustainably managed forest maintains environmental benefits while providing lumber for CLT buildings, low embodied energy, and use of renewable fuels (mill residues for drying) during manufacture. These benefits are a result of the inherent renewable nature of wood and minimal use of fossil fuels during plantation and harvesting and the low quantity of waste generated for CLT buildings because they are generally prefabricated in a manufacturing unit and assembled at a construction site. A simple back-of-the-envelope calculation shows that the dimension lumber needed for manufacturing CLT for this building would be produced in 1 to 2 days from an ''average'' Oregon sawmill.

Table 2.—Rankings for attributes measuring overall sustainability and subcategories measuring environmental, economic, and social attributes.[a]

Subcategories	CLT building	RCC building	SF building
Sustainability			
Environmental	3	1	2
Economic	1	2	2
Social	3	2	2
Environmental sustainability			
Water use	3	1	2
Energy	3	1	1
Materials and waste management	3	2	2
Economic sustainability			
Cost for the owner	1	2	2
Cost for the builder	3	2	2
Social sustainability			
Community attribute	2	2	2
Living space	3	3	3
Land use/site	3	2	2

[a] The 3-point scale indicates 3 is the best or highest feature and 1 is the lowest score. CLT = cross-laminated timber; RCC = reinforced concrete construction; SF = steel frame.

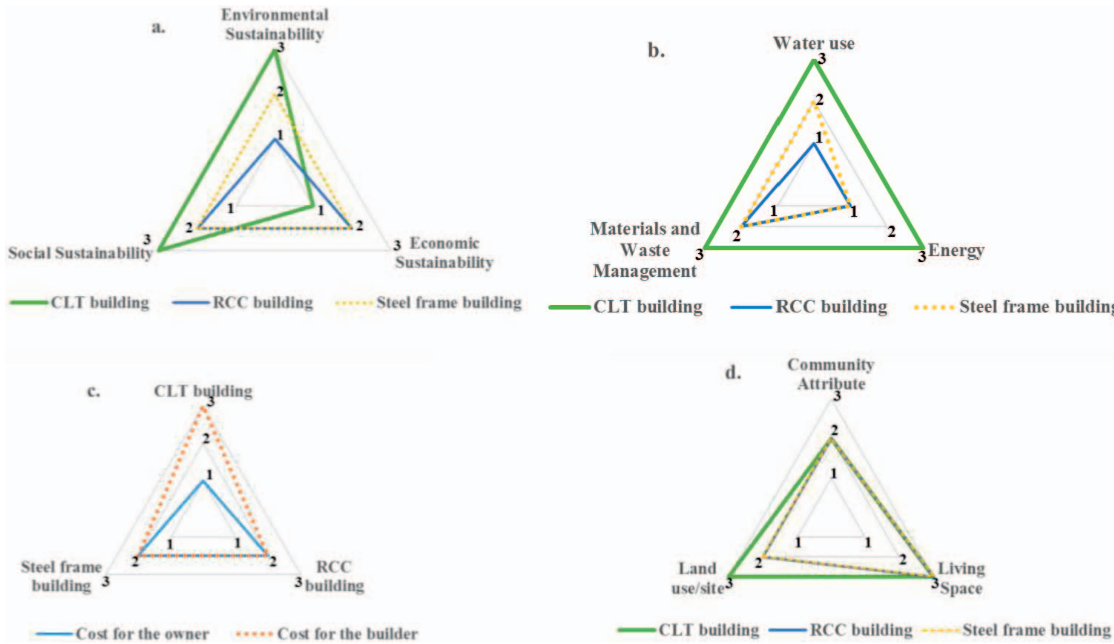

Figure 3.—Sustainability evaluation of cross-laminated timber (CLT), reinforced-concrete construction (RCC), and steel frame buildings on a scale of 1 to 3 (bad to good). (a) Overall sustainability. (b through d) Breakdown of the buildings' sustainability into subcategories. (Color version is available online.)

Thus, there was no concern about the demand for CLT creating unsustainable demand on forests.

Figure 3c shows the breakdown of the performance of the building systems in terms of their economic sustainability. The CLT buildings have the lowest economic sustainability attribute in comparison to RCC and SF buildings. Even though CLT has been widely used in Europe, widespread adoption in the United States requires further exploration of barriers and opportunities in the CLT markets. Currently, there are two functional plants in operation in the United States producing CLT, with only one plant certified for building construction (Dramm 2015). Based on consultations with engineers and architects with construction experience and knowledge of steel or concrete and CLT, the factors for increased cost to owners and builders of CLT buildings include the availability of CLT panels in the United States versus importing panels, transportation fees, the learning curve associated with building with a new product, and the availability of trained labor and machinery. On the other hand, the markets for SF and RCC buildings are already well established, thus having higher economic sustainability attributes than CLT. A variety of federal tax credits are available for the use of renewable materials (Arundel 2008) that benefit using CLT as a building material over steel and concrete, but the initial costs of CLT panels when the market is still emerging overshadow the federal tax credits available.

Figure 3d shows the sustainability of buildings in the social sustainability attribute. CLT has better performance than RCC and SF buildings in this attribute. Although all buildings have similar indoor air quality and lighting and provide similar benefits to the neighborhood, CLT buildings score higher on indicators such as biophilic design, an innovative method to incorporate nature into manmade environments (Kellert et al. 2011) and protect and restore habitat because of the inherent renewable nature of the building material. The potential for the rapid assembly of CLT buildings and a reduction in disruption to neighbors and traffic has been shown with some initial buildings (Kremer and Symmons 2015) but was not included as a social benefit. Using wood as a building material produced from sustainably managed forests also helps protect habitats in comparison to manufacturing and using steel and concrete (Lippke et al. 2007). For indicators such as brownfield construction and the heat island effect (defined in Appendix A), all three building materials were given the same rating scale of high and low, respectively.

Conclusions

This study intended to demonstrate the use of the MADSS tools and methodology for building systems. This work also focused on a new building system, CLT, that has the potential to create unique environmental and social benefits. Clearly, the indicators can be changed to meet the interests and priorities of a different set of stakeholders, and the scores can change as the CLT system is further developed and more data become available.

In this work, a list of 24 environmental, social, and economic indicators; 8 subcategories; and 3 attributes were developed from prior work by LEED and Pivo (2008). Expert opinions and literature data were then used to obtain ratings for these indicators (aggregated to subcategories and attributes using the utility table) for the CLT, RCC, and SF building systems. CLT buildings processed from sustainably managed forests have several positive environmental attributes compared with RCC and SF building designs. The results of this study also show the benefits to society of using CLT, although the initial costs of using CLT might be higher owing to the lack of an established market.

This study is intended to be an initial analysis to identify hot spots in the various indicators utilized for evaluation. For example, the water use in an SF building has a medium rating, and providing water-saving measures during manufacturing, construction, or use of buildings by occupants might increase the score of the water use subcategory to a high rating. Similarly, the current high cost of using CLT may decrease rapidly as a manufacturing base is developed and the local construction industry gains experience.

This study is an effort to provide an integrative assessment of environmental, economic, and social attributes of CLT, RCC, and SF buildings. The MADSS model draws on various disciplines, including engineering, architecture, economics, and environmental science, and in the process converts into a qualitative scale their underlying principles and influence on CLT, RCC, and SF building systems. The indicators and scores, and consequently the results, may change if the context, location, building type or design, and other factors are altered owing to the subjective nature of this model. A complete environmental LCA and socioeconomic analysis of a CLT building would be valuable to detail the specific environmental impacts and the economic and social impacts of construction in a specific location. The multi-criteria decision-making tools identify the areas where further sensitivity analysis needs to be conducted. A combination of holistic sustainability indicators, LCA, and multi-criteria decision-making tools provides the decision maker with the ability to allocate resources appropriately on issues of interest and to reduce data burdens associated with conducting whole-building LCA and cost analysis.

Literature Cited

American Iron and Steel Institute. 2016. SteelWorks: The online resource for steel. https://www.steel.org. Accessed May 8, 2016.

Arundel, J. D. 2008. New markets tax credits. Tulane Law School Annual Institute on Federal Taxation. Vol. 19, No. 57. p. 1.

Baldwin, R., A. Yates, N. Howard, and S. Rao. 1998. BREEAM 98 for offices: An environmental assessment method for office buildings. Construction Research Communications Ltd. pp. 1–36.

Belton, V. and T. Stewart. 2002. Multiple Criteria Decision Analysis: An Integrated Approach. Kluwer, Boston.

Bohanec, M. 2011. DEXi: Program for Multi-Attribute Decision Making User's Manual version 3.03. IJS Report DP-10707. Jozef Stefan Institute, Ljubljana, Slovenia.

Bohanec, M., J. Cortet, B. Griffiths, M. Žnidaršič, M. Debeljak, S. Caul, J. Thompson, and P. H. Krogh. 2007. A qualitative multi-attribute model for assessing the impact of cropping systems on soil quality. *Pedobiologia* 51(3):239–250. http://dx.doi.org/10.1016/j.pedobi.2007.03.006

Burnard, M. D. and A. Kutnar. 2015. Wood and human stress in the built indoor environment: A review. *Wood Sci. Technol*. 49(5):969–986. http://doi.org/10.1007/s00226-015-0747-3

Cementos Argos. 2014. Environmental Product Declaration for Concrete. Cementos Argos, Alpharetta, Georgia. https://www.argos.co/usa

Chen, Y. J. 2012. Comparison of environmental performance of a five-storey building built with cross-laminated timber and concrete. Thesis. Sustainable Building Science Program, Department of Wood Science, University of British Columbia, Vancouver.

Clayton, M. J. 1997. Delphi: A technique to harness expert opinion for critical decision-making tasks in education. *Educ. Psychol*. 17:373–386.

Conte, E. and V. Monno. 2012. Beyond the buildingcentric approach: A vision for an integrated evaluation of sustainable buildings. *Environ. Impact Assess. Rev*. 34:31–40. http://dx.doi.org/10.1016/j.eiar.2011.12.003

Crespell, P. and S. Gagnon (Ed.). 2010. Cross laminated timber: A primer. Special Publication 52. FPInnovations, Quebec.

Dramm, R. 2015. CLT supply chain: ''From forest to market.'' USDA Forest Products Laboratory, Madison, Wisconsin.

Ecotrust. 2014. New market tax credits. http://www.ecotrust.org/press-releases/ecotrust-awarded-35-million-in-new-federal-tax-credits. Accessed May 31, 2016.

Espinoza, O., V. R. Trujillo, M. F. L. Mallo, and U. Buehlmann. 2015. Cross-laminated timber: Status and research needs in Europe. *BioResources* 11:281–295.

Falk, A. 2013. Cross-laminated timber: Driving forces and innovation. *Struct. Arch. Concepts Appl. Challenges*. pp. 511–518.

Fell, D. R. 2010. Wood in the human environment: Restorative properties of wood in the built indoor environment. Dissertation. University of British Columbia, Vancouver.

Foster, D., J. Aber, C. Cogbill, C. Hart, E. Colburn, A. D'Amato, B. Donahue, C. Driscoll, A. Ellison, T. Fahey, B. Hall, M. Hunter, L. Irland, W. Keeton, D. Kittredge, K. Lambert, J. Levitt, R. Lilieholm, D. Orwig, and J. Thompson. 2010. Wildlands and Woodlands: A Vision for the New England Landscape. Harvard University Press, Cambridge, Massachusetts.

Gagnon, S., E. M. Bilek, L. Podesto, and P. Crespell. 2013. CLT: Introduction to cross-laminated timber. FPInnovations, Quebec. pp. 1–45.

Guggemos, A. and A. Horvath. 2005. Comparison of environmental effects of steel- and concrete-framed buildings. *J. Infrastruct. Syst*. 11:93–101. DOI:10.1061/(ASCE)1076-0342(2005)11:2(93)

Hartig, T., K. Korpela, G. W. Evans, and T. Gärling. 1997. A measure of restorative quality in environments. *Scand. Housing Plann. Res*. 14:175–194. DOI:10.1080/02815739708730435

Institut Bauen und Umwelt. 2012. EPD KLH solid timber panels. Declaration number EPD-KLH-2012111-E. Konigswinter, Germany.

International Energy Agency. 2007. Key World Energy Statistics. International Energy Agency, Paris.

Kellert, S. R., J. Heerwagen, and M. Mador. 2011. Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life. John Wiley & Sons, New York.

Kremer, P. D. and M. A. Symmons. 2015. Mass timber construction as an alternative to concrete and steel in the Australia building industry: A PESTEL evaluation of the potential. *Int. Wood Prod. J*. 6(3):138–147.

Lehmann, S. 2013. Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions. *Sustain. Cities Soc*. 6:57–67. http://dx.doi.org/10.1016/j.scs.2012.08.004

Lippke, B., J. Comnick, and L. R. Johnson. 2007. Environmental performance index for the forest. *Wood Fiber Sci*. 37:149–155.

MacMillan, D. C. and K. Marshall. 2006 The Delphi process—An expert-based approach to ecological modelling in data-poor environments. *Anim. Conserv*. 9:11–19.

Mendoza, G. A. and H. Martins. 2006. Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. *Forest Ecol. Manag*. 230:1–22.

Mendoza, G. A. and R. Prabhu. 2009. Evaluating multi-stakeholder perceptions of project impacts: A participatory value-based multi-criteria approach. *Int. J. Sustain. Dev. World Ecol*. 16:177–190. DOI:10.1080/13504500902919672

Nyrud, A. Q. and T. Bringslimark. 2010. Is interior wood use psychologically beneficial? A review of psychological responses toward wood. *Wood Fiber Sci*. 42(2):202–218.

OregonBest. 2016. Tall wood buildings. http://oregonforests.org/Tallwood. Accessed May 8, 2016.

Parish, E. S., V. H. Dale, B. C. English, S. W. Jackson, and D. D. Tyler. 2016. Assessing multimetric aspects of sustainability: Application to a bioenergy crop production system in East Tennessee. *Ecosphere* 7(2):e01206.

Pelzer, E., G. Fortino, C. Bockstaller, F. Angevin, C. Lamine, C. Moonen, V. Vasileiadis, D. Guérin, L. Guichard, R. Beau, and A. Messéan. 2012. Assessing innovative cropping systems with DEXiPM, a qualitative multi-criteria assessment tool derived from DEXi. *Ecol. Indic*. 18:171–182.

Pérez-Lombard, L., J. Ortiz, and C. Pout. 2008. A review on buildings energy consumption information. *Energy Build*. 40:394–398. http://dx.doi.org/10.1016/j.enbuild.2007.03.007

Pivo, G. 2008. Responsible property investment criteria developed using the Delphi method. *Build. Res. Inf*. 36:20–36.

Pivo, G. and P. McNamara. 2005. Responsible property investing. *Int. Real Estate Rev*. 8:128–143.
Radics, R., N. Rajagopalan, S. Dasmohapatra, and S. Kelley. 2015. Use of Multi-Attribute Decision Support System to Compare the Social, Environmental, and Economic Impacts of Using Woody Feedstocks for Pellet Production. (Unpublished.)
Reeb, C. W., R. Venditti, R. Gonzalez, and S. Kelley. 2016. Environmental LCA and financial analysis to evaluate the feasibility of bio-based sugar feedstock biomass supply globally: Part 2. Application of multi-criteria decision-making analysis as a method for biomass feedstock comparisons. *BioResources* 11(3):6062–6084.
Robertson, A. B., F. C. F. Lam, and R. J. Cole. 2012. A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete. *Buildings* 2:245–270.
Scott, J. A., W. Ho, and P. K. Dey. 2012. A review of multi-criteria decision-making methods for bioenergy systems. *Energy* 42:146–156.
Tyrväinen, L., A. Ojala, K. Korpela, T. Lanki, Y. Tsunetsugu, and T. Kagawa. 2014. The influence of urban green environments on stress relief measures: A field experiment. *J. Environ. Psychol*. 38:1–9. http://dx.doi.org/10.1016/j.jenvp.2013.12.005
US Forest Service. 2015. Mass Timber Research Workshop. US Forest Service, Madison, Wisconsin.
US Green Building Council. 2005. LEED-NC: Green Building Rating System for New Construction and Major Renovations. US Green Building Council, Washington, D.C.
Vasileiadis, V. P., A. C. Moonen, M. Sattin, S. Otto, X. Pons, P. Kudsk, A. Veres, Z. Dorner, R. Van der Weide, E. Marraccini, and E. Pelzer. 2013. Sustainability of European maize-based cropping systems: Economic, environmental and social assessment of current and proposed innovative IPM-based systems. *Eur. J. Agron*. 48:1–11.
Vilcekova, S., M. Kusnir, E. K. Burdova, and Z. Budaiova. 2015. Sustainability assessment of buildings. *J. Multidiscip. Eng. Sci. Technol*. 2(9):2609–2615.
World Business Council for Sustainable Development. 2015. Cement sustainability initiative. http://www.wbcsdcement.org/index.php/en/key-issues/water. Accessed May 8, 2016.
Xing, S., Z. Xu, and G. Jun. 2008. Inventory analysis of LCA on steel- and concrete-construction office buildings. *Energy Build*. 40:1188–1193. http://dx.doi.org/10.1016/j.enbuild.2007.10.016
Yang, J., P. S. Brandon, and A. C. Sidwell. 2008. Smart and Sustainable Built Environments. John Wiley & Sons, New York.
Yurtdas, I., H. Peng, N. Burlion, and F. Skoczylas. 2006. Influences of water by cement ratio on mechanical properties of mortars submitted to drying. *Cem. Concr. Res*. 36:1286–1293. http://dx.doi.org/10.1016/j.cemconres.2005.12.015
Zumbrunnen, P. and J. Fovargue. 2012. Mid-rise CLT buildings, The UK's experience and potential for Australia and New Zealand. *World* 15:19.

Appendix A

Description of indicators in the DEXi tree

1. Environmental sustainability
   a. Water use
      i. Water use during manufacturing—This indicator refers to the water consumed during manufacturing of the building's raw materials. This indicator specifically applies to manufacturing of wood (including growth and harvest), cement, and steel. All other materials, such as carpet, flooring, paint, and insulation, are considered to be providing a similar burden in all three buildings. Cement production requires water for cooling heavy equipment, for emissions control, and for preparing slurry in wet process kilns (World Business Council for Sustainable Development 2015). Steel manufacturing consumes between 45,000 and 65,000 gallons of water per ton of finished steel (American Iron and Steel Institute 2016).
      ii. Water use during construction—This indicator refers to the water used during construction of the building by the various processes. This indicator measures only water used by wood, concrete, and steel at the construction site. Concrete is a mixture of coarse and fine aggregates, cement, and water. The ratio of water to cement commonly used is 0.5 tons of water per ton of cement (Yurtdas et al. 2006).
      iii. Water use by buildings and occupants during the use phase—This indicator refers to the water used by the occupants of the building during its use phase. The building envelope influences the water required by the cooling towers.
   b. Energy
      i. Embodied energy—This indicator refers to the amount of energy consumed during the mining of natural resources, manufacturing, transport, and construction of the building. The embodied energy was reported as 2.93 and 3.91 GJ/m^2 for steel and concrete buildings, respectively, by Xing et al. (2008). Guggemos and Horvath (2005) reported values of 9.5 and 8.3 GJ/m^2 for steel and concrete buildings, respectively. Robertson et al. (2012) reported embodied energy values of 3.51 and 3.49 GJ/m^2 for RCC and CLT buildings, respectively. Different studies use dissimilar sizes and heights of buildings, causing variations in results.
      ii. Renewable energy—This indicator addresses the renewable energy consumed during the manufacturing, construction, and use of buildings. Renewable energy can be the use of biomass, wind, and solar as energy sources during the manufacturing, construction, and use of buildings.
      iii. Optimal energy usage performance—This indicator refers to the energy used during the operation and maintenance phase of a building. The material properties of the buildings influence the amount of energy consumed even if all buildings are manufactured with similar insulation capabilities.
   c. Materials and waste management
      i. Inclusion of renewable materials—This indicator refers to the inclusion of renewable materials in the building materials, thereby reducing the load on the extraction and manufacturing of virgin material. This can include recycled materials, such as fly ash or recycled steel, or renewable materials, such as wood used in manufacturing.
      ii. Waste generated—This indicator refers to the waste generated during construction processes related to the building. Solid and nonhazardous wastes are measured in this indicator.
      iii. Reuse of materials—This indicator refers to the potential for the reuse of materials after their useful life in buildings. Deconstruction of the building after its useful life or repurposing of materials during major renovations is also measured in this indicator.

2. Economic sustainability
   a. Cost for the owner
      i. Building cost—This indicator refers to the cost of designing, planning. and constructing a building. The longer it takes to design, plan, and construct a building, the costlier the building is. CLT buildings are prefabricated materials, thus saving on construction costs, and are an efficient method to construct, thus making it cost competitive with traditional materials, such as concrete and steel (Crespell and Gagnon 2010, Gagnon et al. 2013, Espinoza et al. 2015).
      ii. Operation and maintenance cost over lifetime—This indicator refers to the cost of operating and maintaining a building incurred by the owner.
      iii. Resale value—This indicator refers to the resale value of the property based on the condition of building, the preference for the building material, and the performance of the building over its lifetime
   b. Cost for the builder
      i. Financing options and tax credits—This indicator refers to the financing options available to the builder for constructing a building and depends on tax credits, such as new market tax credits or green building credits, available to the builder.
      ii. Labor, equipment, and machinery costs—This indicator refers to the labor, equipment, and machinery costs incurred by the builder for any specialized equipment and machinery required for construction. CLT buildings have fast construction times. In Europe, crews of two, four, or eight carpenters plus one or two mobile crane operators are used to produce outputs ranging from 1,000 to 8,000 ft^2/day (Crespell and Gagnon 2010).
      iii. Construction costs—This indicator refers to the costs incurred owing to materials price volatility, ease of construction, and specialized training required for personnel and the availability of local materials. The fast pace of construction of CLTs compared with steel and concrete structures reduces costs for the builder.
3. Social sustainability
   a. Community attribute
      i. Surrounding density and diverse uses—This indicator refers to the density of buildings and the publicly available diverse uses constructed or affected by the existing building (CLT, RCC, or SF)
      ii. Biophilia effect: nature in design—This indicator refers to the relationship between nature and the built environment. The incorporation of natural elements into the living space is considered in the building.
      iii. Jobs and businesses created—This indicator refers to the jobs and businesses created during the manufacturing, construction, operation, and subsequent maintenance of the building.
   b. Living space
      i. Indoor air quality—This indicator refers to the indoor air quality of the building based on the building materials.
      ii. Lighting—This indicator refers to the amount of indoor and outdoor lighting required for the building based on the building materials.
      iii. Comfort—This indicator refers to the thermal and acoustic comfort experienced by the residents of the building and is dependent on the building envelope of choice. It measures the thermal conductivity and sound reduction index of comparable wall sections.
   c. Land use/site
      i. High-priority and brownfield construction—This indicator refers to the type of site selected for construction.
      ii. Protect and restore habitat—This indicator refers to the habitat protection achieved by the building materials through manufacturing, use, and end of life.
      iii. Heat island—This indicator refers to the contribution of the building to the significant warming of surrounding areas based on the construction material.

Appendix B.—Utility table.[a]

Indicators	CLT building (rank)	RCC building (rank)	SF building (rank)
Sustainability	Intermediate (2)	Low (1)	Intermediate (2)
Environmental sustainability	High (3)	Low (1)	Intermediate (2)
Water use	Low (3)	High (1)	Medium (2)
During manufacture	Low (3)	High (1)	Medium (2)
During construction	Low (3)	High (1)	Medium (2)
By buildings and occupants during use	Low (3)	Medium (2)	Medium (2)
Energy usage	Efficient (3)	Inefficient (1)	Inefficient (1)
Embodied energy	Low (3)	High (1)	High (1)
Renewable energy usage	Significant (3)	Some (2)	Some (2)
Optimal energy usage performance	Optimized energy performance (3)	Some energy usage optimization (2)	Some energy usage optimization (2)
Materials and waste management	High (3)	Some (2)	Some (2)
Inclusion of renewable materials	High (3)	Medium (2)	Medium (2)
Waste generated	Low (3)	High (1)	High (1)
Reuse of materials	High (3)	Medium (2)	High (3)
Economic sustainability	Low (1)	Intermediate (2)	Intermediate (2)
Cost for the owner	High (1)	Medium (2)	Medium (2)
Building cost	High (1)	Medium (2)	Medium (2)
O&M cost over lifetime	Medium (2)	Medium (2)	Medium (2)
Resale value	Medium (2)	Medium (2)	Medium (2)
Cost for the builder	Low (3)	Medium (2)	Medium (2)
Financing options and tax incentives	High (1)	Medium (2)	Medium (2)
Labor, equipment, and machinery cost	Medium (2)	Medium (2)	Medium (2)
Construction cost	Medium (2)	Medium (2)	Medium (2)
Social sustainability	High (3)	Intermediate (2)	Intermediate (2)
Community attribute	Medium level of benefits from neighborhood (2)	Medium level of benefits from neighborhood (2)	Medium level of benefits from neighborhood (2)
Surrounding density and diverse uses	Some services are available (2)	Some services are available (2)	Some services are available (2)
Biophilia effect: nature in design	High (3)	Low (1)	Low (1)
Jobs and businesses created locally	High (3)	Low (1)	Low (1)
Living space	Many benefits (3)	Many benefits (3)	Many benefits (3)
Indoor air quality	Comfortable (3)	Comfortable (3)	Comfortable (3)
Lighting	Sufficient (3)	Sufficient (3)	Sufficient (3)
Comfort	High (3)	Medium (2)	Low (1)
Land use/site	High site protection (3)	Some site protection (2)	Some site protection (2)
High-priority/brownfield construction	High environmental improvement (3)	High environmental improvement (3)	High environmental improvement (3)
Protect/restore habitat	Habitat protected, restored, or improved (3)	No habitat protection (1)	No habitat protection (1)
Heat island	Low (3)	Low (3)	Low (3)

[a] CLT = cross-laminated timber; RCC = reinforced concrete construction; SF = steel frame; O&M = operations and maintenance.