AXIOLOGY-BASED VALUE QUANTIFICATION MODELING FOR BUILDINGS

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Abstract: A report published by the National Research Council of the National Academies identified the research on understanding and quantifying the value of our infrastructure systems to their stakeholders and how this value is impacted by the various planning, design, construction, and operation decisions as a "national imperative". However, there is still a lack of understanding and formalized modeling of what different stakeholders value (e.g., energy conservation, safety, economic growth) in our infrastructure systems and how to valuate (i.e., quantify the worth) our infrastructure systems based on these values. This paper presents the authors' work in the area of axiology-based valuation modeling of buildings. "Axiology" is a theory of value (worth) that explores questions such as what are the objects that we value and how to measure the value of these objects. In this paper, the authors propose a mathematical value quantification model for quantifying the degree that a building (and its objects) fulfills stakeholder values based on its properties. The proposed model is primarily theoretically grounded in axiology. It builds on two key notions in Hartman's formal axiology that (1) object valuation depends on its properties, and (2) valuation has systemic, extrinsic, and intrinsic dimensions. The model was initially validated through a case study. The model offers a way to assess the value of our built infrastructure based on stakeholder values; it could facilitate value-sensitive decision making by embodying stakeholder values into project planning and design towards better synergy between human values and the built environment.

1 INTRODUCTION

A report published by the National Research Council of the National Academies (NRC) identified the research on understanding and quantifying the value of infrastructure systems to their stakeholders and how this value is impacted by the various planning, design, construction, operation, and investment decisions as a "national imperative" (NRC 2009). Similarly, industry organizations and institutes (e.g., SE 2012, NIBS 2012) and individual researchers (e.g., Levitt 2007) have emphasized the need for maximizing the lifecycle environmental, social, and economic value of infrastructure projects. "Potential projects for one type of infrastructure are not evaluated against other projects to determine how the greatest overall value might be achieved" (NRC 2009). The lack of such value quantification methods 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). In order to quantify the value (worth) of an infrastructure, there is a need to understand what stakeholders value (e.g., safety, energy conservation, cost saving), and accordingly, quantify the value (worth) of the infrastructure based on these stakeholder values. Discovering stakeholder values and quantifying the value of infrastructure based on these values are, thus, key prerequisites for facilitating value-sensitive decision making towards maximizing the collective value of our built infrastructure.
Despite the evident need for infrastructure value quantification and value-sensitive decision making, inadequate attention has been given to the theoretical and empirical study of value over the years (Barima 2009). Major gaps still exist in the area of value analysis of built infrastructure: (1) existing value approaches (e.g., value engineering) usually focus on function analyses and define value as a ratio of “function” to its “cost” (Kelly 2007) without a comprehensive interpretation of the concept of “value” based on stakeholder values, (2) existing integrated approaches (e.g., integrated project delivery) promote collaboration with the aim to increase value (AIA 2007), but do not provide a metric for measuring “value” or a well-defined method for value-sensitive analysis. As such, two main knowledge gaps exist: (1) there is a lack of understanding and modeling of what the value (worth) of an infrastructure is, and (2) there is a lack of formalized quantification models that can quantify such value. In the context of built infrastructure development, there is a need to better understand, conceptualize, and reason about “value quantification” in a holistic sense and considering stakeholder values.

To address this need, in this paper, the authors propose a mathematical value quantification model for quantifying the degree that a building (and its objects) fulfills stakeholder values based on its properties. The proposed model is primarily theoretically grounded in axiology. Axiology is a theory of value (worth) that explores questions such as what are the things that we value and how to measure the value of these things (Smith and Thomas 1998). The model builds on two key notions in Hartman’s formal axiology that (1) object valuation depends on its properties, and (2) valuation has systemic, extrinsic, and intrinsic dimensions.

2 BACKGROUND

Axiology is a theory of value or worth. It is a study of value concepts, value types, interrelationships, and valuation methods (Allen and Varga 2006). The term “axiology” is derived from the Greek word “axios” meaning value or worth. Axiology aims to answer questions such as how to define and measure the value (worth) of things (Smith and Thomas 1998). Formal axiology is a branch of axiology that was introduced by Robert Hartman. Hartman (1967) proposed to mathematically define the value of “things” in an objective manner based on their properties. He proposed that the value of an object depends on the extent to which its properties correspond to the properties of its concept. According to Hartman, a “good” thing (1) has a concept name, (2) this concept is characterized/defined by a set of properties, and (3) this thing possesses all of the properties in this set (El-Gohary 2010). Hartman also introduced three basic dimensions (types) of valuation (El-Gohary 2010): (1) Systemic Valuation: valuates a “thing” based on a finite number of properties in terms of rigid conformance to a system or a formal construct (e.g., conformance to the definition of circle, or conformance to a regulatory system). Systemic valuation, thus, sees “things” either black or white (e.g., a thing is a circle or not a circle, a person is complying with the law or not); (2) Extrinsic Valuation: valuates a “thing” based on a finite number of properties, but in a flexible way in terms of goodness and badness degrees based on practical aspects, such as functionality, economics, etc. A “thing” has potentially an infinite number of properties, but in practice extrinsic valuation is based on only a few of these properties; and (3) Intrinsic Valuation: valuates a “thing” based on an infinite number of properties in terms of personal judgment based on aesthetical, emotional, or spiritual aspects, etc. A “thing” can be valuated systemically, extrinsically, and/or intrinsically (El-Gohary 2010).

3 APPROACH AND METHODOLOGY

The proposed value quantification model is developed using an axiology-based approach. The model builds on two key notions in Hartman’s formal axiology that (1) object valuation depends on its properties, and (2) valuation has systemic, extrinsic, and intrinsic dimensions. Hartman’s three types of valuation (i.e., systemic, extrinsic, and intrinsic valuation) were adapted to the context of building valuation. In the context of building valuation, both extrinsic and systemic valuation valuate a building (or its objects) based on how good its properties are in fulfilling each of the stakeholder values. Systemic valuation is a rigid valuation that views property goodness as either “black or white” (i.e., a property is either good or bad), while extrinsic valuation is a flexible valuation that views property goodness as a spectrum (i.e., a property is good, fair, bad, etc.). Intrinsic valuation, on the other hand, valuates a building (or its objects) based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. In
developing the mathematical quantification functions of the proposed model, the authors also benchmarked some techniques (e.g., simple additive weighting) of multiple attribute decision making (MADM) approaches and adapted concepts from social welfare theory.

The methodology for developing the proposed model included five main tasks: (1) conducting theoretical studies on formal axiology, (2) identifying and modeling the main concepts for value quantification, (3) identifying potential indicators to measure the goodness of properties, (4) selecting indicators based on a set of well-defined principles, (5) constructing mathematical formulations for value quantification, and (6) conducting a case study for initial validation. In their prior work, the authors presented their research efforts in indicator identification and selection (Zhang and El-Gohary 2014). In this paper, the authors focus on presenting the mathematical formulations for value quantification and its initial validation.

4 PROPOSED VALUE QUANTIFICATION MODEL

4.1 Main Model

The proposed main value quantification model, showing the most abstract value quantification concepts, is depicted in Figure 1. At the highest level of abstraction, a thing is a “stakeholder value”, a “value bearer”, a “value bearing property”, a “property indicator”, a “benchmark of measure”, a “property goodness degree”, a “property value significance”, or a “value fulfillment degree”. A “stakeholder value” is a thing that is of worth, merit, or utility to a stakeholder (e.g., energy conservation, safety, cost saving). The hierarchy of stakeholder values, which includes 50 stakeholder values, is presented in Zhang and El-Gohary (2015). A “value bearer” is an object (e.g., a building or a building element) that holds value. A “value bearer” has one or more “value bearing properties” (e.g., thermal resistance, fire resistance, height). A “benchmark of measure” is a yardstick against which an indicator is measured to define the goodness of a property. A “property goodness degree” is a numeric degree that defines how good/bad a property is in fulfilling a specific “stakeholder value”. A “property value significance” is a quantifiable measure of the importance/relevance of a specific property in fulfilling a specific “stakeholder value” for a specific “value bearer”. A “value fulfillment degree” is a numeric degree indicating how much a value is fulfilled. As per Figure 1, each “function of” relation represents the mathematical function between the different quantification concepts. The following subsections describe how property goodness, property value significance, and value fulfillment are quantified.

![Figure 1: Main value quantification model](image)

4.2 Quantifying Property Goodness

Property goodness indicates how good/bad a property is in fulfilling a specific stakeholder value. Property goodness could be systemic, extrinsic, or intrinsic. Systemic property goodness is “black or white” – a property is either good or bad. Extrinsic property goodness is a spectrum of goodness – a property could be good, fair, bad, etc. Intrinsic property goodness is mostly assessed based on personal
judgment in terms of aesthetical, emotional, or spiritual aspects. The degree of goodness of a property is expressed as a metric-free numerical number called “property goodness degree” (PGD), and is derived based on comparing property indicators (PIs) against well-defined benchmarks. PGD is, thus, a function of PI and benchmark of measure (BOM). Corresponding to the type of property goodness, PGD could be assessed systemically, extrinsically, and/or intrinsically.

Systemic property goodness is assessed systemically. In this type of assessment, a property is either good or bad; the PI either meets or not meets the BOM. Systemic property goodness assessment, thus, results in a dichotomous PGD (either 1 or 0). For example, the PGD of land type (value bearing property) of a building (value bearer) in fulfilling land pollution prevention (stakeholder value) is either 1 (if the developer selects a previously developed field for project development) or 0 (if the developer selects a greenfield).

Extrinsic property goodness is mostly assessed extrinsically. In this type of assessment, a property has a spectrum of goodness in terms of how the PI measures up against a BOM. Extrinsic property goodness assessment, thus, results in a PGD that ranges from 0 to 1, which indicates how good the property is. Different extrinsic property goodness assessment functions are defined, depending on the type of assessment: max-best, min-best, or mid-best assessment. Accordingly, PGD is defined based on Eq. 1 to Eq. 3, where $PGD_{ijk}$ = property goodness degree of property $i$ of value bearer $k$ in fulfilling stakeholder value $j$; $PI_{ijk}$ = property indicator of property $i$ of value bearer $k$ in fulfilling stakeholder value $j$; BOM$_{minij}$ = minimum benchmark of measure of property $i$ in fulfilling stakeholder value $j$; and BOM$_{maxij}$ = maximum benchmark of measure of property $i$ in fulfilling stakeholder value $j$.

When conducting a max-best assessment (Eq. 1), the minimum benchmark represents the lowest degree of goodness, below which the property becomes totally bad; whereas the maximum benchmark represents a high enough degree of goodness, above which a property becomes “good-enough”. Accordingly, (1) when the PI falls below the minimum benchmark, the PGD falls to 0, (2) when the PI falls within the range of minimum and maximum benchmarks, the PGD monotonically increases with the increase of the PI until reaching the maximum benchmark, and (3) when the PI reaches (or is above) the maximum benchmark, the PGD becomes at its maximum of 1. For example, low-emitting material (value bearing property) of a ceiling (value bearer) in fulfilling indoor air quality improvement (stakeholder value) can be assessed using max-best assessment, where a higher percentage of compliant low-emitting material (PI) indicates better/more low-emitting material until it reaches 100% (maximum benchmark).

$$[1] \quad PGD_{ijk} = \begin{cases} \frac{PI_{ijk} - BOM_{minij}}{BOM_{maxij} - BOM_{minij}} & \text{if } PI_{ijk} < BOM_{minij} \\ BOM_{minij} & \text{if } BOM_{minij} \leq PI_{ijk} < BOM_{maxij} \\ 1 & \text{if } PI_{ijk} \geq BOM_{maxij} \end{cases}$$

When conducting a min-best assessment (Eq. 2), the minimum benchmark represents a high enough degree of goodness, below which a property becomes “good-enough”; whereas the maximum benchmark represents the lowest degree of goodness, above which the property becomes totally bad. For example, water consumption (value bearing property) of a water closet (value bearer) in fulfilling water conservation (stakeholder value) can be assessed using min-best assessment, where a lower amount of water usage per flush (PI) indicates better water consumption until it falls to 1.28 gpf (minimum benchmark).

$$[2] \quad PGD_{ijk} = \begin{cases} \frac{BOM_{maxij} - PI_{ijk}}{BOM_{maxij} - BOM_{minij}} & \text{if } PI_{ijk} \leq BOM_{minij} \\ BOM_{minij} & \text{if } BOM_{minij} < PI_{ijk} \leq BOM_{maxij} \\ 0 & \text{if } PI_{ijk} > BOM_{maxij} \end{cases}$$

When conducting a mid-best assessment (Eq. 3), there is a certain range within which the property becomes “good enough”; when the PI falls within that range, the PGD is at its maximum. The PGD
decreases when the PI falls out of this range until it becomes totally bad, when the PI reaches the minimum or maximum benchmark (both representing the lowest degree of goodness). For example, thermal comfort level (value bearing property) [of a living room (value bearer) in fulfilling thermal comfort improvement (stakeholder value)] can be assessed using mid-best assessment, where the thermal comfort level is the best when the air temperature is within a range of 69 °F to 73 °F (good enough range).

\[
[PGD]_{ij} = \begin{cases} 
0 & \text{if } P_{ij} < BOM_{minij} \\
\frac{P_{ij} - BOM_{minij}}{BOM_{maxij} - BOM_{minij}} & \text{if } BOM_{minij} \leq P_{ij} < BOM_{minij}' \\
1 & \text{if } BOM_{minij}' \leq P_{ij} < BOM_{minij}' \\
\frac{BOM_{maxij} - P_{ij}}{BOM_{maxij}' - BOM_{maxij}} & \text{if } BOM_{maxij}' \leq P_{ij} < BOM_{maxij}' \\
1 & \text{if } P_{ij} \geq BOM_{maxij}' 
\end{cases}
\]

Intrinsic property goodness is mostly assessed intrinsically. In this type of assessment, a property is assessed flexibly based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. Stakeholders can directly assign a PGD within the range of 0 to 1 based on their personal judgment of the goodness of the property. For example, a stakeholder can directly assign a PGD of 1 to a white interior wall color if white is his/her most favorite color for a wall. The detailed methodology for assessing intrinsic property goodness is beyond the scope of this paper.

4.3 Quantifying Property Value Significance

Property value significance (PVS) represents the significance, importance, or relevance of a specific property of a specific value bearer in fulfilling a specific stakeholder value. Properties may have different significances to value quantification. Determining the PVSs for the various building properties may not be easy or apparent. PVSs could be determined extrinsically and/or intrinsically.

Using extrinsic PVS determination approaches, PVSs are determined in a flexible and objective manner based on norms, relative impact of property, expert opinion, etc. Selecting which approach to use for extrinsic PVS determination depends on the type of property, the type of PVS, and the availability of data. A norm-based approach determines PVSs based on weightings embedded in applicable norms, such as standards, advisory practices, rating systems (e.g., LEED, BREEAM). For example, the PVSs of recycled material, reused material, and regional material (value bearing properties) [of a wall (value bearer) in fulfilling material conservation (stakeholder value)] can be directly obtained from LEED, which uses "credit weighting" to represent the point allocation between different credit categories. The LEED credit weightings for "material reuse", "recycled content", and "regional materials" are equal (2 points for each) (USGBC 2009). Accordingly, the three properties are assigned equal PVSs of 0.33 (after normalization). Because norm-based data are well-established by an authority or advisory body, a norm-based approach is preferred for PVS determination, if relevant norm-based data (e.g., score/point weightings) are available. Other approaches should be used when such data are not available.

An impact-based approach determines PVSs by evaluating the potential impacts of each property with respect to a set of impact categories. For example, disability adjusted life years (DALY) weighting (Blanc et al. 2008) can be used to determine the significance of environmental-related properties (e.g., air pollutant emissions) of a value bearer (e.g., a building or a building element) in fulfilling the environmental values (e.g., air pollution prevention) by assessing their potential impacts on human health using existing assessment tools (e.g., IMPACT 2002+). For example, particulate matter (PM) emissions (value bearing property) of a building (value bearer) affect human health more severely than lead emissions (value bearing property) (Blanc et al. 2008) and, thus, has a higher PVS (0.98) than that of lead emissions (0.02).

An expert-based approach determines PVSs based on expert opinion. It is a suitable approach to use when norm-based data are not available or when it is difficult to assess the potential impact of the
properties. For example, the PVS of sound resistance and sound absorption (value bearing property) [of a wall (value bearer) in fulfilling acoustical performance improvement (stakeholder value)] can be determined by soliciting acoustical consultant/expert opinion using a budget allocation process (BAP). In BAP, an expert is given a set of properties of a value bearer in fulfilling a specific stakeholder value. The expert is asked to allocate a “budget” of one hundred points to the individual properties in the property set, based on their expert judgment of the relative PVSSs of the respective properties. To ensure objectivity and correctness in PVS determination, it is important to select experts with knowledge and expertise in the specific technical domain related to the type of value bearer and stakeholder value (e.g., expertise in acoustical performance of buildings).

Using intrinsic PVS determination approaches, PVSSs are determined in a flexible and personal manner based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. For example, the significance of color (value bearing property) [of a wall (value bearer) in fulfilling aesthetics (stakeholder value)] is determined based on the personal opinion of the stakeholders. Similar to intrinsic property goodness assessment, stakeholders can directly assign a numerical number between 0 to 1 to a PVS based on their personal judgment of the significance, importance, or relevance of the property of the value bearer in fulfilling their own stakeholder value. The detailed methodology for intrinsic PVS determination is beyond the scope of this paper.

4.4 Quantifying Value Fulfillment

Value fulfillment represents how much a value is fulfilled. It depends on how good/bad the properties fulfill the value (i.e., PGD) and how significant the property is in fulfilling this particular value (i.e., PVS). “Highly good” properties (e.g., net-zero energy consumption), in comparison to “good” properties, tend to contribute to the fulfillment of a stakeholder value in extra higher degrees. Thus, to quantify value fulfillment of each stakeholder value, a value fulfillment degree (VFD) is defined by aggregating the PGDs and PVSSs of individual properties, while taking into account the extra higher level of contribution of highly good properties. The VFD function, thus, is composed of two sub-functions: (1) a property goodness aggregation (PGA) function that aggregates the PGDs and PVSSs of individual properties, and (2) a high property goodness (HPG) function that rewards states of HPG.

The PGA function aggregates the PGDs and PVSSs of individual properties to define how much a value is fulfilled by these properties. The PGA function uses simple additive weighting. Simple additive weighting is one of the most widely used MADM methods (Andresen 2000). A simple additive weighting function is a linear aggregating function that allows for compensability (i.e., possibility of offsetting a disadvantage on some criteria by a sufficiently large advantage on another criteria) among criteria (OECD 2008). Simple additive weighting is suitable for value fulfillment quantification for three reasons. First, when aggregating PGDs and PVSSs for individual properties to define the VFD of a stakeholder value, properties of one value bearer are compensatory in value fulfillment. For example, for fulfilling material conservation (stakeholder value), a floor (value bearer) with small amount of recycled material (value bearing property) can be compensated with large amount of reused material (another value bearing property). Second, a simple additive weighting method is able to provide an aggregated VFD (numerical number) for each value bearer. This allows further aggregation of the VFDs and for valuating a value bearer irrespective of the existence of other alternatives. Third, research shows that simple additive weighting methods yield “extremely close approximations” to other non-linear aggregating methods (e.g., generalized means) while remaining easier to understand (Andresen 2000).

The HPG function rewards states of HPG because of its higher contribution to the fulfillment of stakeholder values. The HPG function adapts concepts from social welfare theory. Social welfare theory is the study that assesses the collective welfare of a society or a group by combining individual opinions, preferences, interests, or welfare (Feldman and Serrano 2006). When calculating the degree of value fulfillment during value quantification, the aim is to find a good/satisfactory overall state of the aggregated value bearing properties based on the goodness degrees and value significances of the individual properties. This is analogous with social welfare assessment in which a social welfare function is used as a measure of the aggregated well-being (the good or satisfactory state) of a group based on the allocation of requisites (such as income) among the individuals of that group. However, unlike social welfare
assessment in which states of poverty are undesirable (and thus penalized), in value assessment states of "wealth" [i.e., states of high goodness of individual properties (“highly good properties”) such as net-zero energy consumption] are valued (and thus rewarded). While “highly bad properties” (e.g., 15 min fire rating) are also undesirable (not valued) during value quantification, such states of badness are already eliminated during regulatory compliance assessment. As such, for defining the VFD, two lines are established: “high property goodness (HPG) line” and “high property badness (HPB) line”. The HPG line represents the state of high goodness for a property, and is above the minimum benchmark and below the maximum benchmark. When the PGD of a property is at/above the HPG line, such property contributes to the fulfillment of a stakeholder value in an extra high degree. The HPB line represents the state of the property being highly bad and is usually at (or below) the minimum benchmark established by regulatory requirements. An HPB line is, thus, unnecessary in well-regulated societies that establish minimum requirements in the form of regulations, codes, standards, etc.

The HPG line could be assessed extrinsically or intrinsically. Systemic property cannot have HPG states because it could only be either good or bad. Similar to extrinsic property goodness assessment, extrinsic HPG line assessment assesses the state of high goodness in terms of how it measures up against a BOM, which could use max-best, min-best, or mid-best assessments. Accordingly, the HPG line is defined based on Eq. 4 to Eq. 6, where HPGLij= high property goodness line of property i in fulfilling stakeholder value j; HGBOMij = high goodness benchmark of measure of property i in fulfilling stakeholder value j; BOMminij = minimum benchmark of measure of property i in fulfilling stakeholder value j; and BOMmaxij = maximum benchmark of measure of property i in fulfilling stakeholder value j. Eq. 4 to Eq. 6 are used for max-best, min-best, and mid-best assessment, respectively.

\[ \text{HPGL}_{ij} = \begin{cases} \frac{\text{HGBOM}_{ij} - \text{BOM}_{\text{min}ij}}{\text{BOM}_{\text{max}ij} - \text{BOM}_{\text{min}ij}} & \text{BOM}_{\text{min}ij} \leq \text{HGBOM}_{ij} < \text{BOM}_{\text{max}ij} \\ \frac{\text{BOM}_{\text{max}ij} - \text{HGBOM}_{ij}}{\text{BOM}_{\text{max}ij} - \text{BOM}_{\text{min}ij}} & \text{BOM}_{\text{min}ij} < \text{HGBOM}_{ij} \leq \text{BOM}_{\text{max}ij} \\ \frac{\text{BOM}_{\text{max}ij} - \text{HGBOM}_{ij}'}{\text{BOM}_{\text{max}ij} - \text{BOM}_{\text{max}ij}'} & \text{BOM}_{\text{min}ij} \leq \text{HGBOM}_{ij} < \text{BOM}_{\text{min}ij}' \\ \frac{\text{BOM}_{\text{min}ij}'}{\text{BOM}_{\text{max}ij}'} & \text{HGBOM}_{ij} < \text{BOM}_{\text{min}ij}' \end{cases} \]

Similar to intrinsic property goodness assessment, intrinsic HPG line assessment is a flexible and personal high goodness assessment that is conducted based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. The detailed methodology for intrinsic HPG line assessment is beyond the scope of this paper.

The HPG function is a measure of the extent of high goodness in the set of properties of the value bearer. The function estimates the degree of HPG in the whole set by considering how far each PGD is above the HPG line. HPG is then rewarded by the HPG function, using a coefficient \( \alpha \), because of its higher contribution to the fulfillment of stakeholder values. The coefficient \( \alpha \) defines the extent of rewarding HPG; and is a numerical number between 0 and 1. An \( \alpha \) of 1 represents a full extent of reward, while an \( \alpha \) of 0 represents no reward at all.

The VFD function is an addition of the PGA function (which ranges from 0 to 1) and the HPG function (which ranges from 0 to 1), thereby making the HPG acting as an “extra bonus”. The VFD function is defined in Eq. 7, where VFD\(_{jk}\) = value fulfillment degree of stakeholder value j by value bearer k; n = total number of properties that contribute in fulfilling stakeholder value j; PGD\(_{ijk}\) = property goodness degree of property i of value bearer k in fulfilling stakeholder value j; PVS\(_{ij}\) = property value significance of property i in fulfilling stakeholder value j; \( \alpha \) = a coefficient for rewarding high property goodness; and HPGL\(_{ij}\) = high property goodness line of property i in fulfilling stakeholder value j.

\[ \text{VFD}_{jk} = \sum_{i=1}^{n} \text{PGD}_{ijk} \times \text{PVS}_{ij} + \alpha \sum_{i=1}^{n} \text{PVS}_{ij} \times \max[0, (\text{PGD}_{ijk} - \text{HPGL}_{ij})] \]
A case study was conducted to initially validate the proposed value quantification model. A duplex apartment building model was used in this case study. It is one of the common Building Information Model (BIM) published by buildingSMART alliance (a council of the National Institute of Building Sciences) for evaluating model or software functionality and applicability (buildingSMART 2015). The case study focused on analyzing the value fulfillment of the exterior wall system of the building. The exterior wall system is designed using concrete block with brick veneer. The detailed information on the design of the exterior wall system is summarized in Table 1. A set of stakeholder values were selected for this case study analysis, including: (1) material conservation, (2) indoor air quality improvement, (3) acoustical performance improvement, and (4) fire safety.

<table>
<thead>
<tr>
<th>Stakeholder Value</th>
<th>Property</th>
<th>PI</th>
<th>Unit</th>
<th>Pls of the Wall</th>
<th>BOM Min</th>
<th>BOM Max</th>
<th>BOM Reference</th>
<th>HGBOM</th>
<th>HGBOM Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material conservation</td>
<td>Recycled material</td>
<td>Percentage of recycled material</td>
<td>% 77.75</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>50</td>
<td>USGBC 2013b</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reused material</td>
<td>Percentage of reused material</td>
<td>% 5.5</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>25</td>
<td>USGBC 2013b</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Regional material</td>
<td>Percentage of regional material</td>
<td>% 35.43</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>50</td>
<td>USGBC 2013b</td>
<td></td>
</tr>
<tr>
<td>Indoor air quality improvement</td>
<td>Low-emitting material</td>
<td>Percentage of low emitting material</td>
<td>% 85.23</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>90</td>
<td>USGBC 2013b</td>
<td></td>
</tr>
<tr>
<td>Acoustical performance improvement</td>
<td>Sound resistance</td>
<td>STC*</td>
<td>NA</td>
<td>61.9</td>
<td>45</td>
<td>70</td>
<td>ICC 2012</td>
<td>55</td>
<td>USGBC 2013a</td>
</tr>
<tr>
<td></td>
<td>Sound absorption</td>
<td>NRC**</td>
<td>NA</td>
<td>0.05</td>
<td>0</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Fire safety</td>
<td>Fire resistance</td>
<td>Fire rating hour</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>ICC 2012</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

*STC stands for sound transmission class rating
** NRC stands for noise reduction coefficient
The results of the model-based analysis, including the PIs, BOMs, HGBOMs, PVSs, PGDs, and VFDs, are summarized in Tables 2 and 3. A 0.5 α coefficient was used in the analysis, which represents a mid-extent of rewarding high property goodness. The results of the VFDs of material conservation, indoor air quality improvement, acoustical performance improvement, and fire safety are 0.442, 0.852, 0.738, and 1.000, respectively. These results indicate that this concrete block wall fulfills material conservation value in a low degree, fulfills indoor air quality improvement and acoustical performance improvement in a relatively high degree, and fulfills fire safety in an extremely high degree. This value quantification results could provide decision makers with a sound numerical measurement as a basis for decision making, for example when making trade-offs (e.g., which values to fulfill in priority) or selecting design alternatives.

<table>
<thead>
<tr>
<th>Stakeholder Value</th>
<th>Property</th>
<th>PGDs</th>
<th>PVSs</th>
<th>VFDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material conservation</td>
<td>Recycled material</td>
<td>0.778</td>
<td>0.33</td>
<td>0.442</td>
</tr>
<tr>
<td></td>
<td>Reclaimed material</td>
<td>0.055</td>
<td>0.33</td>
<td>0.852</td>
</tr>
<tr>
<td></td>
<td>Regional material</td>
<td>0.354</td>
<td>0.33</td>
<td>0.738</td>
</tr>
<tr>
<td>Indoor air quality improvement</td>
<td>Low-emitting material</td>
<td>0.852</td>
<td>1.00</td>
<td>0.852</td>
</tr>
<tr>
<td>Acoustical performance</td>
<td>Sound resistance</td>
<td>0.676</td>
<td>0.90</td>
<td>0.738</td>
</tr>
<tr>
<td>improvement</td>
<td>Sound absorption</td>
<td>0.050</td>
<td>0.10</td>
<td>1.000</td>
</tr>
<tr>
<td>Fire safety</td>
<td>Fire resistance</td>
<td>1.000</td>
<td>1.00</td>
<td>1.000</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS AND FUTURE WORK

This paper presents an axiology-based mathematical value quantification model for quantifying the value fulfillment of one value bearer based on one stakeholder value. A value fulfillment degree (VFD) function is proposed for value quantification. The VFD function identifies the fulfillment degree of each stakeholder value based on the goodness of the properties and the significances of the properties in fulfilling particular stakeholder values. In doing so, a highly good property is rewarded in the function because of its higher contribution to the fulfillment of stakeholder values. Property goodness is a measure that defines how good a property is in fulfilling a specific stakeholder value, which is assessed systemically, extrinsically, or intrinsically. Property value significance is a measure that represents the significance, importance, or relevance of a specific property of a specific value bearer in fulfilling a specific stakeholder value, which is determined extrinsically or intrinsically. The model was initially validated through a case study, which demonstrates the applicability of the model in quantifying the VFDs of material conservation, indoor air quality improvement, acoustical performance improvement, and fire safety (stakeholder value) of a concrete block exterior wall system (value bearer).

In their future/ongoing research, the authors will further explore value aggregation that includes three types of aggregation: (1) subvalue aggregation (along a stakeholder value hierarchy): mathematically aggregating the subvalues (e.g., resource conservation, pollution prevention) to define the supervalue (e.g., environmental value), (2) object value aggregation (along an object hierarchy): mathematically aggregating the values of the parts (e.g., wall, ceiling, floor, etc.) to define the value of the whole (e.g., building), and (3) collective value aggregation (along a stakeholder hierarchy): mathematically aggregating the values of individual stakeholders to define the collective value of the group of stakeholders.

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