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Performance-based Engineering Approach to the Best Decision for Energy-efficient and Sustainable Building Design

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MOTIVATION

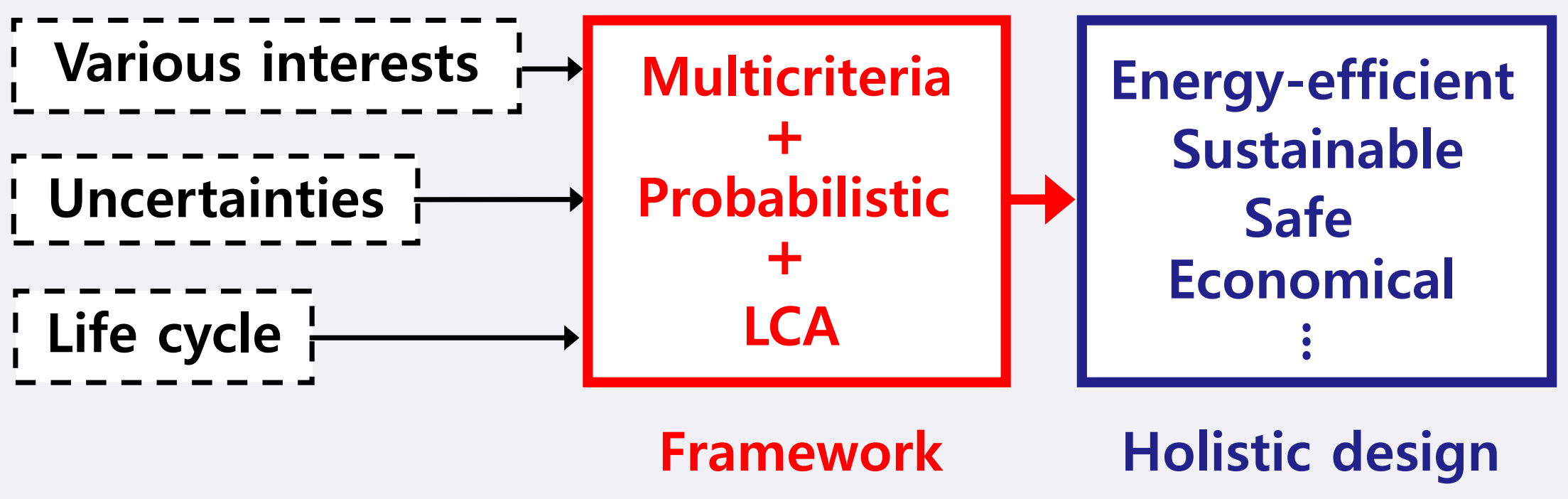
In any stage of a construction project, the decision-making processes play a crucial role from many different standpoints. Multicriteria analysis is a useful tool to be used from the beginning of project planning. However, most multicriteria decision making methods applied in construction management are <u>deterministic</u>. They provide simple and clear concepts to stakeholders, but may <u>distort reality due to sources of uncertainty</u>. In this research, the performance-based engineering (PBE) approach, an extensively used probabilistic approach developed by UC-Berkeley researchers, substitutes for deterministic quantification and provide a deeper understanding of the value of each design alternative.

MAIN OBJECTIVES

Develop a framework to make the best decision for building design, which is

- ✓ **Energy-efficient**
- ✓ **Sustainable**
- ✓ **Safe**
- ✓ **Economical, etc.**

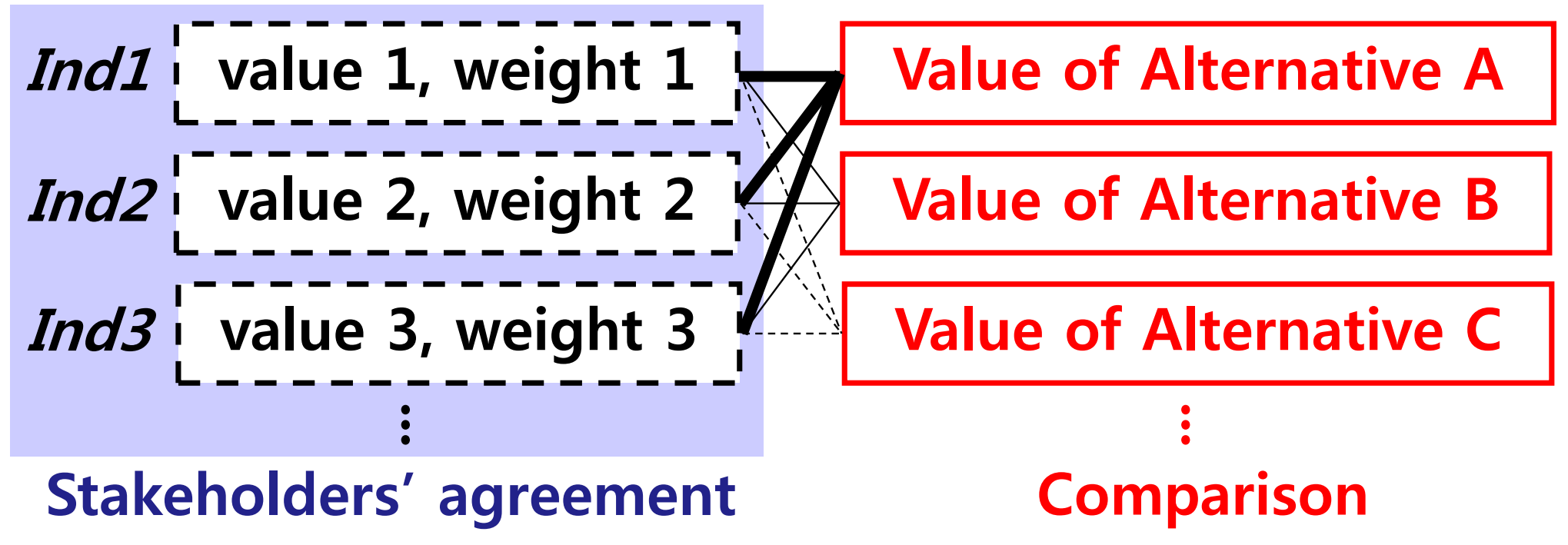
considering interests of **various stakeholders** and accounting for **all sources of uncertainties** during the **life cycle** of the building.


Various interests
Uncertainties
Life cycle
Multicriteria
+
Probabilistic
+
LCA
Energy-efficient
Sustainable
Safe
Economical
⋮
Framework
Holistic design

MULTI-CRITERIA DECISION MAKING (MCDM)

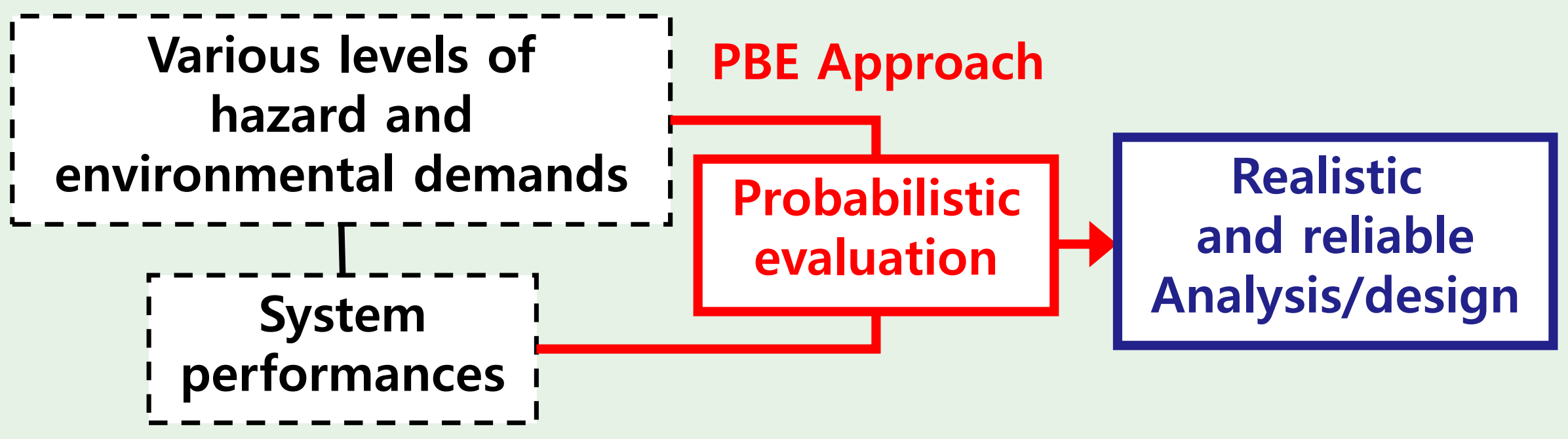
Based on the value for each **indicator** which quantifies each design aspect, the overall evaluation of a design alternative is performed. To reflect the **relative importance** of these design aspects, **weights** are determined by stakeholders through a process where the following questions should be answered (Bandte, 2000):

- ✓ Is preference information required?
- ✓ Is preference presented as relative weights?
- ✓ Will the weights be generated during the process?


Ind1 value 1, weight 1
Ind2 value 2, weight 2
Ind3 value 3, weight 3
⋮
Value of Alternative A
Value of Alternative B
Value of Alternative C
⋮
Stakeholders' agreement
Comparison

PERFORMANCE-BASED ENGINEERING (PBE) METHODOLOGY

- **Design framework** resulting in the **desired system performances at various intensity levels** of the hazard/environmental demands
- **Explicit calculation** of system performance measures in a rigorous **probabilistic** manner without heavily relying on expert opinion
- Outcome in terms of the **direct interests** of various stakeholders


Various levels of hazard and environmental demands
System performances
PBE Approach
Probabilistic evaluation
Realistic and reliable Analysis/design

$$P\left(DV_j^n \middle| EDP_j^i\right)=\sum_k P\left(DV_j^n \middle| DM_k\right) p\left(DM_k \middle| EDP_j^i\right)$$

$$P\left(DV_j^n \middle| IM_m\right)=\sum_i P\left(DV_j^n \middle| EDP_j^i\right) p\left(EDP_j^i \middle| IM_m\right)$$

$$P\left(DV^n \middle| IM_m\right)=\sum_j P\left(DV_j^n \middle| IM_m\right)$$

$$P\left(DV^n\right)=\sum_m P\left(DV^n \middle| IM_m\right) p\left(IM_m\right)$$

- ✓ Intensity Measure (IM)
- ✓ Engineering Demand Parameter (EDP)
- ✓ Damage Measure (DM)
- ✓ Decision Variable (DV)

IM can be average outdoor temperature for energy expenditure and CO_2 emission. For structural safety under extreme loads, IM can be a spectral quantity, e.g. acceleration (*Sa*) based on selected probability of exceedance (POE) & return period at the building site.

MODEL FOR INTEGRATION OF VALUES FOR EVALUATION OF SUSTAINABILITY (MIVES)

Similar to the Analytic Hierarchy Process (AHP), MIVES estimates the value of each design alternative based on weights. The process consists of the following 4 stages:

- Tree construction
- Application of value functions: *unique feature*
- Weight assignment
- Overall evaluation, i.e. selection of "best" solution

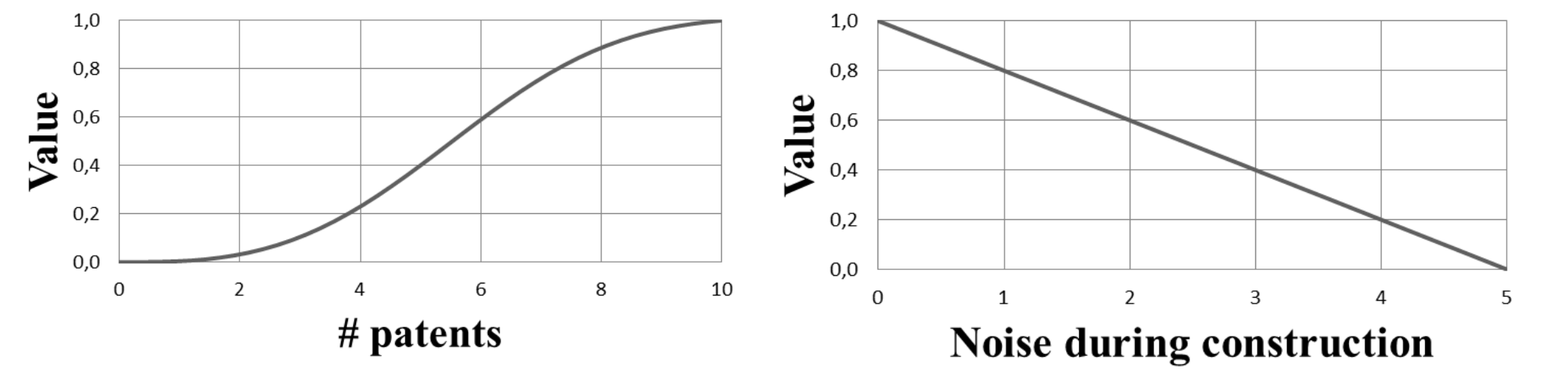
overall value of alternative *k*

$$V_k=\sum_{i=1}^{N_{ind}} W^i \cdot V^i\left(X_k^i\right)$$

weight for indicator *i*

value of indicator *i*

Value functions transform the response of each indicator into a normalized value (between **0** and **1**).



PBE-MIVES

PBE approach is combined with MIVES where multiple indicators are considered in a probabilistic manner.

Assume 3 indicators (DVs) are considered, namely CO_2 emissions, energy expenditures, & economic loss during the life cycle of a building, with corresponding probability density functions (PDFs):

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

Using the weights and value functions, the overall value is:

$$V(a,b,c)=V_{CO2}(a)+V_E(b)+V_{ST}(c)=w_{CO2}u_{CO2}(a)+w_E u_E(b)+w_{ST}u_{ST}(c)$$

If the DVs are **mutually independent**, the joint PDF is:

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

else

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

FUTURE WORK

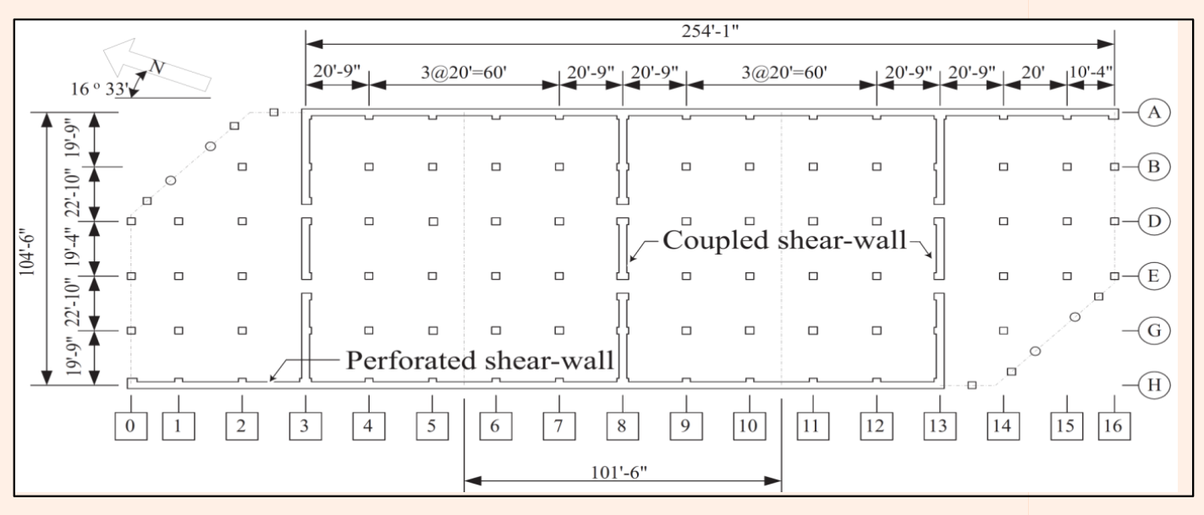
- **Selecting major indicators and corresponding weights in office building design**
- **Collecting data/defining probability distributions & correlations for office buildings in the tropics**
- **Accounting for results obtained from various testbeds, e.g. on newly developed façade systems**
- **Evaluating the efficiency of a newly developed technologies, e.g. novel façade systems**

<u>References</u>

- Bandte, O. (2000). "A probabilistic multi-criteria decision making technique for conceptual and preliminary aerospace systems design". PhD Thesis. Georgia Institute of Technology.
- Mosalam, K. and Günay, S. (2011). "Probabilistic seismic assessment: PEER formulation". Prepared for CEB-FIP TG7.7 State-of-the-Art document: Probabilistic Performance-Based Seismic Design.

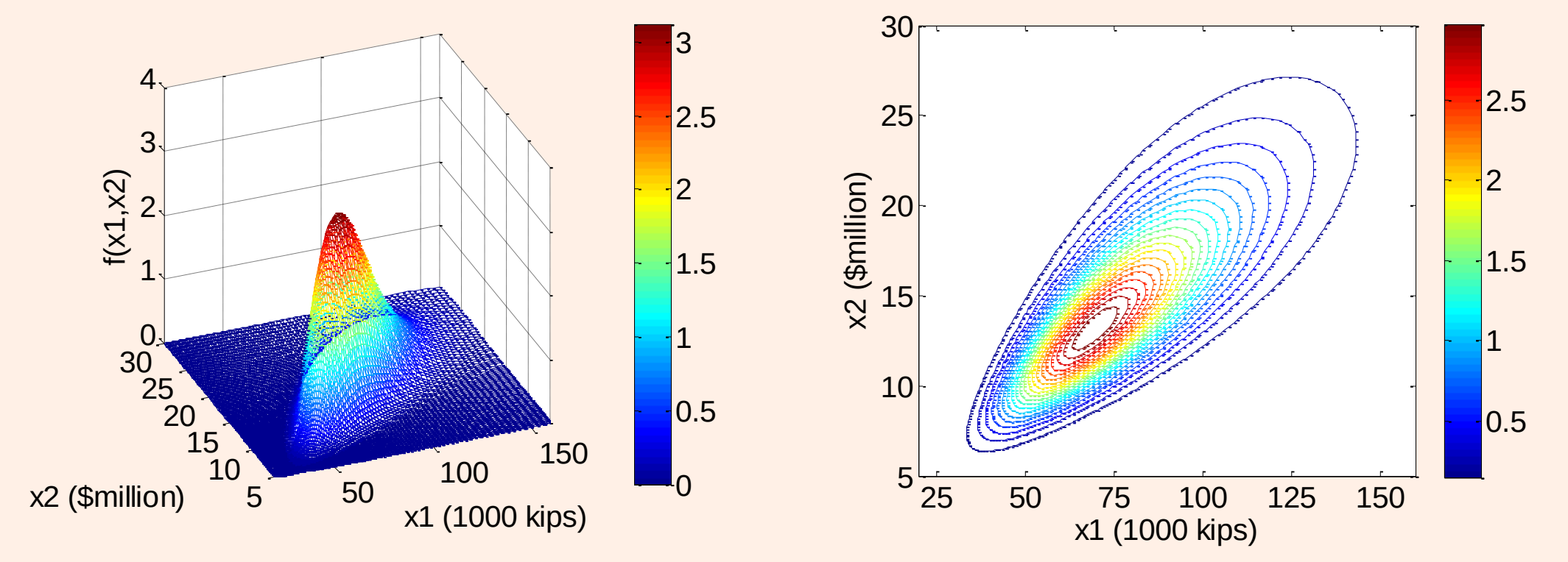
EXAMPLE: APPLICATION OF PBE-MIVES

UCS on UCB campus is a modern RC shear-wall building with major research laboratories. Consider 2 design alternatives for fuel consumption (Btu) ratios:



- **Plan 1** Electricity : Natural gas = 5 : 2
- **Plan 2** Electricity only

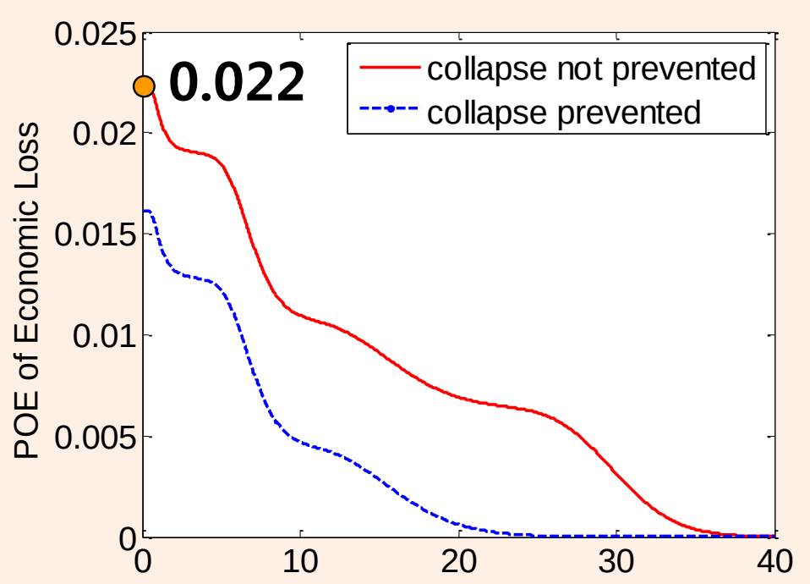
- ✓ Bivariate lognormal distribution assumed for CO_2 emissions (x_1) and energy expenditures (x_2) for the building life span, 50 years
- ✓ Mean values estimated based on the US data for office buildings in the West-Pacific region (DOE, EIA, & EPA)
- ✓ Standard deviation assumed 30% of corresponding mean value
- ✓ Coefficient of correlation (x_1 & x_2) assumed 0.8



PDF of CO_2 emissions (x_1) & energy expenditures (x_2) for **Plan 1**

- ✓ Economic loss (x_3) due to EQ with 2% POE in 50 years
- ✓ x_3 is independent from x_1 & x_2
- ✓ Linearly decreasing value functions for x_1, x_2, & x_3

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



Twofold response of economic loss (x_3) (Mosalam & Günay, 2011)

Expected value of an alternative

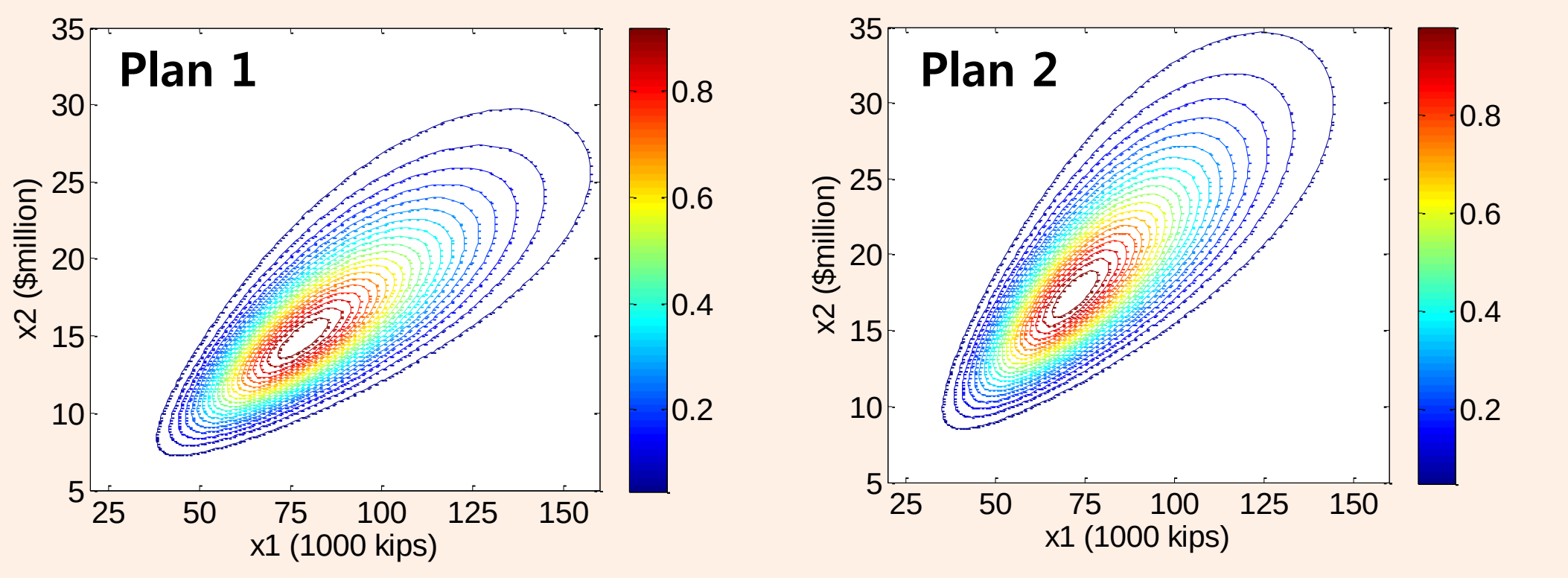
$$V_{prob}=\int_\Omega Vfd\Omega$$

If there is no loss due to EQ, i.e. $x_3 = 0$

Case 1: $0 \le x_1 \le 80$, $0 \le x_2 \le 15$
V_{prob} = **309.52 (Plan 1)**, 223.56 (Plan 2)

Case 2: $0 \le x_1 \le 80$, $0 \le x_2 \le 20$
V_{prob} = 393.95 (Plan 1), **449.61 (Plan 2)**

⇨ **Domain dependency!**



Contours of ***Vf*** of CO_2 emissions (x_1) and energy expenditures (x_2) for **Plans 1 and 2** [Economic loss due to structural damages x_3 = 0]

Weight assignment for 3 indicators

Requirement	*W_r* [%]	Criteria	*i*	Indicator	*W_i* [%]	Unit
Environmental	25.0	Utilization	1	CO_2 emissions	100.0	1000 kips
Economic	75.0	Life cost	2	Energy expenditures	60.0	$million
			3	Economic loss	40.0	$million

CONCLUDING REMARKS

- In a holistic approach to identify the "best" alternative, the following should be considered:
  - ✓ Interests of various stakeholders
  - ✓ Whole life cycle
  - ✓ All sources of uncertainties
- PBE approach provides a realistic and reliable solution in MCDM.
- PBE-MIVES is a viable approach, especially as a simple and efficient probabilistic MCDM tool.
- Since PBE-MIVES is a probabilistic method, the "best" alternative depends on the PDF of each indicator, correlations, the pre-defined domain, etc.

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