Identifying Sustainable Designs Using Preferences over Sustainability Attributes

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Abstract

We consider the problem of assessing the sustainability of alternative designs (e.g., for an urban environment) that are assembled from multiple components (e.g., water supply, transportation system, shopping centers, commercial spaces, parks). We model the sustainability of a design in terms of a set of sustainability attributes. Given the (qualitative) preferences and tradeoffs of decision makers over the sustainability attributes, we formulate the problem of identifying sustainable designs as the problem of finding the most preferred designs with respect to those preferences. We show how techniques for representing and reasoning with qualitative preferences can be used to identify the most preferred designs based on the decision maker's stated preferences and tradeoffs.

Introduction

In many applications like urban planning, the design of green buildings and space crafts, decision makers often look for designs that are more sustainable than others among all the designs that satisfy the functional requirements. Typically, the sustainability of the various alternative designs are assessed with respect to a set of *sustainability attributes* that describe various aspects of the designs such as its initial and maintenance cost, the amount of pollutants (e.g., toxic, greenhouse gases) it releases into the environment, and the amount of renewable energy used to source the energy needs of the design. Identifying the most sustainable designs among a set of alternatives depends on the preferences and tradeoffs of the decision maker over such sustainability attributes, in addition to the functional requirements of the design problem.

For example, in designing a sustainable building, a decision maker might prefer to source the energy needs of the building using renewable energy sources (such as solar or wind energy) over non-renewable energy sources (such as fossil fuels). Furthermore, the decision maker may choose to trade off one sustainability attribute against another (e.g., renewability of the energy source against cost of the building); and in other settings, the decision maker might find it useful to assign relative importance to sustainability attributes (e.g., controlling the amount of greenhouse gas emissions being more important than using renewable energy sources). A similar problem arises in the design of space crafts (Lutz et al. 2010). In order to make a space craft design more sustainable for a mission, the decision maker may seek a more energy efficient space craft design, i.e., one which consumes lesser electricity per unit time in comparison to various other feasible designs of the space craft. This requires more energy efficient components (with lesser power ratings) to be used in the design of the space craft. Similarly, the decision maker may also want to minimize the cost of the initial design of the space craft, and hence among two components with the same power ratings, the less expensive one may be part of the preferred design. In addition, the decision makers may also consider the overall cost of the design to be more important than its efficiency in terms of power consumption. Preferences such as the above may be qualitative (Brafman, Domshlak, and Shimony 2006) (e.g., binary preference relations over the domains) or quantitative (Fishburn 1970; Keeney and Raiffa 1993) (e.g., utility functions).

Problems in sustainable design (e.g., building design) typically involve choosing and assembling multiple components (such as siding walls, flooring and heating system in the case of a building design) from a repository that satisfy the functional requirements of the design. Each component of the design contributes to the sustainability of the design with respect to each of the sustainability attributes, and choosing some components over others to be included in the design might make the design more sustainable based on the preferences and tradeoffs of the decision maker over the sustainability attributes. The sustainability of a design is thus a function of the sustainability of the components that make up the design and the decision maker's stated preferences and tradeoffs.

In the sustainable design of a space craft (Lutz et al. 2010) for example, an expensive component simply adds to the cost of the entire space craft as a whole. However, the power rating of a space craft may not be a simple sum of the power ratings of its components. In fact it may depend on the arrangement of the components in parallel or sequence in the circuitry. Furthermore, in order to determine the subset of most sustainable designs among all feasible designs, there is a need to compare two designs with respect to all the sustainability attributes in terms of the intra-attribute and relative

importance preferences of the stakeholders. This is called dominance testing, i.e., does one design dominate the other with respect to the stated sustainability preferences?

Hence, in order to identify sustainable designs from a set of alternatives, there is a need for principled methods that assess and compare alternative designs based on (a) the preferences and tradeoffs of the decision maker with respect to the sustainability attributes, and (b) the impact of various components and materials that are included in the design.

Our approach to the problem of identifying the most sustainable design(s) involves representing sustainability requirements (in addition to the functional requirements) of the decision makers in terms of *qualitative preferences* over a set of application specific sustainability attributes of the design alternatives. We propose to leverage the existing body of work in the AI literature for representing and reasoning with qualitative preferences over multiple attributes. Following the representation language given in (Santhanam, Basu, and Honavar 2010b), we represent sustainability preferences of the decision makers in the form of: (a) intra-attribute preferences, i.e., preferences over the various possible values that can be taken by each attribute; and (b) relative importance among the attributes, i.e., which of the sustainability attributes the stakeholders care more about. While intra-attribute preferences make one design preferred over another in terms of a particular attribute, relative importance preferences allow one attribute to be traded off against others.

In this paper we restrict our scope to preferences over an attributes that do not depend on specific values assigned to other attributes (i.e., unconditional preferences). However, our approach can be extended to use other more expressive languages, particularly CP-nets (Boutilier et al. 2004), TCP-nets (Brafman, Domshlak, and Shimony 2006), and UCP-nets (Boutilier, Bacchus, and Brafman 2001) that can represent and reason with conditional preferences. We leverage on existing dominance testing strategies that are well studied in the AI literature (Santhanam, Basu, and Honavar 2010b; 2010a; Boutilier et al. 2004; Brafman, Domshlak, and Shimony 2006) that have been successfully used in other design applications such as Web services composition (Santhanam, Basu, and Honavar 2008). We provide a generic model and a practical approach that can be used along with existing design tools for identifying sustainable designs in various application domains.

Illustrative Example

In order to explain our approach to sustainable design, we consider the problem of building design, where the decision maker is tasked with identifying sustainable building designs from a set of candidate designs that meet some pre-specified functional requirements of the building.

Sustainability attributes The sustainability of a building depends on how cost-effective, environmentally preferable and safe are the components and materials used in the design. Key factors in determining the sustainability of a component used in the design of a building include its energy costs, potential global warming effects in terms of greenhouse gas emissions, and environmental, health, and safety concerns related to the potential release of toxic chemicals and pollutants from the components and materials (Lippiatt 2007).

The Building for Environmental and Economic Sustainability (BEES 4.0) tool (Lippiatt 2007) released by the National Institute of Standards and Technology (NIST[1]) considers several attributes for measuring sustainability of components and materials used in building design. This decision support tool is intended towards aiding building decision makers to choose components and materials in their design that increase the sustainability of the building as a whole. The tool includes actual environmental and economic performance data for 230 building products over these sustainability attributes. In our example we consider the following four attributes (included in the BEES tool) as indicators of sustainability of components for the purpose of this discussion.

- *Initial Cost (IC)*: This determines the cost of constructing the building as per the design.
- *Future Cost (FC)*: This determines the cost of maintaining and operating the building for its intended purpose.
- *Renewability (RE)*: This measures how much renewable (and non-renewable) energy is embodied in the materials used to construct the building. For example, the use of components that are made of renewable materials (such as wood) for components such as doors, windows, siding walls, etc. in the construction of the building, and the use of renewable energy sources (such as solar power) to meet the energy needs of the building makes a design more sustainable in terms of this attribute.
- *Toxicity/Greenhouse Gas Emission (TG)*: During the construction and operation of a building, several chemicals are released into the environment. Ecological toxicity refers to the potential of a pollutant that is released into the environment to harm ecosystems. Similarly, greenhouse gases such as carbon dioxide (CO2) are believed to contribute to global warming, so a sustainable building will minimize the emissions of greenhouse gases during construction and operation.

Preferences For each of the above attributes, we allow the following values: Excellent (E), Good (G), Average (A), Bad (B) and Poor (P). These levels indicate the sustainability of the component[2], and the intra-attribute preferences for all the attributes correspond to $E > G > A > B > P$. For example, a component that has 'P' as the value of the attribute Renewability (RE), it indicates that the component consumes a lot of non-renewable energy sources, and is not preferable to another component valued at 'B' for RE. Similarly, a component that has 'A' for the attribute initial cost (IC) is con-

[1] `http://www.nist.gov`

[2] The BEES 4.0 (Lippiatt 2007) tool provides values on a numeric scale for each of the attributes for the components, but we use qualitative levels that roughly correspond to those numerical values in order to simplify our discussion in our paper.

Function	Component	IC	FC	RE	TG
Heating	Electric	G	B	B	B
Heating	Gas	A	G	B	B
Heating	Solar	P	E	E	E
Flooring	Ceramic Tile	A	E	B	B
Flooring	Vinyl Tile	E	G	A	G
Flooring	Natural Cork	P	E	G	E
Siding	Brick&Mortar	P	E	P	B
Siding	Aluminum	G	G	G	A
Siding	Cedar	A	A	G	G

Table 1: Available Building Components in the Repository

Design	Heating	Flooring	Siding
D_1	Electric	Vinyl Tile	Aluminum
D_2	Gas	Ceramic Tile	Brick&Mortar
D_3	Gas	Vinyl Tile	Aluminum
D_4	Solar	Ceramic Tile	Brick&Mortar
D_5	Solar	Natural Cork	Aluminum

Table 2: Candidate Building Designs

sidered more economically sustainable (less expensive) than another with a level of 'P'.

Furthermore, suppose that the the decision maker has some preferences in terms of the relative importance of the sustainability attributes, such that:

- Future Cost is more important than Initial Cost and Renewability
- Toxicity/Greenhouse gas emission is more important than Initial Cost

Functional Requirements In order to simplify the discussion, we consider only three aspects of the functional requirements of a building design: (a) the heating mechanism; (b) the type of flooring; and (c) the type of external wall siding used in the design. Suppose that the only choices available (for each of the components in the repository) are as given in Table 1. The table also shows the valuations[3] of the components with respect to the sustainability attributes.

A candidate design constitutes a combination of the heating mechanism (Electric/Gas/Solar), type of flooring (Ceramic Tile/Vinyl Tile/Natural Cork), and external wall siding (Brick&Mortar/Aluminum/Cedar), thus satisfying the functional requirements. Suppose that the decision maker is tasked with choosing the most sustainable design(s) from five candidate building designs as given in Table 2.

In this example, the problem we address corresponds to identifying the most sustainable design(s) from those given in Table 2, i.e., designs with preferred values (closer to E) for the sustainability attributes, while at the same time respecting the relative importance among the attributes.

[3]The valuations for the flooring and external siding wall components are roughly based on data for the respective materials from the BEES 4.0 (Lippiatt 2007) tool.

Model

Designs and Feasible Designs

A design problem consists of a repository of available components from which we are interested in assembling designs that satisfy some given functionality φ. Formally, we represent a design problem as a tuple $\langle R, \oplus, \models, \varphi \rangle$ where

- $R = \{C_1, C_2 \ldots C_r\}$ is a set of available components
- $\oplus$ denotes a *design* operator that functionally aggregates components and encodes how the components interact when included within the same design. $\oplus$ is a binary operation on components C_i, C_j in the repository that produces a design $C_i \oplus C_j$
- $\models$ is a satisfaction relation that evaluates to $true$ when a design satisfies the given functional requirements φ
- φ is a set of functional requirements that each candidate solution to the design problem is required to satisfy

Definition 1 (Candidate or Feasible Design). *Given a design problem $\langle R, \oplus, \models, \varphi \rangle$, a design $D = C_{i_1} \oplus C_{i_2} \oplus \ldots C_{i_n}$ is an arbitrary collection of components $C_{i_1}, C_{i_2}, \ldots, C_{i_n}$ s.t. $\forall j \in [1, n] : C_{i_j} \in R$.*

A feasible design or a candidate design is a design D that satisfies the functional requirements φ, denoted by $D \models \varphi$.

The repository of available components R in our example problem of building design is given in Table 1. The functional requirements φ in our problem state that a building design is feasible if it includes exactly one heating component (electric, gas, or solar heating), one flooring component (ceramic, vinyl tile, or natural cork) and one siding component (brick&mortar, aluminum or cedar siding). The set of candidate or feasible designs considered in the example is given Table 2.

Sustainability Attributes

Let $X = \{X_1, X_2, ..X_n\}$ be the set of sustainability attributes in a design problem, each X_i having a domain of possible values Dom_i. We define the valuation of a component in terms of the sustainability attributes as follows, similar to the definition of the valuation of Web services with respect to their non-functional properties in (Santhanam, Basu, and Honavar 2008).

Definition 2 (Valuation of a Design Component). *The valuation of a component $C_j \in R$ with respect to the attribute $X_i \in X$ is denoted by $V_{C_j}(X_i)$. The overall valuation of the component C_j is described by the tuple $V_{C_j} = \langle V_{C_j}(X_1), V_{C_j}(X_2), \ldots V_{C_j}(X_n) \rangle$ of valuations.*

In our running example, the sustainability attributes are $X = \{IC, FC, RE, TG\}$, and all the attributes have the same domain, namely $\{E, G, A, B, P\}$. According to the above definition, the overall valuation of the heating component Gas with respect to the above sustainability attributes is: $V_{Gas} = \langle V_{Gas}(IC), V_{Gas}(FC), V_{Gas}(RE), V_{Gas}(TG) \rangle = \langle G, B, B, B \rangle$.

Preferences over Sustainability Attributes

Our goal is to find the most preferred designs among those that are feasible, with respect to a set of sustainability attributes X. In order to identify the most preferred designs, it is necessary that the decision maker specifies his/her preferences over the attributes. We propose to represent preferences over the values of the sustainability attributes X as follows.

- Intra-attribute preferences ($\succ_i$): For each attribute X_i, $\succ_i$ is a binary preference relation on Dom_i such that if $u, v \in Dom_i$ then $u \succ_i v$ if and only if u is preferred to v in terms of the sustainability attribute X_i.
- Relative importance preferences ($\rhd$): Given a set of sustainability attributes X, $\rhd$ is a binary preference relation on X such that $X_i \rhd X_j$ if and only if X_i is relatively more important than X_j.

In our example of building design, the intra-attribute preferences can be represented as $E \succ_i G \succ_i A \succ_i B \succ_i P$, $i = \{IC, FC, RE, TG\}$ and the relative importance preferences can be represented as $FC \rhd IC$, $FC \rhd RE$ and $TG \rhd IC$.

Solution Approach

Our goal is to identify most sustainable designs from a set of candidate designs based on their sustainability attributes. Because the sustainability of a design is a function of the sustainability attributes of its components, we hereby propose to measure the sustainability of a design in terms of the same attributes that describe the sustainability of its components. Before we proceed to identify the most sustainable designs in our approach, the following non-trivial questions need to be addressed.

a) *Aggregation:* Given a sustainability attribute $X_i \in X$ and a design $D = C_1 \oplus C_2 \oplus \ldots C_n$, each C_j having its own valuation $V_{C_j}(X_i)$ with respect to X_i, how do we define the *aggregated* valuation of the D with respect to X_i? Further, given two designs D_1 and D_2, how do we determine whether D_1 is more sustainable in comparison to D_2 with respect to X_i?

b) *Dominance:* Given two designs, how do we compare them in terms of their sustainability attributes with respect to the stated sustainability preferences? Note that comparing designs is more complicated than simply comparing components, because the sustainability of a given design depends on the sustainability of the components that make up the design.

In our running example, consider the designs $D_1 = Electric \oplus VinylTile \oplus Aluminum$ and $D_2 = Gas \oplus CeramicTile \oplus Brick\&Mortar$ (see Table 2). The following examples correspond to the above questions.

a) *Aggregation:* How do we compute $D_1(IC)$, $D_1(FC)$, etc.? How do we determine if D_1 is more sustainable than D_2 with respect to RE, i.e., is $D_1(RE) \succ_{RE} D_2(RE)$?

c) *Dominance:* Is D_1 more sustainable than D_2 overall?

We now proceed to describe our approach to addressing the above questions.

Design	Valuation
D_1	$\langle G, B, B, B \rangle$
D_2	$\langle P, G, P, B \rangle$
D_3	$\langle A, G, B, A \rangle$
D_4	$\langle P, E, P, B \rangle$
D_5	$\langle P, G, G, A \rangle$

Table 3: Valuations of the Candidate Building Designs

Aggregation

Let $D = C_1 \oplus C_2 \oplus \ldots C_n$ be a design. For each sustainability attribute X_i, we define an appropriate aggregation function Φ_i that computes the valuation of D with respect to X_i, denoted $D(X_i)$, based on the set $\{C_1(X_i), C_2(X_i), \ldots C_n(X_i)\}$ of valuations. Therefore, we have

$$\Phi_i : \mathscr{P}(Dom_i) \longrightarrow \mathscr{F}(X_i)$$

where $\mathscr{F}(X_i)$ denotes the range of the aggregation function. The range $\mathscr{F}(X_i)$ of Φ_i depends on the choice of aggregation function and the domain of the attribute X_i.

In our running example, all the attributes in X have the domain $\{E, G, A, B, P\}$; E is the most preferred and P is the least preferred value in terms of sustainability. We choose an aggregation function that computes the worst value (lowest or minimum) among all the components in the design. This choice is based on the rationale that the sustainability of a design is only as good as its least sustainable component. For example, even if one of the components, say C in a design D is known to release high amounts of toxic gases, i.e., $C(TG) = P$, then the entire design suffers, i.e., $D(TG) = P$, regardless of the levels of toxicity of all other components in the design. Others choices for aggregation functions can be also used, and some of them are mentioned later in the section. We use the following aggregation function which was introduced in (Santhanam, Basu, and Honavar 2008) to compute the aggregated valuations of composite Web services with respect to their non-functional attributes.

Definition 3 (Aggregation: Choosing the Minimum Valuation). *Given a set S of valuations of an attribute X_i, the aggregation function Φ_i is defined by*

$$\Phi_i(S) := \{min_{s \in S} s\}$$

Assuming the above aggregation function for all the four sustainability attributes, namely IC, FC, RE and TG, the valuations of the sustainability attributes of the candidate design S_2 given in Table 2 is computed as follows.

$$\begin{aligned} V_{S_2}(IC) &= \Phi_{IC}(\{V_{Gas}(IC), V_{CeramicTile}(IC), \\ &\quad V_{Brick\&Mortar}(IC)\}) \\ &= \Phi_{IC}(\{A, A, P\}) \\ &= \Phi_{IC}(\{A, P\} \\ &= P \end{aligned}$$

Definition 4 (Overall Valuation of a Design (Santhanam, Basu, and Honavar 2008)). *The valuation of a design $D = C_1 \oplus C_2 \ldots C_n$ with respect to the attribute $X_i \in X$ is*

defined as $V_D(X_i) = \Phi_i(V_{C_1}(X_i), V_{C_2}(X_i), \ldots V_{C_n}(X_i))$, *where* Φ_i *is the aggregation function with respect to* X_i.

The overall valuation of the design D *over all* m *attributes in* X *is described by the tuple* $V_D = \langle V_D(X_1), V_D(X_2), \ldots V_D(X_m)\rangle$ *of valuations.*

The overall sustainability of the candidate designs with respect to the four sustainability attributes for our running example are given in Table 3.

The next step is to compare two designs with respect to a given attribute X_i. Because of the nature of the aggregation of function we have chosen, the ranges $\mathscr{F}(IC), \mathscr{F}(FC), \mathscr{F}(RE), \mathscr{F}(TG)$ of the aggregation function is same as their domains, namely $\{E, G, A, B, P\}$. Hence, in this case it is easy to compare the aggregated valuations in any two designs, using the corresponding intra-attribute preference relations. In this case, it amounts to $\succ_{IC}, \succ_{FC}, \succ_{RE}, \succ_{TG}$. For example, $D_3(TG) = A$ and $D_4(TG) = B$, which means that D_3 is more sustainable in terms of the attribute TG in comparison with D_4.

However, in general the aggregation function Φ_i may have a range $\mathscr{F}(X_i)$ that is different from the domain Dom_i of the attribute, in which case the originally specified intra-attribute preference relation $\succ_i$ cannot be used to compare two designs with respect to X_i. In such settings, a new preference relation $\succ'_i$ can be defined on $\mathscr{F}(X_i)$ in order to compare two designs with respect to the aggregated valuations for X_i.

Other Types of Aggregation Some examples of aggregation functions are given below.

1. *Summation.* This is applicable in cases where an attribute is real-valued and represents some kind of additive cost. For example, the cost of a space craft is the sum of the costs of its constituent components. If S is the set of valuations of the individual components with respect to attribute X_i , then

$$\Phi_i(S) := \{\Sigma_{s \in S} s\}$$

2. *Best/Maximum.* Here, the valuation of a design with respect to an attribute is the best (as opposed to worst in our example), i.e., the maximum among the valuations of its components. This type of aggregation is a natural one to consider while designing systems with low risk such as job scheduling, where it does not hurt to have some components that are bad, but it is important to have at least a few that have good values for the attribute X_i.

$$\Phi_i(S) := \{min_{s \in S} s\}$$

3. *Best/Worst Frontier.* In some settings, it is possible that the intra-attribute preference over the values of an attribute is a partial order (not necessarily a ranking or a total order). Hence, it may not be possible to compute the valuation of a design as the best or worst among the valuations of its components because a unique maximum or minimum may not exist. For example, it may be useful to compute the valuation of a design as the *minimal set* of valuations among the valuations of its components, which we call the *worst frontier*. The *worst frontier* represents the worst possible valuations of an attribute X_i with respect to $\succ_i$, i.e., the minimal set[4] among the set of valuations of the components in a design.

Dominance

We have so far only considered the intra-attribute preferences ($\succ_i$ and $\succ'_i$) of the decision maker in comparing designs, with respect to one sustainability attribute at a time. We now proceed to show how designs can be compared by factoring in all the attributes and the preferences of the decision maker, leveraging existing work in the area of qualitative decision theory (Doyle and Thomason 1999; Brafman and Domshlak 2009).

The previous section showed how to evaluate a design with respect to a single attribute as a function of its components using an aggregation function, and compare two designs based on their aggregation function with respect to that attribute. However, to find sustainable designs with respect to both the intra-attribute and the relative importance preferences, we need to compare designs with respect to their aggregated valuations over all attributes. We call this comparison as *dominance testing*, and we present a specific dominance relation introduced in (Santhanam, Basu, and Honavar 2010b) for performing such a comparison.

Definition 5 (Witness based Dominance (Santhanam, Basu, and Honavar 2010b)). *Dominance* $\succ_d$ *is a binary relation defined as follows. Let* U, V *be two designs, and* X *the set of sustainability attributes describing the valuations of their components.*

$$\begin{aligned} U \succ_d V \Leftrightarrow \quad & \exists X_i \ : \ U(X_i) \succ'_i V(X_i) \ \wedge \\ & \forall X_k \ : \ (X_k \rhd X_i \vee X_k \sim_{\rhd} X_i) \ \Rightarrow \\ & \quad (U(X_k) \succ'_k V(X_k) \vee U(X_k) = V(X_k)) \end{aligned}$$

In the above, we call the attribute X_i as the *witness* of the relation. The dominance relation $\succ_d$ is derived from and respects both the intra-attribute preferences ($\succ_i$) as well as the relative importance preferences ($\rhd$) of the decision maker. The definition states that a design U dominates V if and only if we can find a witness attribute X_i such that with respect to the intra-attribute preference $\succ_i$, the aggregated valuation of U dominates V when compared using $\succ'_i$, and for all attributes X_k which the decision maker considers more important than ($\rhd$) or indifferent to ($\sim_{\rhd}$) the witness X_i, the valuation of X_k in U is at least as preferred as ($\succ'_i$ or equals) the valuation of X_k in V.

When the above dominance relation is applied to our running example, we have $FC \rhd IC$, $FC \rhd RE$ and $TG \rhd IC$, resulting in the following comparisons.

- $D_5 \succ_d D_1$ with FC as witness
- $D_5 \succ_d D_2$ with RE as witness
- $D_5 \succ_d D_3$ with RE as witness
- $D_4 \succ_d D_1$ with FC as witness

[4]Note that if $\succ_i$ is a total order, then worst frontier represents the minimum or lowest element in the set with respect to the total order.

- $D_4 \succ_d D_2$ with FC as witness
- $D_3 \succ_d D_2$ with IC as witness

Other dominance relations such as *pareto dominance* (denoted $\succ_p$) can be used to compare designs based on their aggregated valuations for the sustainability attributes. In pareto dominance, a design is preferred to another if it is preferred to ($\succ'_i$) or equals the other with respect to every attribute, and in addition it is preferred ($\succ'_i$) to the other with respect to *at least* one attribute. However, pareto dominance considers all attributes equally important, i.e., it ignores the relative importance over the sustainability attributes specified by the decision maker. The following comparisons result from applying pareto dominance to our running example.

- $D_5 \succ_p D_2$
- $D_4 \succ_p D_2$
- $D_3 \succ_p D_2$

As expected, pareto dominance is unable to ascertain that D_5 and D_4 are more sustainable than D_1, and that D_5 is more sustainable than D_3 due to ignoring the relative importance preferences.

Identifying Sustainable Designs

We can observe that because of considering multiple attributes at a time, and due to the influence of the decision maker's preferences, the dominance relation may not provide us a ranking over the set of candidate designs. In other words, there may be pairs of designs that are incomparable with respect to the decision maker's preferences, or the dominance relation is a partial order (as opposed to a total order). In such a case, the set of most sustainable designs can be computed as the set of candidate designs that are *not dominated* by any other other candidate designs.

Definition 6 (Non-dominated Set). *The non-dominated set of designs with respect to a set S of designs and a (partially ordered) dominance relation $\succ$, denoted $\Psi_\succ(S)$, is a subset of S such that none of the elements in S are preferred to any element in $\Psi_\succ(S)$.*

$$\Psi_\succ(S) = \{S_i \in S | \nexists S_j \in S : S_j \succ S_i\}$$

Note that as per this definition, $\Psi_\succ(S)$ is the *maximal* set of elements in S with respect to the relation $\succ$. It is also easy to observe that this set is non-empty as long as S is non-empty, i.e., at least one most sustainable design can be identified if it exists. In our running example, we find that $\Psi_{\succ_d}(\{D_1, \ldots, D_5\} = \{D_4, D_5\}$ and $\Psi_{\succ_p}(\{D_1, \ldots, D_5\} = \{D_1, D_3, D_4, D_5\}$

Conclusion

In summary, we show how to use reasoning about qualitative preferences to solve the problem of identifying sustainable designs, given a set of preferences of the decision maker over a set of sustainability attributes of the components that make up a design. We use existing methods in qualitative decision theory to compare design alternatives and choose the most sustainable ones with respect to the decision maker's stated preferences and tradeoffs. Our solution constitutes (a) evaluating each design in terms of each sustainability attribute by aggregating the values taken by the components that make up the design (using an aggregation function that can be attribute specific); and (b) comparing two designs and determining the more sustainable design using a dominance testing strategy that respects the decision makers' preferences and tradeoffs.

In this paper we have shown the use of our approach to identify the most sustainable designs for a building with respect to functional requirements and sustainability preferences of the decision maker. We have illustrated the use of qualitative intra-attribute and relative importance preferences using a specific aggregation function and dominance relation. However, other choices of aggregation functions and dominance relations can also be used in our model such as those mentioned in (Brafman, Domshlak, and Shimony 2006; Wilson 2004). In addition, qualitative preferences can be combined with or replaced by quantitative preferences, which have been well studied in the context of multi-attribute utility theory (Fishburn 1970; Keeney and Raiffa 1993).

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