Quantifying the Environmental, Social, and Economic Value of Educational Building Projects using BIM Data

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ABSTRACT

A recent report by the National Research Council of the National Academies (NRC) has defined the research on understanding and quantifying the environmental, social, and economic value of our infrastructure systems to their stakeholders as a "national imperative". There is still a lack of understanding and formalized modeling of what different stakeholders value (the values, e.g. energy conservation) in our infrastructure systems and how to valuate (i.e. quantify the worth) our infrastructure systems based on these values. In our previous work, we conducted theoretical and empirical studies to identify what different stakeholders value in educational buildings. In this paper, we focus on presenting our value quantification model – our model for quantifying the worth of an educational building based on different stakeholder values. We also present our methodology for selecting the indicators that will be used for value quantification. The paper also discusses our approach of integrating our valuation model with Building Information Modeling (BIM), so we can automatically extract the data needed for valuation from an existing BIM project model. We conclude the paper with a case study.

INTRODUCTION

A recent report by the National Research Council of the National Academies (NRC) has identified the research on understanding and assessing the value of our infrastructure systems to their stakeholders and the impacts of this value on decision-making as a "national imperative" (NRC 2009). "Because the infrastructure systems in the United States are deteriorating and require significant reinvestment, now is the time to conduct a fundamental reexamination of the value of infrastructure systems that guide their planning, construction, operation, and investment" (NRC 2009). We need to understand what stakeholders value (e.g. safety, energy conservation, cost saving, etc.), and accordingly, quantify the value (worth) of the built infrastructure based on these stakeholder values. The lack of such value evaluation/valuation has led many stakeholders to debate the value of our infrastructure and, in turn, has reinforced the need of value-sensitive decision-making (NRC 2009).

Despite the need for value-sensitive decision-making, major gaps still exist in the area of infrastructure system value assessment: 1) existing value approaches (e.g. value engineering) are usually function-focused analyses that define value as a ratio of "function" to its "cost" (Kelly 2007); but, from a more holistic perspective, "value" is a complex concept that carried rich and varied meaning based on the values of the person/stakeholder perceiving the value, and the type of value being considered (Barima 2010); 2) existing integrated approaches (e.g. integrated project delivery) promote collaboration to increase value, but do not provide a metric for measuring "value" or a well-defined method for value-sensitive analysis; and 3) value-based decision-making practices need to be more stakeholder-sensitive (Green 1999). As such, two main knowledge gaps exist: 1) there is a lack of understanding and formal modeling of what stakeholders value and how to valuate our infrastructure systems based on these stakeholder values; and 2) there is a lack of formalized theory-based methods for value-sensitive analysis of infrastructure project designs.

APPROACH AND METHODOLOGY

To bridge the above-mentioned knowledge gaps, in this paper, we propose our axiology-based valuation approach. Axiology is a theory of value and worth. It aims at answering questions such as how to define the types of values and how to measure these values (Smith and Thomas, 1998). Formal axiology is a branch of axiology that was introduced by Robert Hartman. Hartman (1967) introduced three basic dimensions of valuation: systemic valuation, extrinsic valuation, and intrinsic valuation. In our previous work, we conducted theoretical and empirical studies to discover stakeholder values (e.g. air pollution prevention, water conservation, safety) (Zhang and El-Gohary 2014) in the context of educational buildings. In this paper, we further present our preliminary value quantification model: our model for quantifying the value (worth) of an educational building based on different stakeholder values and using Building Information Modeling (BIM)-based design data. The model combines systemic, extrinsic, and intrinsic valuation.

As such, as illustrated in Figure 1, our research methodology involves four main tasks: 1) value discovery (refer to Zhang and El-Gohary 2014), 2) valuation model development, 3) integration with BIM, and 4) validation. Our methodology for developing our valuation model includes: 1) conducting theoretical studies on formal axiology, 2) semantically modeling the main valuation concepts, 3) identifying potential indicators to measure individual values, 4) selecting indicators based on a set of well-defined principles, and 5) constructing mathematical formulations for quantification.

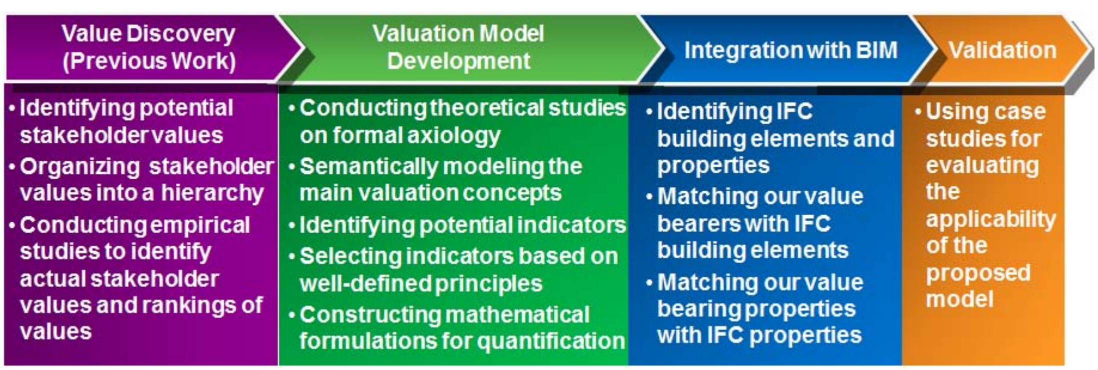


Figure 1. Research methodology.

In the remainder of this paper, we present our upper-level semantic valuation model. We then present our methodology and work in selecting the indicators for valuation. We also discuss our approach for integrating our valuation model with BIM so we can extract the data needed for our valuation model from an existing BIM model. Finally, we conclude the paper with a case study as an initial validation effort.

VALUATION MODEL DEVELOPMENT

Preliminary semantic valuation model. Our preliminary upper-level semantic valuation model, showing the most abstract valuation concepts, is depicted in Figure 2. At the highest level of abstraction, a thing is a "stakeholder value", a "value bearer", a "value bearing property", a "valuation amount", a "property indicator", a "standard of measure", a "property goodness degree", a "property value significance", a "value fulfillment degree", or a "value worth". A "stakeholder value" is a thing that is of worth, merit, or utility to a stakeholder (e.g. energy conservation). A "stakeholder value" could be an "environmental value", a "social value", or an "economic value". The hierarchy of stakeholder values is presented in Zhang and El-Gohary (2014). A "value bearer" is an object (in our case, a building or a building element) that has a value. A "value bearer" has one or more "value bearing properties" (e.g. material recycled content, thermal resistance) that determines its "valuation amount". A "property indicator" is a measure by which a property can be assessed. A "standard of measure" is the yardstick against which an indicator is measured to define the goodness of the property. A "property goodness degree" is a numeric degree that defines how good/fair/bad a property is. A "property value significance" is a quantifiable measure of the importance/relevance of a specific property in fulfilling a specific value. In assessing a specific value, different properties of a value bearer may have different significance levels. For example, given that a wall has a set of properties (e.g. height, color, fire resistance), the color may be of less significance than the fire resistance when assessing the "fire protection" value. A "value fulfillment degree" is a numeric degree indicating how much a value is fulfilled. A "value worth" is the worth/importance of a value to a stakeholder. The same value can have different worths to different stakeholders. A "valuation amount" is a quantifiable amount of the worth of the value bearer based on stakeholder values and value fulfillment degrees.

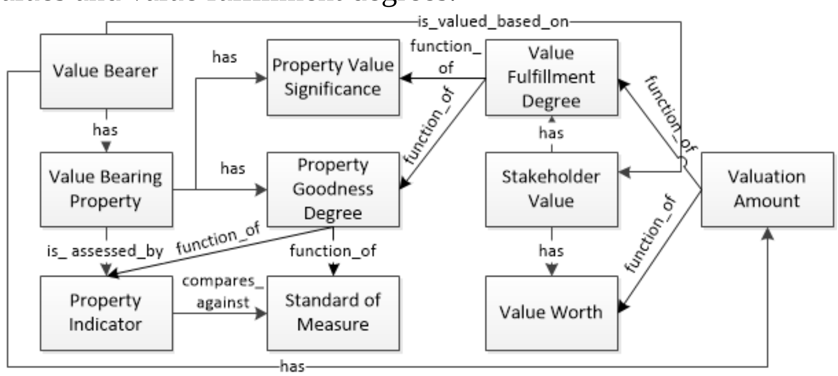


Figure 2. Preliminary valuation model.

Multi-dimensional valuation. Our valuation model provides a multi-dimensional view by combining the three main dimensions of valuation: extrinsic, intrinsic, and systemic valuation**.**

- Extrinsic valuation: valuates a value bearer based on the goodness of the properties of the value bearer. This type of valuation is conducted by utilizing a set of well-defined property indicators, and comparing the indicators with the standard of measures (a measure from regulatory standards, codes, best practices, etc.) to determine the property goodness degree. Extrinsic valuation provides a property goodness degree ranging from 0 to 1 indicating how good/fair/bad the property is.

- Systemic valuation: is similar to extrinsic valuation in terms of the valuation process. However, systemic valuation provides a dichotomous property goodness degree (either 1 or 0) based on a "black-white valuation" – either fulfill or not fulfill the standard of measure. For example, the property goodness degree of the "land type" property (for "land pollution prevention" value) is either one (developer selects a developed field for project development) or zero (developer selects a greenfield).
- Intrinsic valuation: valuates a value bearer based on personal opinion or judgment of a stakeholder. For example, the valuation of building aesthetics could be based on personal preferences of stakeholders. As such, using intrinsic valuation, the property goodness degree is subjectively determined by stakeholders and could range from 0 to 1.

PROPERTY INDICATOR IDENTIFICATION AND SELECTION

As per Figure 2, in order to valuate a value bearer based on its value bearing properties, property indicators are defined and used to measure how good/fair/bad each property (e.g. material recycled content) is in fulfilling each value (e.g. material conservation). However, because of the overwhelming abundance of potential indicators, it is crucial to establish a well-defined methodology for the selection of a set of effective indicators (instead of selecting the indicators in an arbitrary or ad-hoc manner). Therefore, we have established and used the following principles for indicator selection:

1. Relevance to project context: property indicator selection should start from understanding the project context (e.g. project type). Different projects, with different contexts, usually require different property indicators. For example, in valuating the "water pollution prevention" value, the following indicators are not relevant/valid in the context of educational building construction: concentrations of phosphorous, fluoride, chlorine, and sulphate in groundwater and surface water.
2. Reliability and scientific soundness: a selected indicator should offer a reliable measure, which means it should have a sound scientific basis.
3. Data availability during valuation phase (design phase in our case): indicator selection should consider the data availability during the design phase. For example, for the "soil preservation" value, data for post-development soil quality indicators (e.g. soil PH value, soil organic matter content, and soil aggregate stability) are not available during the design phase; and therefore these indicators should not be used for valuation.
4. Clear cause and effect links: the causal links of certain effects must be clearly identified in order to select appropriate indicators. For example, for the "air pollution prevention" value, some air pollutants, such as lead (Pb) and Mercury (Hg), are not caused by an educational building project development; and, thus, indicators measuring these pollutants should not be considered in valuation.
5. Independence: the selected indicators should be independent from each other. The consideration of selecting relatively independent indicators is crucial for efficient valuation. This will eliminate/reduce the possibility of over-counting certain values when conducting value aggregation.
6. Consistency in measurement: the selected indicators should have the same level of measurement and should use comparable units or, alternatively, they should be normalized into numbers with comparable units.
7. Understandability and easiness of implementation and interpretation: the selected indicators and associated calculations must be understandable to users. Overly complex indicators might lead to confusion and might result in inaccurate outcomes.

8. Limiting the number of indicators per property: for each property, a limited set of well-defined indicators should be selected and used. Using too many indicators has the potential risk of diluting the usefulness of individual indicators.

A partial set of our selected property indicators, which we identified based on these selection principles, is presented in Table 1.

Table 1. A Partial Set of Selected Property Indicators.

Stakeholder Value	Property Indicator (Partial List)	Unit	Valuation Type	Reference
Air Pollution Prevention	1. Amount of CO2 equivalent emissions 2. Amount of air pollutants emissions (e.g. NOx, SOx, dust, particulate)	tons/sf /year	Extrinsic Valuation	ISI 2013, iiSBE 2012, BRE 2012, Umich 2004
Water Pollution Prevention	1. Difference between discharge rate and quantity of stormwater before and after development 2. Amount of average total suspended solids load removal	1. cf/s 2. mg/L	Extrinsic Valuation	USGBC 2009, BRE 2012
Waste Pollution Prevention	Amount of solid waste recycled, re-used (diverted from direct disposal)	tons/sf/year	Extrinsic Valuation	ISI 2013, Umich 2004
Land Pollution Prevention	Type of selected land (selecting either developed field or greenfield)	N/A	Systemic Valuation	USGBC 2009
Light Pollution Prevention	Lighting power density	W/sf	Extrinsic Valuation	USGBC 2009
Noise Pollution Prevention	Average noise level	dB	Extrinsic Valuation	BRE 2012
Water Conservation	Amount of Potable water usage	gallon/ sf/year	Extrinsic Valuation	USGBC 2009, BRE 2012, Autodesk 2013
Energy Conservation	1. Amount of energy usage 2. Total renewable energy contribution percentage	1.KWh/sf/year 2.%	Extrinsic Valuation	USGBC 2009, iiSBE 2012, Autodesk 2013
Material Conservation	1. Material recycled content value 2. Amount of reused material usage 3. Amount of rapidly renewable material usage 4. Amount of regional material usage	1.$ 2.$ 3.$ 4.lbs	Extrinsic Valuation	USGBC 2009, ISI 2013, Autodesk 2013
Land Conservation	Average property density within the density boundary	sf/acre	Extrinsic Valuation	USGBC 2009, BRE 2012
Habitat Preservation	Habitat Performance Score/ Change in Plant species richness	N/A	Extrinsic Valuation	CIRIA 2003, BRE 2012
Soil Preservation	Percentage of disturbed soils restored	%	Extrinsic Valuation	iiSBE 2012, ISI 2013
Biodiversity Enhancement	Impact on biodiversity score	N/A	Intrinsic Valuation	CIRIA 2003

INTEGRATION WITH BIM

In order to conduct the valuation of a building project in an efficient manner, we propose to automatically extract the data needed for valuation from an existing BIM project model. To achieve that, we need to integrate our valuation model with the Industry Foundation Classes (IFC) model. A BIM model is intended to represent all the geometrical and non-geometrical information of a building. IFC is a data model that is used as a standard format in BIM-based project modeling. Each IFC class represents a concept. "IfcBuildingElement" is a class that represents the basic components of a building (e.g. IfcWall, IfcWindow). "IfcProperty" is a class that represents the basic properties of the components. Our approach for integrating the valuation model with BIM is illustrated in Figure 3. Our approach relies on 1) matching "value bearers" to IfcBuildingElements, and 2) matching "value bearing properties" to IfcProperties. However, "perfect" one-to-one matching is not always possible; not all properties in our valuation model have corresponding IfcProperties with equivalent names and semantics. In many of the cases, mismatches occur. For example, a terminology mismatch may occur when two concepts are represented by two different terms but have equivalent meanings (e.g. "sound resistance" vs. "acoustic rating"). In our matching algorithm, we define each matching case and how we deal with that case. For example, for the above-mentioned example, a one-to-one match between "sound resistance" and "acoustic rating" is established. The methodology for matching and integration is beyond the scope of this paper.

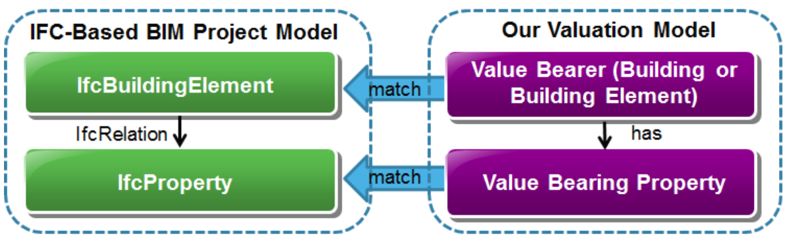
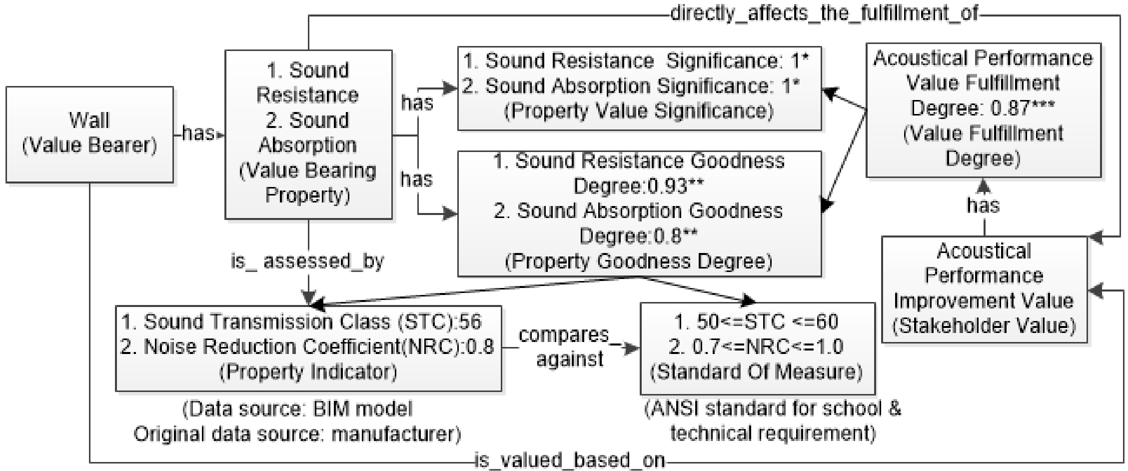


Figure 3. Framework of integrating with IFC-BIM Model.

CASE STUDY

In order to initially validate our valuation model, we conducted a case study that focuses on analyzing a one-story elementary school building project. Figure 4 illustrates part of the case study that shows the assessment of the acoustical performance improvement value of an exterior wall of a classroom. Improving the acoustical performance of classrooms is extremely important for an elementary school design. Because up to 60% of the classroom activities involve speech between teachers and students, classrooms need to provide a learning environment that supports clear communication (CISCA 2013). In our model, we use two indicators (sound transmission class (STC) and noise reduction coefficient (NRC)) to measure two main properties that are relevant to a wall's acoustical performance (sound resistance and sound absorption). In our case, the wall is made of concrete block material, generating a relatively high STC. It is also insulated with absorptive material (e.g. fiberglass insulations) to improve the sound absorption. The analysis together with the calculations are illustrated in Figure 4. As per Figure 4, the value fulfillment degree of the acoustical performance is 0.87, indicating a relatively high degree of fulfillment. This value fulfillment degree provides building designers/stakeholders with a sound and numeric measurement of the acoustical performance, which can aid in decision-making, for example when comparing different design alternatives.



*Determination of property value significance is based on acoustical consultant input.
**Sound resistance goodness degree= STC indicator value / maximum requirement in standard of measure=56/60=0.93
**Sound absorption goodness degree= NRC indicator value / maximum requirement in standard of measure=0.8/1.0=0.8
*** Acoustical performance value fulfillment= (sound resistance significance * sound resistance goodness degree + sound absorption significance * sound absorption goodness degree) / number of properties=(1x0.93+1x0.8)/2=0.87

Figure 4. Valuation of the acoustical performance improvement value of a wall (partial).

CONCLUSIONS

In this paper, we present our preliminary valuation model for quantifying the worth of an educational building based on different stakeholder values. The theoretical foundation of the model is based on axiology (the theory of value). Our valuation model combines three valuation dimensions: extrinsic, intrinsic, and systemic valuation. As part of our modeling methodology/effort, we established and used a set of well-defined principles to select the indicators that are used for quantification. We also presented our approach of integrating our valuation model with BIM so we can automatically extract the data needed for valuation from an existing BIM project model. We used a case study for initial validation of our model. The case study shows the applicability of the model in valuating an educational building based on stakeholder values and building properties, and the model's potential in facilitating value-sensitive decision making.

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