SinBerBEST
Annual Meeting 2013

Technical Session 2

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

H. Lee, K.M. Mosalam & S.P. Chiew

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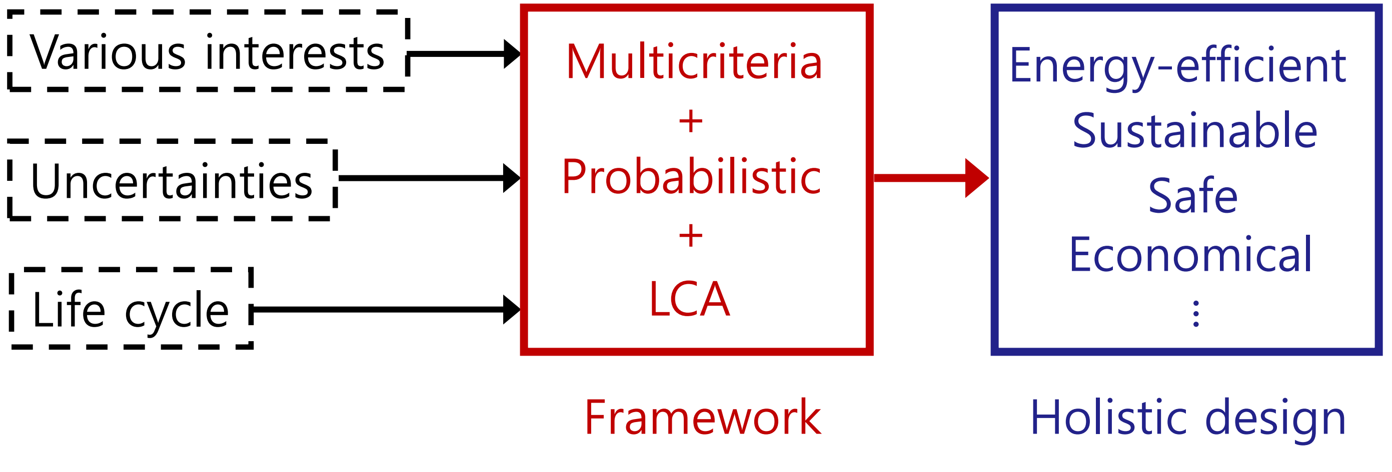
PBE-Approach to the Holistic Best Design Decision

❑ Objective

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

- ✓ Energy-efficient
- ✓ Sustainable
- ✓ Safe
- ✓ Economic, etc.

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



PBE-Approach to the Holistic Best Design Decision

Decision-Making Process:

MIVES (Model for Integration of Values for Evaluation of Sustainability)

4 steps:

- Tree Construction
- Value Function
- Weight Assignment
- Selection Amongst Alternatives

PBE-Approach to the Holistic Best Design Decision

MIVES: Decision-Making Process

- **Tree Construction**

San José and Garrucho (2010); Pons (2011)

The branches of a tree should accomplish the followings:

✓ Relevance
✓ Difference-making for each one of the alternatives
✓ Minimal number of items

Iyengar (2012) [http://www.trendhunter.com/keynote/sheena-iyengar]

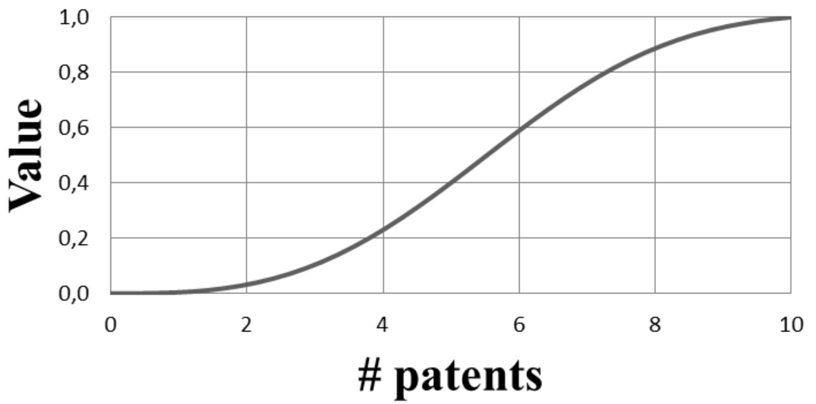
✓ **Cut**: Use 3 levels of unfolded branches, and every branch to have 5 sub-branches or less in the successive unfolding steps;
✓ **Concretize**: Use indicators that experts and stakeholders can understand;
✓ **Categorize**: Use more categories and fewer choices; and
✓ **Condition**: Gradually increase the complexity.

PBE-Approach to the Holistic Best Design Decision

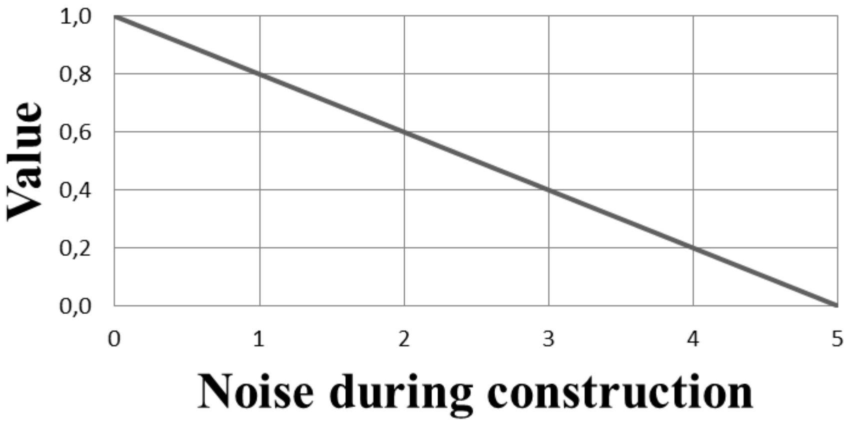
❑ MIVES: Decision-Making Process

- **Value Functions**
  - ✓ Non-negative increasing/decreasing functions, $0 \leq V^i\left(X_k^i\right) \leq 1$
  - ✓ Linear, concave, convex, S-shaped, etc.
  - ✓ Presence of value functions allows for consideration of a broad range of indicators and relaxes need for using indicators with same units.

Examples



Number of **new patents** used in building design



Annoyance to neighbours (**noise**) during construction

PBE-Approach to the Holistic Best Design Decision

❑ MIVES: Decision-Making Process

▪ Weight Assignment

Requirement	W_{req} %	Criteria	W_{crit} %	*i*	Indicator	W_{ind} %	Unit
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	#
		⋮	⋮	⋮	⋮	⋮	⋮
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
		Utilization	40.0	20	Noise, dust, smell	10.0	0-5
				21	Energy consumption	45.0	MJ/year
				22	CO_2 emission	45.0	kg/year
		⋮	⋮	⋮	⋮	⋮	⋮

Slides 9 to 11

PBE-Approach to the Holistic Best Design Decision

❑ MIVES: Decision-Making Process

- **Selection Amongst Alternatives**

Integration of values of every indicator of an alternative *k*

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

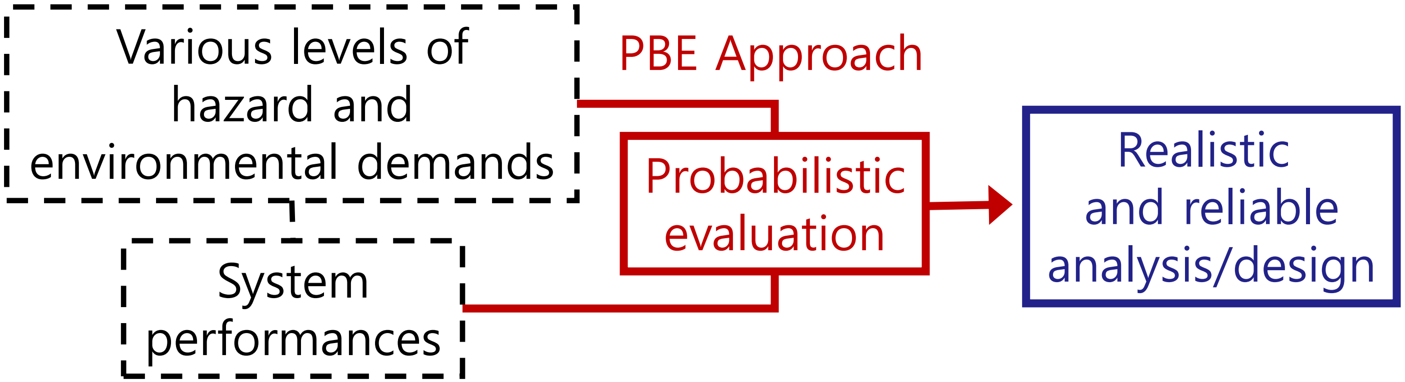
Weights — Value function

✓ The overall value of each alternative is determined → The alternative that has the **highest** value, i.e. closest to **1.0**, becomes the most suitable alternative, i.e. the "**best**" solution.

PBE-Approach to the Holistic Best Design Decision

❑ PBE approach

- Design framework resulting in the desired system performances at various intensity levels of hazards or 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

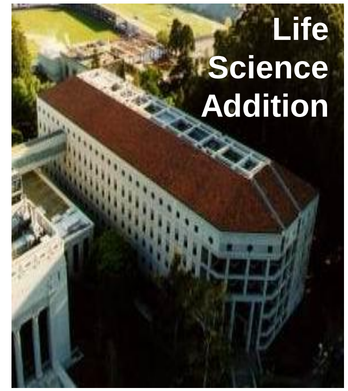


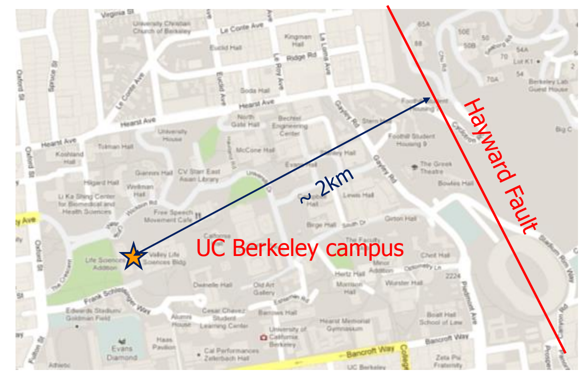
Testbed for PBE-Approach

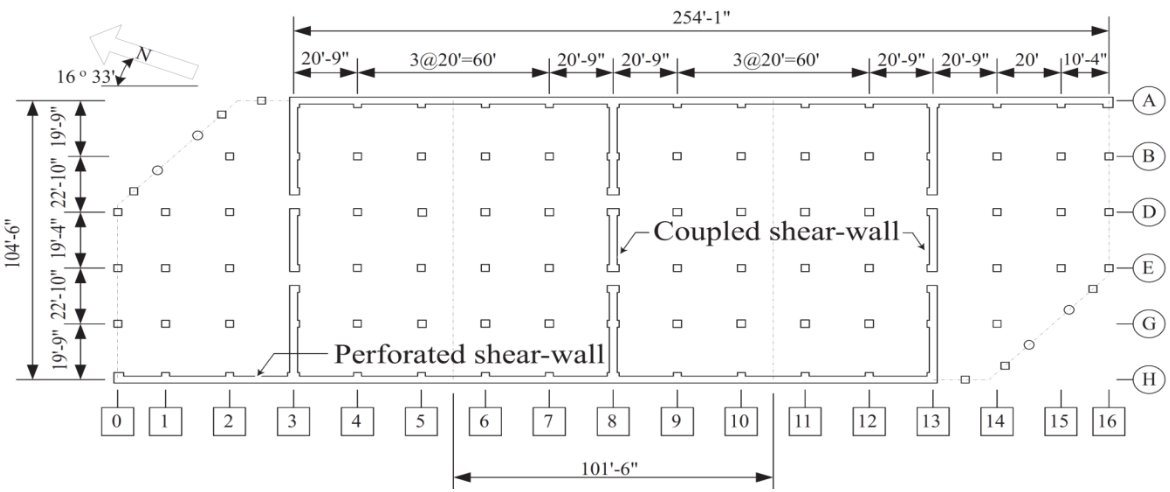
Example building: UCS building at UCB

Economic loss due to EQ [**2% POE in 50 years**]

POE and PDF can be calculated based on the total probability theorem.

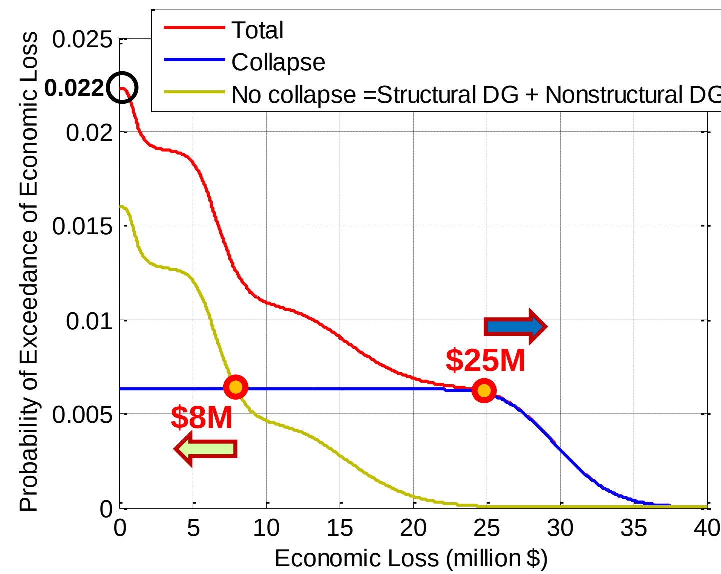






Plan view of the UCS building located at UC-Berkeley campus

Lee & Mosalam, 2006



Loss Curve

Mosalam & Günay, 2011

PBE-Approach: Extension to Indicators in the Tree

PBE for Earthquake Engineering

$$P(DV) = \sum \left[P(DV \mid EDP_{NC}, IM) \cdot p(EDP_{NC} \mid IM) + P(DV \mid EDP_{C}) \cdot p(EDP_{C} \mid IM) \right] \cdot p(IM)$$

- ✓ **Intensity Measure (IM)**
- ✓ **Decision Variable (DV)**
- ✓ **Collapse (C) & No Collapse (NC)**

For structural safety: IM can be *Sa* [spectral quantity] based on a certain POE & return period at a specific site.

PBE for Sustainability

$$P(SDV) = \sum P(SDV \mid EM) \cdot p(EM \mid CV) \cdot p(CV)$$

- ✓ **Climate Variable (CV)**
- ✓ **Energy Measure (EM)**
- ✓ **Sustainability Decision Variable (SDV)**

For Indicators, e.g. sustainability decision variable such as CO_2 emission: IM can be substituted with one of the environmental demands, CV, e.g. average outdoor temperature.

PBE-Approach: PBE-MIVES

Multiple Indicators in a Direct Probabilistic Manner

Assume **3** indicators DV_{CO2}, DV_E and DV_{ST} with PDFs:

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

Weights: w_{CO2}, w_E & w_{ST}, **Value functions**: u_{CO2}, u_E, & u_{ST} → Overall value for the indicators:

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

If DV_{CO2}, DV_E & DV_{ST} are **mutually independent**, the joint PDF is:

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

else,

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

Conditional probability distribution should be defined.

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

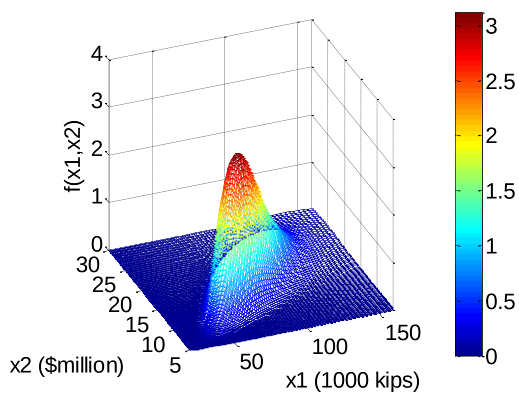
$P(DV^n)$: POE of n^{th} value of DV, $p(DV > DV^n = a)$: probability of DV exceeding a, *the* n^{th} value of DV.

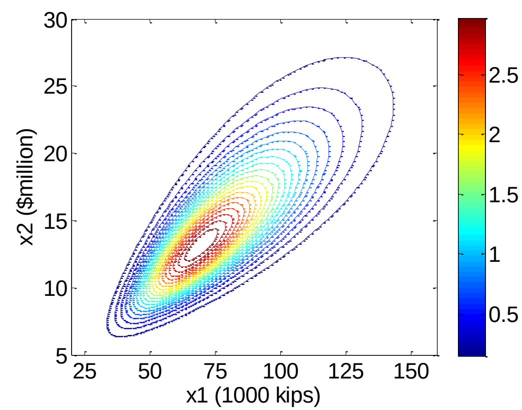
PBE-MIVES: Application to the UCS Building

- **Two alternatives with different fuel consumption ratios**

  Electricity : Natural gas = 5 : 2 (**Plan 1**) in Btu, Electricity only (**Plan 2**)

- **Assumptions for the energy expenditure and CO_2 emission**
  - ✓ Bivariate lognormal distribution assumed for energy expenditure and CO_2 emission for **50** years (**building life span**).
  - ✓ Each mean value estimated based on data for **office buildings** in the West-Pacific region (by DOE, EIA, & EPA).
  - ✓ Standard deviation assumed as **30%** of the corresponding mean value.
  - ✓ Coefficient of correlation assumed as **0.8**.





Probability density function of CO_2 emission (x_1) and energy expenditure (x_2) for **Plan 1**

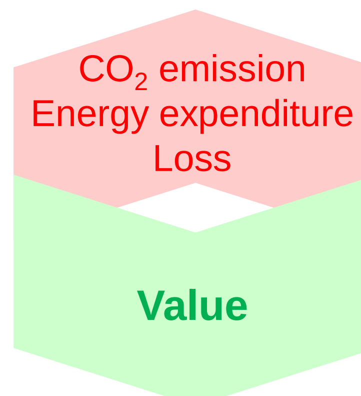
PBE-MIVES: Application to the UCS Building

Tree Construction and Weight Assignment

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	Losses	40.0	$million

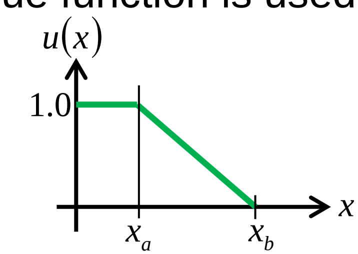
correlated (1000 kips; $million — indicators 1 and 2)

independent ($million — indicator 3)



Value Functions

Linearly decreasing value function is used for each indicator.



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

PBE-MIVES: Application to the UCS Building

Selection Amongst Alternatives

$$V_{prob} = \int_{\Omega} V f d\Omega$$

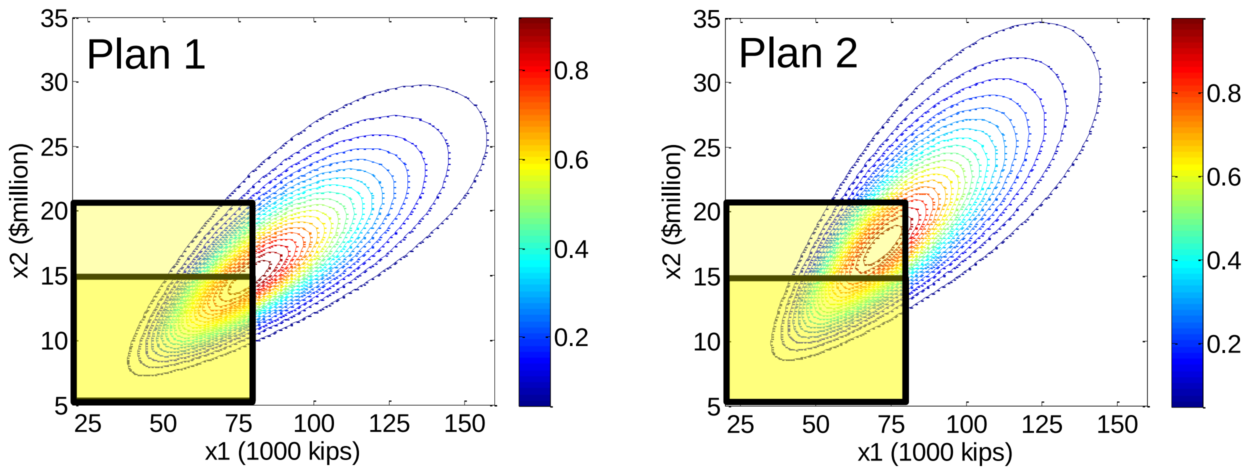
The expected value of each alternative in a pre-defined domain → rank alternatives

No economic loss due to EQ, i.e. $\boldsymbol{x_3 = 0}$

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

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

Domain Dependency !

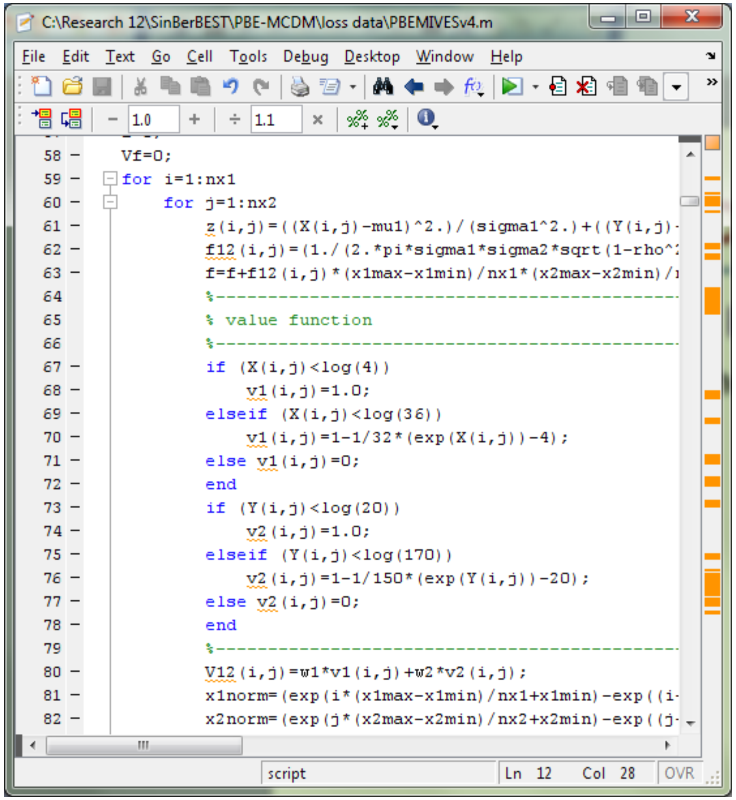


Contours of ***Vf*** of CO_2 emissions (x_1) and energy expenditures (x_2) for Plans 1 and 2 of the UCS example building
[Monetary loss due to structural damages $x_3 = 0$]

Concluding Remarks

- ✓ The probabilistic nature of the indicators can be considered in MCDA either indirectly by calculating the value of each indicator in a probabilistic manner or directly by formulating the value determination equation in a probabilistic framework.
- ✓ The correlation between the different indicators is taken into account in the direct formulation and it is the preferred method when there is significant interdependency between indicators.
- ✓ In the comparison of V_{prob} in the UCS application building, considered range of indicators can change the value of the alternatives and affect the final decision. Attention should be paid to the selection of the proper range of indicators.

Matlab code for PBE-MIVES



Future Work

- ✓ Selecting major indicators (including those for safety and health in construction activities) 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

Thank You!

Questions? Comments?