The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Performance-based Engineering Approach for Sustainable Building Design in Singapore

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ABSTRACT

A wide range of interests and stakeholders are involved in the construction and operation processes of a building, and its life cycle is significantly long compared to other products used in our daily life. Therefore, a comprehensive decision-making approach is important to be developed and exercised in a project during not only its construction phase but also its operation. As a tool to select the best solution amongst various alternatives, Multi-criteria decision analysis (MCDA) is used in order to integrate all the components, all the stakeholders and all the standpoints of a project during its whole life cycle. The cornerstone of MCDA is to quantify the value of each alternative and to achieve relative comparisons. In some MCDA, deterministic models are used, since they provide simple and clear concepts to stakeholders. However, such deterministic models may distort reality, which has many sources of uncertainty. The Performance-based engineering (PBE) approach, which is an extensively used probabilistic approach in structural and mechanical engineering, can substitute for deterministic quantification and provide a deeper understanding of the value of each alternative. In this paper, the PBE approach to the MIVES (Model for Integration of Values for Evaluation of Sustainability), one of the multi-criteria decision-making (MCDM) methods, is discussed, and an example of PBE-MCDM to a hypothetical residential building in Singapore is presented for demonstration of the developed approach.

1. INTRODUCTION

Project management is an area of knowledge highly developed during the last century. It was not applied to construction management in its early development but

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nowadays is spreading in many fields (Ormazabal 2002). In any stage of a construction project, the decision-making processes play a crucial role from many standpoints involving not only the engineering aspects (civil, environmental, industrial, etc.) but also the basic sciences such as mathematics and social sciences. Multi-criteria analysis is a powerful and useful tool to be adopted from the beginning of any project planning. Therefore, knowledge about the decision-making processes has become a multidisciplinary field.

There are several decision-making systems used by the research community and the industry where the goal is typically to arrange alternatives in their order of importance. In this paper, we use an “indicator” for each one of the involved aspects to quantify an alternative considered in the study at hand. Moreover, as an enhancement to the status quo, the effect of natural hazards can be added as an indicator through the consideration of the probability of exceedance (POE) of certain losses within a given return period of the hazard in question. This addition allows the decision makers to consider the whole life cycle and all the components of a building in order to select the most valuable alternative from a holistic point of view although it might be initially more expensive. In order to reach this holistic view, any decision-making system should consider the following points, among others:

1) All stakeholders involved in the decision-making stage;
2) Future stakeholders not present during the decision-making stage, i.e. sustainability of the decision;
3) All the components of the project and its whole life cycle, i.e. the holistic nature; and
4) Making all aspects of the decision comparable even if they cannot be measured with the same units.

It is noted that if the decision-making process is simple, only the consideration of the first point can be adequate. The model presented in this paper is concretized in order to fit into the selection process of solutions for construction of public and residential buildings, such as the selection amongst several alternatives of the energy-efficient building envelope.

2. DECISION-MAKING SYSTEMS

The literature presents many decision-making systems (DMS), e.g. AHP, ELECTRE, IDS, PROMETHEE & GAIA, TOPSIS (Saaty 1980, 2001; Roy 1968; Brans and Vincke 1985; Brans et al. 1986; Ormazabal 2002; Hwang and Yoon 1981). Some of these systems are interwoven, e.g. IDS uses AHP for obtaining weights. The goal of this paper is the holistic approach in general but, specifically, the consideration of losses due to natural hazards and energy efficiency during the life cycle of the building.

The MIVES (Model for Integration of Values for Evaluation of Sustainability) is used herein as one of the common methods which apply the multi-attribute utility theory (MAUT) to construction projects. Several researchers successfully applied MIVES to select alternatives considering the whole life cycle of the project including social and environmental aspects (Ormazabal et al. 2008; San José and Garrucho 2010; Aguado et al. 2012; Pons et al. 2012).

3. DECISION-MAKING PROCESS

The decision-making process consists of four stages. These stages are described in the following sub-sections.

3.1 Tree Construction

A tree is the group of view-points from which the alternatives are judged. A typical tree related to building construction is presented in Table 1. The goal of this paper is not to determine a specific selection amongst alternatives, but to present the method and uncover its usefulness in order to manage complexity. Therefore, values of the weights and the specific structure of the tree presented in Table 1 are flexible and subject to change. The tree is unfolded into three levels, namely requirements, criteria, and indicators. Requirements are the most general standpoints and indicators are the most specific. Examples of requirements are Functional, Economic, Social and Environmental (San José and Garrucho 2010; Pons et al. 2012). Brief explanations are provided in the following bullets related to each of these requirements and their corresponding criteria and indicators:

- Functional requirement deals with quality perception (graded from 0 to 5) and is related to insiders (users) and outsiders (visitors) separately. Adaptability to changes means the convenience of the design for future changes during the life cycle of the building. Its response is measured as a percentage of the elements which are modular.
- Economic requirement is divided into two branches: construction cost and life cost. Several manufacturers will be involved in construction, maintenance and demolishing. However, the situation is more complicated for the life cycle, where even the user of the structure can change during its life cycle. This issue requires the economic requirement to be unfolded, at least to two criteria related to the separation of these two costs. Regarding the construction cost, the deviation of the cost, as a percentage of the estimated cost of construction, is an indicator that should be treated apart from the direct cost, as specified in Table 1. Life cost is unfolded into utilization, maintenance and losses. It is noted that those indicators are parts of the economic requirement, i.e. the environmental impact of energy consumption during construction and demolition will instead be taken into account when considering the environmental requirement. The "losses" indicator is described separately in the next section.
- Social requirement covers different positive and negative impacts of the considered building construction project. Integration of science, measured as a number of new patents applied in the building, is an attempt to integrate the satisfaction due to the social improvement derived from the innovation, similar to the case when part of the cost of the building reverts on local companies. Annoyance during construction and safety of workers (construction and maintenance) are other indicators concerning social aspects.
- The approach to the environmental requirement is realized by considering the life cycle, i.e. construction, utilization, and demolishing (San José and Garrucho 2010). The criterion "reintegration" could be unfolded into "recycle", "reuse", and

"solid waste". In our case, we only consider the solid waste with its negative impact. The more components of the building are able to be recycled or reused, the more reduction in the environmental disturbance due to the "solid waste" will be achieved.

Table 1: Tree and weights

Requirement	**W_{req} %**	**Criteria**	**W_{crit} %**	***i***	**Indicator**	**W_{ind} %**	**Units**
Functional	10.0	Quality perception	30.0	1	User	75.0	0-5
				2	Visitor	25.0	0-5
		Adaptability to changes	70.0	3	Modularity	100.0	%
Economic	50.0	Construction cost	50.0	4	Direct cost	80.0	$
				5	Deviation	20.0	%
		Life cost	50.0	6	Utilization	40.0	$
				7	Maintenance	30.0	$
				8	Losses	30.0	$
Social	20.0	Integration of science	10.0	9	New patents	100.0	#
		Work for local companies	10.0	10	Turnover	100.0	%
		Annoyance – construction	30.0	11	Dust	40.0	0-5
				12	Noise	40.0	0-5
				13	Street occupation	20.0	0-5
		Safety – construction	50.0	14	Risk of casualties	100.0	0-5
Environmental	20.0	Construction	20.0	15	Water consumption	10.0	m^3
				16	CO_2 emission	40.0	Kg
				17	Energy consumption	10.0	MJ
				18	Raw materials	20.0	Kg
				19	Solid waste	20.0	Kg
		Integration in environment	20.0	20	Visual	100.0	0-5
		Utilization	40.0	21	Noise, dust, smell	10.0	0-5
				22	Energy consumption	45.0	MJ/year
				23	CO_2 emission	45.0	kg/year
		Reintegration	20.0	24	Solid waste	100.0	Kg

* W_{req}: Weight of a requirement, W_{crit}: Weight of a criterion, W_{ind}: Weight of an indicator, *i*: Ordinal number of selected indicators

The branches of an unfolded tree should accomplish the following objectives:

1) Relevance
2) Difference-making for each one of the alternatives
3) Minimal number of items

Simplicity requires the use of only the most relevant aspects of the alternatives.

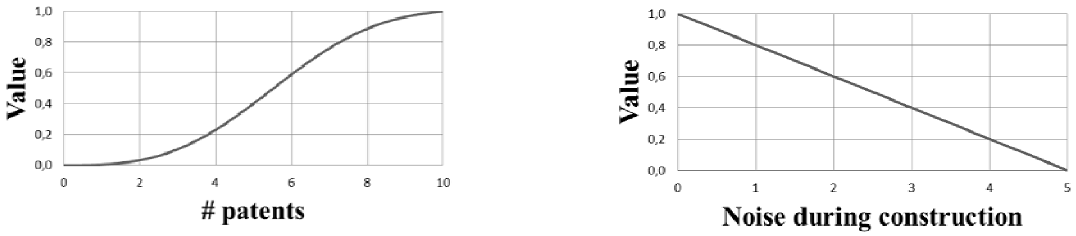
After the initial construction of the tree, branches which are not useful to differentiate the alternatives are deleted, e.g. structural reliability is not included when all alternatives are decided to be safe enough. It is necessary to reduce ("cut") the number of indicators and concretize in order to provide a clear and understandable picture of the problem to all the decision makers. Iyengar (2012) proposes the following four techniques in order to improve the decision-making process:

1) Cut (Less is more): Use three levels of unfolded branches, as used in the MIVES, and every branch to have no more than five sub-branches in the successive unfolding steps;
2) Concretize: Use indicators that both the experts and the stakeholders can understand;
3) Categorize: Use more categories and fewer choices; and
4) Complexity: Gradually increase the complexity.

The above tree construction framework allows us to include the important parameters and judge their relevance when assigning the weights. Some aspects of the tree structure can also be grounded in ethics. Melè (2009) refers to responsible use of natural resources, responsible use of energy, and avoiding pollution in all its forms (atmospheric, water, soil, visual, noise, light, and radioactivity). Corporations are responsible for waste production, disposal and recycling. A good strategy for environmental sustainability should consider increasing resource efficiency and prevent pollution, operating in a transparent and responsible manner based on a well-informed, active stakeholder relationship, and developing and/or using technologies that can provide innovative and potent solutions to render the basis of many of today's material-intensive industries obsolete.

3.2 Value Functions

Value functions transform the response of each indicator into a normalized value (between 0.0 and 1.0). Each one of the alternatives is analyzed from the point of view of every indicator and a response is obtained. The value function assesses to the decision-maker the level of satisfaction that every alternative gives in a selected standpoint. Fig. 1 shows two examples of value functions. In case (a), the value function indicates that the satisfaction is null when no patents are introduced in the building design and operation. The maximum value is reached for 10 new patents, but an increase in the number of patents will not give more satisfaction to the decision-maker. The application of 1 or 2 patents is slightly valuable, as concluded from the S-shape of the function. In case (b), the linear decrease of satisfaction with the increase of the noise level during construction, which is graded from 0 to 5, is shown. Further in-depth discussion about the value functions is not within the scope of this paper. The value functions are concisely presented herein in order to explain the decision-making process. The value function can be defined in many ways where those shown in Fig. 1 are selected from Alarcon et al. (2010). As demonstrated later in this paper for the application example, the value functions introduce the flexibility of using indicators with mixed units.



(a) # of patents in building design & operation
(b) Annoyance to neighbours (noise) during construction

Figure 1: Examples of value functions

3.3 Weight Assignment

Weights play an important role in quantifying the relative importance of each indicator, and accordingly they affect the overall preference evaluation of alternatives in many MCDM models. The AHP, one of the most widely used and extensively refined methods, can be applied to weight assignment. According to Saaty (1980, 2001), AHP consists of comparing the requirements one by one in terms of the criteria belonging to each requirement and similarly for the indicators. As a result, the weights are obtained as listed in Table 1. As indicated in Eq. (1), the sum of the weights of all the indicators of one criterion or all the criteria of one requirement or all requirements in the tree (Table 1) is 1.0 where the total number of these weights is *p*.

$$\sum_{i=1}^{p} w_i = 1.0 \tag{1}$$

3.4 Selection amongst Alternatives

The selection amongst alternatives is based on the calculated values of each one of these alternatives. The value V_k is the result of the integration of the values of every indicator (from 1 to N_{ind}) of any alternative *k*:

$$V_k = \sum_{i=1}^{N_{ind}} W_{req}^{i} \cdot W_{crit}^{i} \cdot W_{ind}^{i} \cdot V^{i}\left(X_k^{i}\right) \tag{2}$$

where the value function, $V^i(X_k^i)$, gives the value of each indicator *i* corresponding to the response of any k^{th} alternative, X_k^i. Other variables in Eq. (2) for a particular indicator *i* are defined in the footnote of Table 1. A sensitivity study is highly desirable to ensure the goodness of the most valuable alternative. The calculation of indicators requires “neutrality” (Ajibade 2009), i.e. the way to obtain the response cannot be pervaded by any kind of bias. Since the sum of all the weights is 1.0 as stated in Eq. (1), and each weight and $V^i(X_k^i)$ are between 0.0 and 1.0, V_k is also between 0.0 and 1.0. The value of each alternative is determined according to Eq. (2) where the alternative that has the highest value, i.e. the value closest to 1.0, can be determined, at least initially until the outcome of the sensitivity study, as the most suitable alternative.

4. CALCULATION OF THE PROBABILITY OF EXCEEDENCE OF AN INDICATOR

There are uncertainties in the determination of each indicator, in general. Hence, a probabilistic approach is required to evaluate the performance of a system in terms of these indicators. The developed framework in this paper is an extension of the performance-based engineering (PBE) methodology to consider the energy efficiency and sustainability in the evaluation process in addition to the usual structural safety (Günay and Mosalam 2012). Other methods can be found in the literature such as those documented in (Thor and Sedin 1980; Karimi and Hüllermeier 2007). Accordingly, structural safety, environmental responsibility, and human comfort constitute the objectives of this extended multi-objective framework and climate, energy, sustainability, and life cycle cost analyses are included in addition to the hazard, structural, damage, and loss analyses of the original PBE methodology (Günay and Mosalam in press). Multi-objective life cycle cost and sustainability curves can be obtained from this methodology to evaluate the performance of an existing structure or to make a decision amongst design alternatives for a new structure.

The Pacific Earthquake Engineering Research (PEER) Center developed a robust PBE focusing on earthquake engineering (PBEE), which is based on explicit determination of system performance measures meaningful to various stakeholder groups such as monetary losses, down time, and casualties based on probabilistic assessment as discussed in (Günay and Mosalam in press; Mosalam and Günay 2011). Fig. 2 presents the general PEER PBEE methodology consisting of four successive analyses: hazard, structural, damage, and loss. The methodology focuses on the probabilistic calculation of meaningful system performance measures to facility stakeholders by considering all the required analysis stages and the involved uncertainties in an integrated manner. It should be noted that Fig. 2 represents a possible idealization of the outline of the methodology, where variations are possible. In other words, the PBE can be one of the solutions to estimate the performance corresponding to each indicator, not only structural losses, but also other indicators such as maintenance cost, and CO_2 emissions during construction and operation.

The PBE results can be used as inputs for the corresponding indicators in MIVES or another Multi-Criteria Decision Analysis (MCDA) method. Even if methods are different in assessing the weights to each criterion, most methods qualitatively determine the preference. Therefore, it is possible to take into account the difference between alternatives for the evaluation of a particular criterion or multiple criteria.

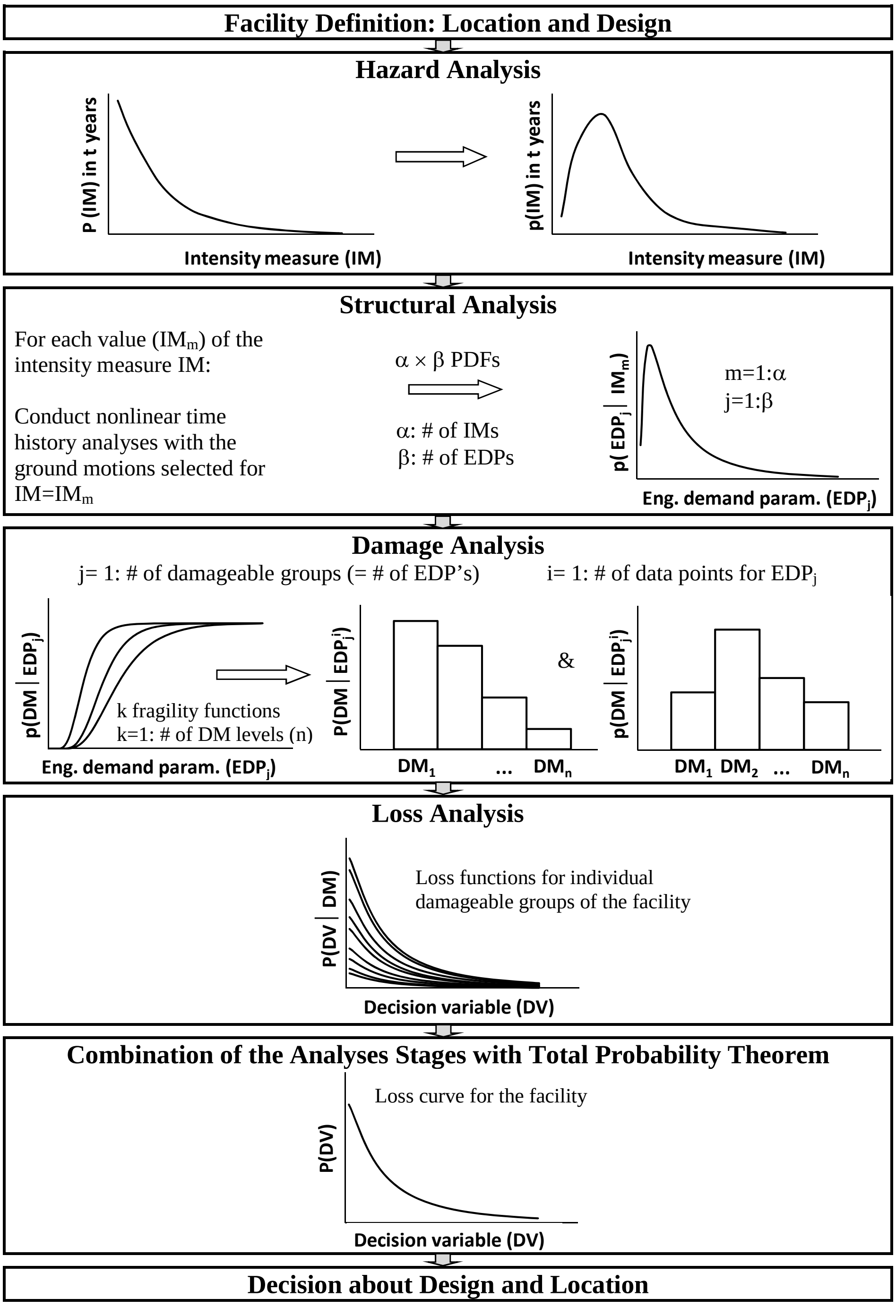


Figure 2: PEER PBEE methodology (Mosalam and Günay 2011)

The PBE methodology can be applied in order to calculate the expected value and POE of each decision variable. In the case of determining the expected value and POE of a specific sustainability random variable (DV_{SUS}), e.g. CO_2 emissions and energy expenditures, we define the following:

1) Climate Variable (*CV*): This can be the average outdoor temperature for the region where the building of interest is located.
2) Energy Measure (*EM*): This can be the energy consumption control level of the building, e.g. difference between outdoor and indoor temperatures. If the building is operated to achieve the most comfortable indoor temperature level all day long, the energy consumption will be different from that on the energy-saving level, even for the same building at the same outdoor temperature.
3) Decision Variable (*DV*): For evaluation of sustainability of the building, this can be a sustainable decision variable (DV_{SUS}), e.g. CO_2 emissions or energy expenditures.

Therefore, we have

$$E\left(DV_{SUS}\right) = \sum_{i}\sum_{m} E\left(DV_{SUS} \middle| EM_i\right) p\left(EM_i \mid CV_m\right) p\left(CV_m\right) \tag{3}$$

$$P\left(DV_{SUS}^{n}\right) = \sum_{i}\sum_{m} P\left(DV_{SUS}^{n} \middle| EM_i\right) p\left(EM_i \mid CV_m\right) p\left(CV_m\right) \tag{4}$$

where CV_m is the m^{th} value of the climate variable, $E(DV_{SUS}|EM_i)$ and $P(DV_{SUS}^{n}|EM_i)$ are, respectively, the expected value of DV_{SUS} and the POE of the n^{th} value of DV_{SUS} when it is subjected to the i^{th} value of the *EM*, $p(EM_i|CV_m)$ is the conditional probability for the i^{th} value of *EM* when the m^{th} value of *CV* is realized, and $p(CV_m)$ is the probability of the m^{th} value of *CV*.

Considering the decision variables as indicators, Eq. (3) can be used to determine the expected value of a value function $V^i(X_k^i)$. The calculated expected values can subsequently be substituted in Eq. (2) to determine the expected value of the overall value V_k. This simple approach is useful to consider the probabilistic nature of the indicators in an indirect manner, as opposed to the direct consideration using Eq. (4) in conjunction with Eq. (10) discussed in the next section. This simplicity offered by Eqs. (2) and (3) is only applicable under the condition of the indicators being uncorrelated.

5. MULTIPLE INDICATORS CONSIDERED IN A PROBABILISTIC MANNER

The probabilistic nature of the indicators is indirectly considered in the above approach by the calculation of the value of each indicator, *i*, and its value function for the k^{th} alternative, $V^i(X_k^i)$, in a probabilistic manner. Alternatively, Eq. (2) can be directly formulated in a probabilistic manner, which is termed as PBE-MIVES in the remaining part of the paper. In this case, since two or more indicators are considered in the MCDM, the probabilistic approach requires more involved calculations than the general MCDM. For example, the general MIVES, including the *indirect* probabilistic approach mentioned above, only deals with a single value for each indicator, and it is not necessary to consider the correlation between them. On the other hand, the conditional probability of each indicator should be defined when the PBE-MIVES is applied. For example, assume that three indicators are considered to estimate the value of each alternative, and that they are the CO_2 emissions (DV_{CO2}), the energy expenditures (DV_E), and the initial cost of the facility (DV_{IC}) during the life cycle of a specific building. Assume that the probability density function (PDF) of each indicator is defined as follows:

$$f_{CO2}\left(DV_{CO2}=a\right)=A, \quad f_E\left(DV_E=b\right)=B, \quad f_{IC}\left(DV_{IC}=c\right)=C \tag{5}$$

where f_{CO2}, f_E, and f_{IC} are the PDFs for DV_{CO2}, DV_E, and DV_{IC}, respectively. If the corresponding weights are respectively w_{CO2}, w_E, and w_{IC}, the combined value of all three indicators at a, b, and c is computed as follows:

$$V\left(a,b,c\right)=V_{CO2}\left(a\right)+V_E\left(b\right)+V_{IC}\left(c\right)=w_{CO2}u_{CO2}\left(a\right)+w_Eu_E\left(b\right)+w_{IC}u_{IC}\left(c\right) \tag{6}$$

where u_{CO2}, u_E, and u_{IC} are the value functions for DV_{CO2}, DV_E, and DV_{IC}, respectively. If DV_{CO2} , DV_E, and DV_{IC} are mutually independent, one obtains,

$$\begin{aligned} f\left(a,b,c\right) &= f_{CO2,E,IC}\left(DV_{CO2}=a, DV_E=b, DV_{IC}=c\right) \\ &= f_{CO2}\left(DV_{CO2}=a\right) f_E\left(DV_E=b\right) f_{IC}\left(DV_{IC}=c\right)=ABC \end{aligned} \tag{7}$$

Otherwise,

$$\begin{aligned} f\left(a,b,c\right) &= f_{CO2,E,IC}\left(DV_{CO2}=a, DV_E=b, DV_{IC}=c\right) \\ &= f_{CO2}\left(DV_{CO2}=a\right) f_{E|CO2}\left(DV_E=b \middle| DV_{CO2}=a\right) f_{IC|CO2,E}\left(DV_{IC}=c \middle| DV_{CO2}=a, DV_E=b\right) \end{aligned} \tag{8}$$

Therefore, the conditional probability distribution should be defined if the decision criteria are not mutually independent. It is noted that the POE (in case of a continuous PDF) for each indicator is calculated as follows:

$$P\left(DV^n=a\right)=p\left(DV>DV^n=a\right)=\int_a^\infty f_{DV}\left(DV\right)d\left(DV\right) \tag{9}$$

where $P(DV^n)$ is the POE of the n^{th} value of DV, and $p(DV > DV^n = a)$ is the probability of DV exceeding a, the n^{th} value of DV. It is noted that the PDFs for each indicator, DV, and accordingly the overall value, V, are nonnegative everywhere, and the integral of each PDF over the entire space is equal to one, so as the V value. For comparison of two or more alternatives, the V value which accounts for the corresponding PDF in the specific domain Ω of interest for the considered indicators, i.e. V_{prob}, can be calculated as follows:

$$V_{prob}=\int_\Omega Vfd\Omega \tag{10}$$

representing the expected value of an alternative, V_k in (2), and can be used to rank the different alternatives.

6. APPLICATION OF PBE-MIVES TO THE HYPOTHETICAL BUILDING

In this paper, an application of the direct probabilistic consideration of the indicators in MIVES is presented for a hypothetical residential building in Singapore, Fig. 3. It is a two-story building with three bedrooms, two bathrooms, a living room, a kitchen, a staircase, a utility room, and a garage. The first floor has interior space of 87.5 m^2 excluding the garage, and the second floor has 75 m^2. Hence, the building has interior space of 162.5 m^2. The roof is assumed to be suitable for installation of solar photovoltaic (PV) panels. Since the roof surface is about 78 m^2, the maximum PV panel surface is also 78 m^2 assuming the panels are closely mounted on the roof.

Decisions in real situations are made based on various requirements. However, for brevity in this paper, only economic and environmental requirements are considered in this example. Table 2 presents the suggested weights for the selected indicators. A comparable study for the UCS building at the UC-Berkeley can be found in Mosalam et al. (2012).

(a) First floor (b) Second floor

Figure 3: Plan views of the hypothetical residential building

Table 2: Decision criteria for the hypothetical example building

Requirement	***W$_r$* [%]**	**Criteria**	***i***	**Indicator**	***W$_i$* [%]**	**Unit**
Environmental	25.0	Utilization	1	CO_2 emissions	100.0	tonne
Economic	75.0	Life cost	2	Energy expenditures	60.0	S$1,000
		Construction cost	3	Initial cost of facility for the solar PV system	40.0	S$1,000†

†In this study, this indicator is treated as deterministic for simplicity.

In case of landed properties in Singapore, the *average monthly* household electricity sales were 1203, 1229, and 1190 kWh in years 2009, 2010, and 2011, respectively (Energy Market Authority (EMA) 2012). Although the given values are independent from the size of the household, they are used in this example due to the lack of data on residential buildings in Singapore, to the best of the authors' knowledge. The corresponding electricity tariffs were 20.5, 23.5, and 26.0 S¢/kWh, and they were increasing in terms of the overall trend from 2005 (EMA 2012). Therefore, one can calculate the charge for electricity used in this hypothetical building per year as S$2959.38, S$3465.78, S$3712.80 in years 2009, 2010, and 2011, respectively.

EMA (2012) also provides the electricity grid emission factors. Simple operating margin (OM) values for years 2009, 2010, and 2011 were 0.5042, 0.5154, 0.5146 kg CO_2/kWh, respectively, and build margin (BM) values were 0.4208, 0.4319, 0.4578 kg CO_2/kWh for years 2009, 2010, and 2011, respectively. In this paper, OM values are used to estimate the CO_2 emissions of the building. Therefore, if all the electricity used in this building was provided by the grid, CO_2 emissions per year are calculated as 7278.6, 7601.1, and 7348.5 kg based on the data from years 2009, 2010, and 2011, respectively.

For the first facility plan (Plan 1), it is assumed that this building is operated by using electricity from the grid only. Assuming that the energy use remains constant (taken as the average of the electricity sales in years 2009 to 2011, i.e. 1207.33 kWh/month) during the life span of the building, taken as 50 years herein (i.e. grid electricity consumption for plan 1 is E_{G1}=1207.33×12×50/1000=724.4 MWh), in which the electricity tariff is assumed to increase by 5% per year, and that energy expenditure in the first year is the average of those from year 2009 to 2011 (i.e.S$3379.32/year), then the total energy expenditure during the life of the building is (3379.32×[1-1.05^{50}]/[1-1.05]=S$707,454) Similarly, CO_2 emission during the life of the building is calculated, using the constant annual emission as the average of that from years 2009 to 2011 (i.e. 7409.4 kg/year), to be 370,470 kg, i.e. 370.5 tonnes. Since this alternative assumes that the building relies fully on the electricity grid, there is no need to use PV panels. Therefore, the installation cost of PV panels is zero.

For the second and third facility plans (Plans 2 and 3), it is assumed that the building is operated by using electricity from the grid and the PV panels installed on the roof. Since the life span of the panels is about 25 years, it is required to replace them at least once. It is assumed that the PV panels can fully cover the roof, and that they will be replaced after 25 years, i.e. once during the 50 years building life span (Plan 2) or every 17 years, i.e. twice (Plan 3). According to EMA and BCA (2011), a typical 10-kW rooftop solar PV system using crystalline modules in Singapore would produce about 11,000 to 12,500 kWh in a year. Since a typical module of 0.6465 m^2 provides rated power, P_{max}, of 0.1 kW, it is feasible to install a 10-kW solar PV system, which is below the maximum installation capacity of (78/0.6465×0.1≈12-kW) limited by the roof surface. In this example, it is assumed that the installed solar PV system can produce 12,000 kWh per year. However, the performance of a solar PV system does not remain on the same level during its life. EMA and BCA (2011) specifies that Initial Warranted Power (IWP) is about 95% of P_{max}, that the warranted power for 10 years is 90% of IWP, and that for 20-25 years is 80% of IWP. Therefore, 80% and 85% of IWP are selected as generated power for 25 years, and for 17 years, respectively.

The solar PV system results in less energy expenditure and CO_2 emission compared to the case of fully relying on the grid, but there are other expenses regarding installation, maintenance, and replacement of the panels. They should be considered to evaluate the cost-effectiveness. If the cost of installation is unknown, c_{ini}, and the cost of solar PV has been decreasing by 4% a year (EMA and BCA 2011), then the total installation cost of the PV system is 1.36c_{ini}, in case of 25-year usage (Plan 2). If one wants to replace the system every 17 years (Plan 3), it is 1.75c_{ini}. The generated electricity based on Plan 2 is (E_{PV2}=12,000×50×0.95×0.80=456,000 kWh), and that based on Plan 3 is (E_{PV3}=12,000×50×0.95×0.85=484,500 kWh) for 50 years.

For the fourth and fifth plans (Plans 4 and 5), it is assumed that the PV system is installed only once. It can be installed at the construction of the building (Plan 4) or it can be mounted on the roof later, e.g. 25 years after the construction (Plan 5). Similar to the assumption for Plan 2, the PV system is considered working normally for 25 years with 80% of IWP. Due to the change in electricity tariff and installation cost with time, Plans 4 and 5 have different energy expenditures and initial costs of the facility. Regarding the initial costs of the facility, Plans 4 and 5 have 1.00c_{ini}, and 0.36c_{ini}, respectively.

The parameters of the PDF for CO_2 emissions and energy expenditures during the building life span, considered 50 years herein, are presented in Table 3. For CO_2 emissions, it is assumed that the same amount of CO_2 is produced each year. For both of CO_2 emissions (x_1) and energy expenditures (x_2), it is assumed that each standard deviation value is 30% of the corresponding mean. For simplicity, it is assumed that the joint distribution of CO_2 emissions (x_1) and energy expenditures (x_2), $f_{CO_2,E}$, is a bivariate lognormal distribution, and that the correlation coefficient, ρ_{ln}, is 0.7. Since the initial cost of the facility (x_3) does not heavily depend on the environment, it is assumed that x_3 is not a random variable in this example, and the probability of x_3 is 1.0 for each plan. As a result, there is no need to define a probabilistic distribution for c_{ini} and only the joint probability of x_1 and x_2 is considered to calculate V_{prob}.

Table 3: Parameters of the probability distribution for CO_2 emissions (x_1) and energy expenditures (x_2) for 50 years life span

	Grid electricity consumptions [MWh]	**CO_2 emissions** [tonne]		**Energy expenditures** [S$1,000]	
		Mean	Standard deviation	Mean	Standard deviation
Plan 1	E_{G1}=724.4	370.5	111.2	707.5	212.3
Plan 2	E_{G1}-E_{PV2}=268.4	137.3	41.2	262.0	78.6
Plan 3	E_{G1}-E_{PV3}=239.9	122.7	36.8	234.1	70.2
Plan 4	E_{G1}-0.5 E_{PV2}=496.4	253.9	76.2	605.9	181.8
Plan 5	E_{G1}-0.5 E_{PV2}=496.4	253.9	76.2	363.5	109.1

Fig. 4 presents the bivariate lognormal distribution function of CO_2 emissions (x_1) and energy expenditures (x_2) for Plan 5. It has a peak near the mean values specified in Table 3, and a long tail which spreads to the positive x_1 and x_2. It is assumed that the value functions for x_1, x_2, and x_3, are piecewise linear (constant, linear with negative slope, and constant) functions as defined as specified in Eq. (11), and that (x_a, x_b) for x_1, x_2, and x_3 are (0, 600), (0, 1000), and (0, 1.75c_{ini}), respectively. It is to be noted that the specific value of the constant c_{ini} does not need to be specified for the purpose of this comparative example between plans 1 to 5.

$$\begin{aligned} u(x) &= 1.0 \quad if\ x \le x_a \\ &= 1.0 - (x - x_a)/(x_b - x_a) \quad if\ x_a < x \le x_b \\ &= 0.0 \quad if\ x > x_b \end{aligned} \tag{11}$$

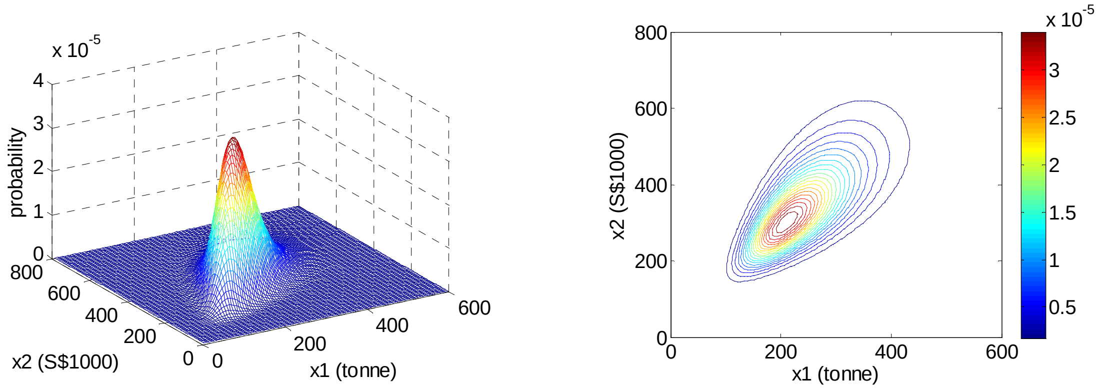


Figure 4: Probability density function of CO_2 emissions (x_1) and energy expenditures (x_2) for Plan 5 of the example residential building

The expected value in Eq. (10), V_{prob}, in a specific domain, Ω, can be determined using Eq. (12). According to weights specified in Table 2, $V_{IC}(x_3) = 0.75 \times 0.4 \times u_3(x_3) = 0.3u_3(x_3)$, and the corresponding probability is 1.0.

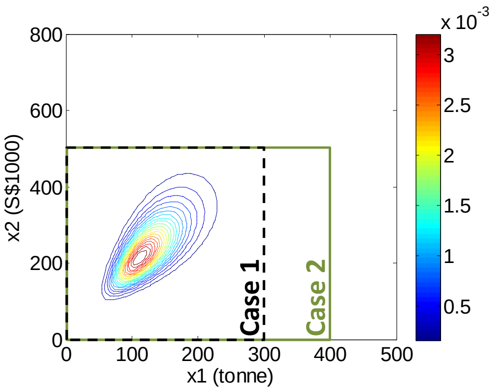
$$V_{prob} = \int_\Omega V f d\Omega = \iint_\Omega \left(V_{CO2}(x_1) + V_E(x_2) + V_{IC}(x_3)\right) f(x_1, x_2)\, dx_1 dx_2 \tag{12}$$

Fig. 5 shows the contour plots of Vf for the two alternatives, Plans 2 and 5. A developed Matlab code was used as a computational platform of PBE-MIVES to calculate V_{prob} and visualize Vf. If two different domains are considered, e.g. $0 \le x_1 \le 300$, $0 \le x_2 \le 500$ (Case 1), and $0 \le x_1 \le 400$, $0 \le x_2 \le 500$ (Case 2), the considered five plans have the expected values, i.e. the mean values of V, and coefficients of variation

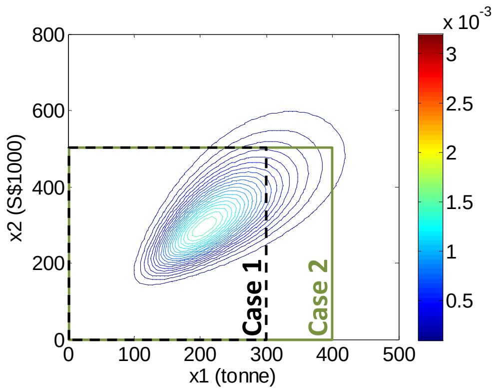
(COV) specified in Table 4. In summary, Plan 2 is the best in the first domain choice, Case 1, but Plan 5 may be the best in the second domain choice, Case 2. This observation implies that the selection of the "best" decision in terms of the mean depends on the selection of the domain, i.e. the range of variables that we are interested in. It is noted that COV of Plans 1 and 4 are significantly higher than that of Plan 5, even though Plans 1, 4, and 5 have similar standard deviation values. Since COV is the normalized standard deviation based on the mean, a very small mean value produces a large COV, Table 4. The small mean is mainly due to the fact that the probability density functions of Plans 1 and 4 have their peaks (Table 3, especially for x_2) outside the two domains of Cases 1 and 2.

Table 4: Calculated mean and COV for *V* of the five plans in the selected domains

	Case 1 $0 \le x_1 \le 300,\ 0 \le x_2 \le 500$		**Case 2** $0 \le x_1 \le 400,\ 0 \le x_2 \le 500$	
	Mean	COV	Mean	COV
Plan 1	0.0786	2.8384	0.1001	2.4476
Plan 2	0.5755	0.1939	0.5761	0.1902
Plan 3	0.5314	0.1739	0.5316	0.1725
Plan 4	0.1638	1.5598	0.1672	1.5341
Plan 5	0.5056	0.6280	0.5894	0.4187



(a) Plan 2



(b) Plan 5

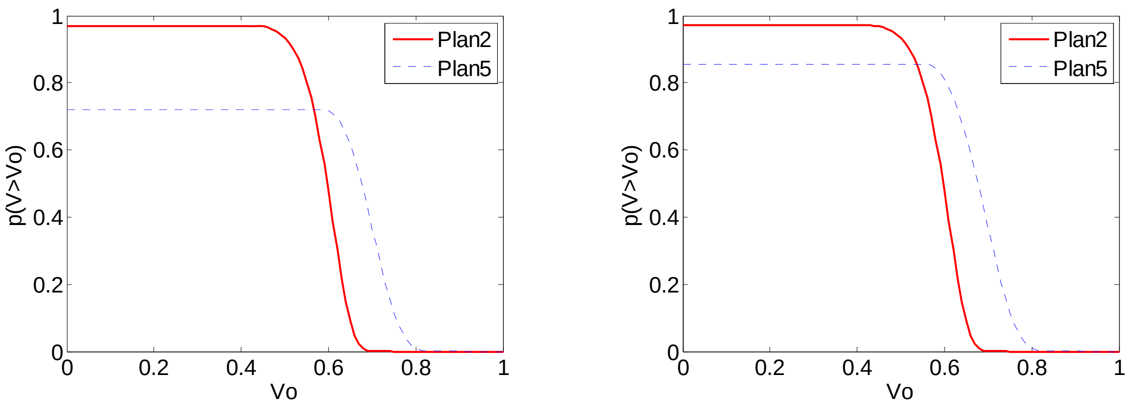
Figure 5: Contours of *Vf* of CO_2 emissions (x_1) and energy expenditures (x_2) for Plans 2 and 5 of the example residential building

It is noted that *Vf* of Plan 2 has a higher peak compared to that of Plan 5, and it is concentrated near the center of the first domain (dashed rectangle), as shown in Fig. 5. Therefore, there is no big difference between V_{prob} in the two domains for Plan 2, i.e. 0.5755 and 0.5761. Since Plan 5 has a wider distribution of *V*, it has significantly larger

V_{prob} in Case 2 compared to that in Case 1. If the COV of V is considered, Plan 5 may not be the best choice even in Case 2.

Fig. 6 presents the probability of V exceeding a specific value V_O for Plans 2 and 5 within the specified two different domains. It is clearly shown that Plan 2 has higher probability when V_O < 0.566 and V_O < 0.535 in Cases 1 and 2, respectively. This is mainly attributed to the higher concentration of $f(x_1, x_2)$ of Plan 2 in each domain. However, Plan 5 becomes higher than Plan 2 above the specified V_O and it produces the larger mean value in Case 2, as discussed above. The distributions of the POE in Fig. 6 indicate that the evaluation based on mean values may not be sufficient when the COV is considered. In this example, Plans 2 and 5 may not be the best choices above V_O = 0.566 in Case 1 and below V_O = 0.535 in Case 2, respectively.

The value of Plan 2 at V_O = 0.0 hardly changes between the two domains (from 0.970 to 0.971) but that of Plan 5 increases significantly (from 0.720 to 0.856). It is noted that the probability of V exceeding zero in Fig. 6 is not 1.0 because the probability within each domain is not 1.0. The values of Plans 2 and 5 in Case 1 remain constant until V_O reaches 0.43 and 0.60, respectively, and those in Case 2 remain constant until V_O = 0.42 and 0.56, respectively. These threshold values in Case 2 are slightly smaller than those in Case 1 because the domain in Case 2 is larger than that in Case 1. The difference in the threshold values of the two plans is due to $V_{IC}(x_3)$. Since the initial cost of Plan 5 is lower than that of Plan 2, V_{IC} of Plan 5 is larger than that of Plan 2. Therefore, even with the same (x_1, x_2), the overall value of Plan 5 is larger than that of Plan 2, i.e. Plan 5 has larger projected surface area of $V > V_O$ over x_1-x_2 plane than that of Plan 2 for the same V_O. Hence, between the two plans, Plan 5 has a larger V_O, which makes the projected line of $V = V_O$ over x_1-x_2 plane touch the border of the specified domain of Case 1 or 2. If there is no difference in V_{IC}, the threshold values are identical for the same domain, e.g. if V_{IC} = 0.0, the threshold value is 0.36 and 0.32 for both plans in Cases 1 and 2, respectively. It is expected that application of different value functions would change the threshold values. This issue will be examined in a future study.



(a) Case 1 (b) Case 2

Figure 6: Probability of V exceeding a specific value, V_O, for Plans 2 and 5 within the specified two domains

7. SUMMARY AND CONCLUSIONS

Multi criteria decision analysis (MCDA) is an appropriate tool in order to reach the "best" decision when selecting amongst alternatives in building construction or operation management. Only a holistic approach, which considers all components, current and future stakeholders, points of view and the complete life cycle, will identify the "best" alternative. Using a specific MCDA tool, e.g. Model for Integration of Values for Evaluation of Sustainability (MIVES), the economic, functional, environmental, and social aspects of the decision-making are integrated in this paper. The performance-based engineering (PBE) approach is incorporated in MIVES to account for the probabilistic nature of the indicators. Tangible benefits derived from the correct application of MCDA are identified, namely minimizing disputes, solving conflicts, strengthening the commitment of stakeholders towards the good running of the project. Achieved conclusions can be itemized as follows:

1) The probabilistic nature of the indicators can be considered in MCDA either indirectly by the calculation of the value of each indicator in a probabilistic manner or directly by formulating the value determination equation in a probabilistic framework.
2) The correlation between the different indicators is taken into account in the direct formulation and it should be the preferred method when there is significant interdependency between the indicators.
3) The adoption of the value functions in the method allows for the consideration of a broad range of indicators and eliminates the necessity of using indicators having the same units.
4) As shown in the hypothetical example building in Singapore, considered range of indicators can change the value of the alternatives and affect the final decision. Therefore, attention should be paid to the selection of the proper range of indicators.
5) As discussed in the example of the hypothetical building in Singapore, the installation of solar PV system reduces dependence on electricity from the grid and accordingly energy expenditures and CO_2 emissions. However, the installation cost is currently significantly high and it varies substantially depending on the local conditions. Fortunately, the cost has been decreasing by virtue of technical development and market growth, and it significantly increases cost-effectiveness of solar PV systems. If this downward trend continues, and if the PV system can work longer, the use of solar PV systems during the whole life span of a building (e.g. Plans 2 and 3 in the illustrated example) will be the best choice in a typical domain of interest of the decision variables.

The proposed methodology can be implemented in a general design approach such as in the Building Information Modelling (BIM) with refinement and systemization. It will contribute a better estimation of each alternative and consequently a better design and operation choices of a building.

ACKNOWLEDGMENT

The presented research is funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. The authors thank J. Armengou, S.-P. Chiew, S. Günay, N. Modrego, and U. Alibrandi for stimulating discussions and technical inputs.

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