Future Extension to Multi-objective Performance-based Sustainable Design

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Introduction

Analogy to Hierarchy of Needs (Maslow, 1963)

Sustainability

PEER
PBEE

Required to guarantee the fulfillment of the basic needs of the future generations

Establish safety and move to the upper levels

Introduction

Analogy to Hierarchy of Needs (Maslow, 1963)

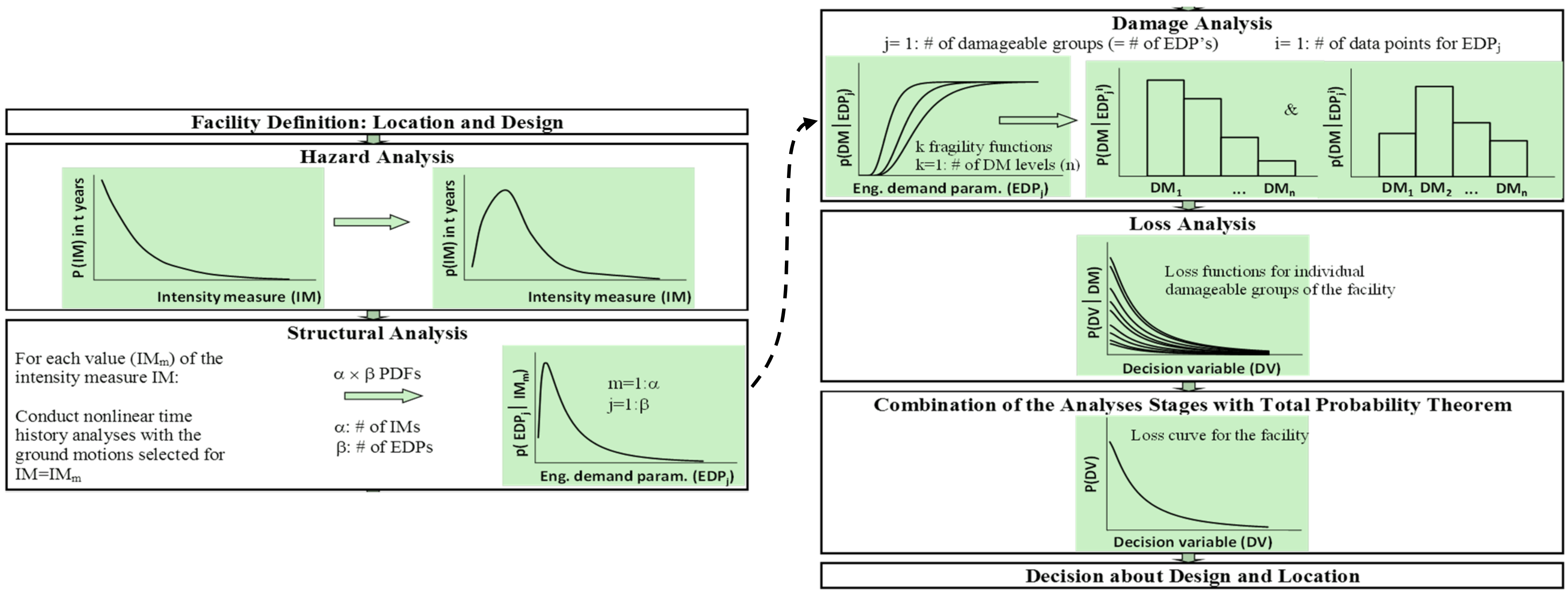
- Basic Needs: Safety Objective → PEER PBEE Probabilistic Formulation
- Upper Level Needs for sustainability: Environmental safety and human comfort objectives → Uncertain and probabilistic by nature
- Motivation for an inherent extension of PEER methodology to a generalized probabilistic multi-objective framework

Objective	Required Analysis Type						
	Hazard	Structural	Damage	Climate	Energy	Sustainability	Life Cycle Cost
Structural Safety	√	√	√				√
Environmental Responsibility				√	√	√	√
Human Comfort				√	√	√	√

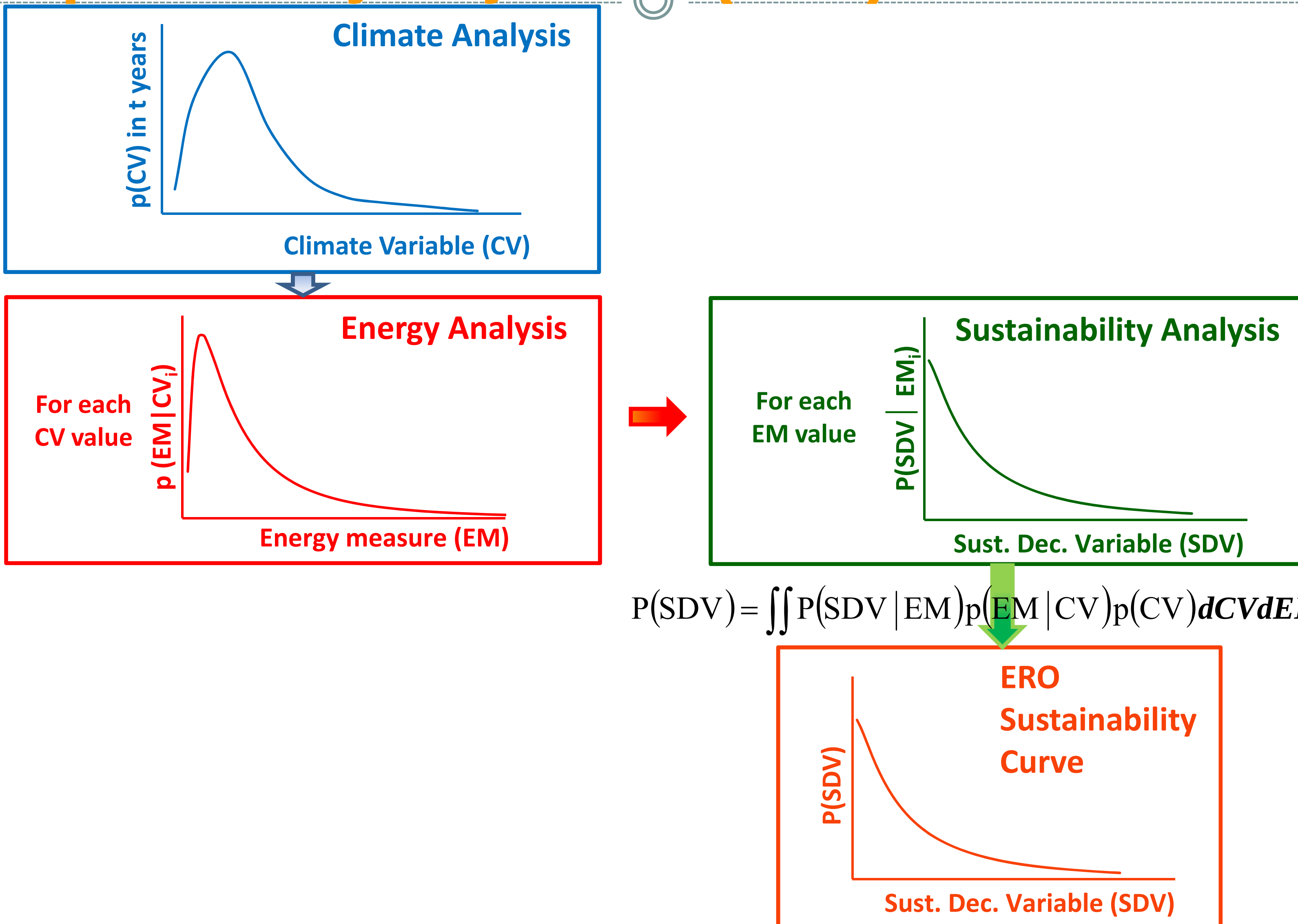
Extended Framework: Safety Objective

Structural Safety Objective:

$$P(DV) = \int\int\int P(DV|DM)\, p(DM|EDP)\, p(EDP|IM)\, p(IM)\, \boldsymbol{dIM\ dEDP\ dDM}$$



Extended Framework: Environmental Responsibility Objective (ERO): Sustainability



$$P(SDV) = \iint P(SDV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$

Extended Framework: Environmental Responsibility Objective (ERO): Sustainability

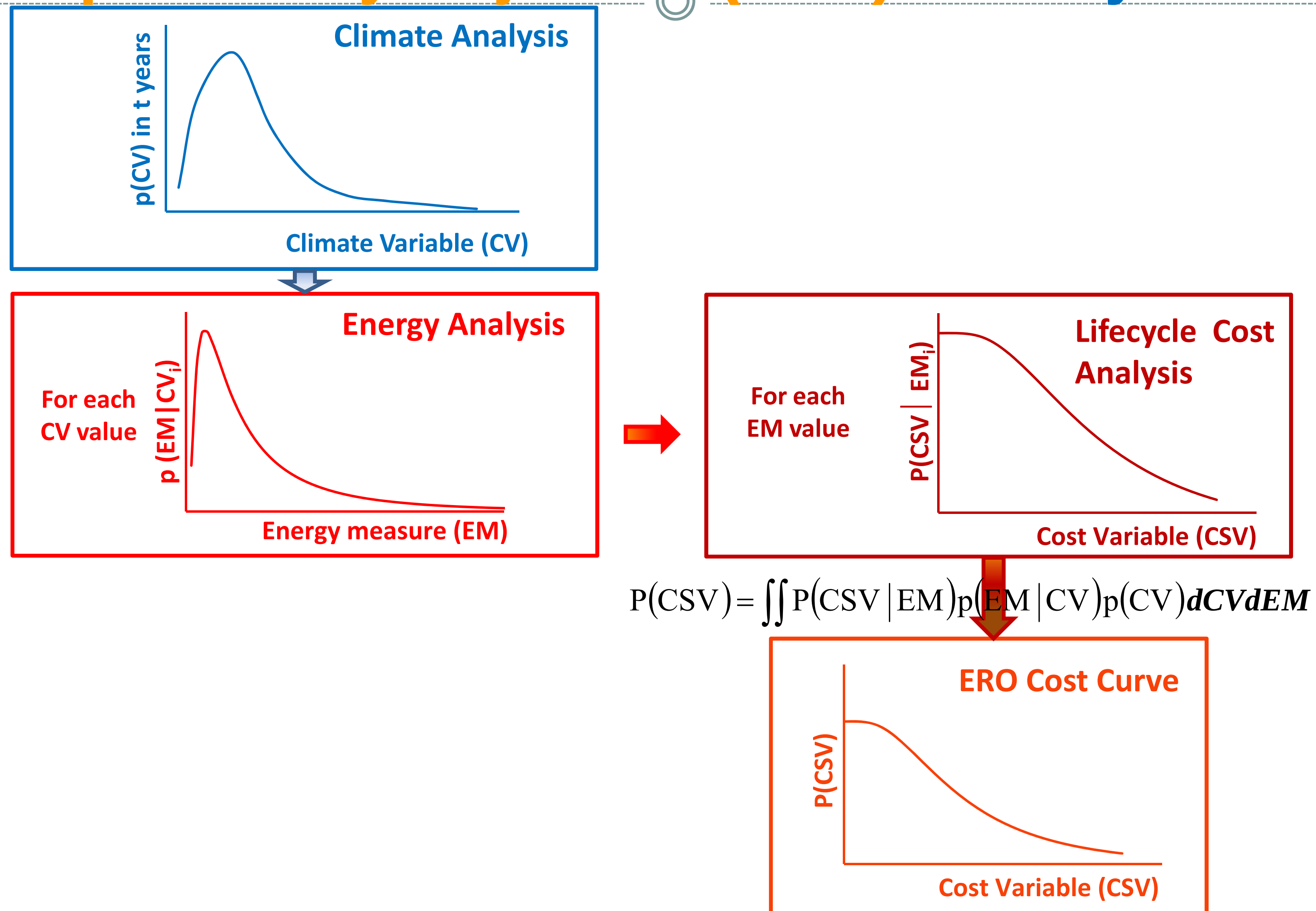
$$P(SDV) = \iint \underbrace{P(SDV|EM)}_{\text{Sustainability Analysis}} \underbrace{p(EM|CV)}_{\text{Energy Analysis}} \underbrace{p(CV)}_{\text{Climate Analysis}} \boldsymbol{dCVdEM}$$

SDV : Sustainability Decision Variable, e.g. Carbon or ecological footprint

EM : Energy measure, e.g. Building energy

CV : Climate Variable, e.g. Temperature change

Extended Framework: Environmental Responsibility Objective (ERO): Life Cycle Cost



$$P(CSV) = \iint P(CSV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$

Extended Framework: Environmental Responsibility Objective (ERO): Life Cycle Cost

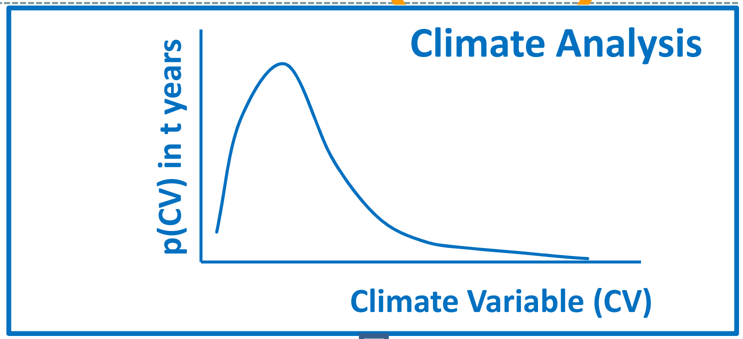
$$P(CSV) = \iint \underbrace{P(CSV|EM)}_{\text{Lifecycle Cost Analysis}} \underbrace{p(EM|CV)}_{\text{Energy Analysis}} \underbrace{p(CV)}_{\text{Climate Analysis}} \, \boldsymbol{dCVdEM}$$

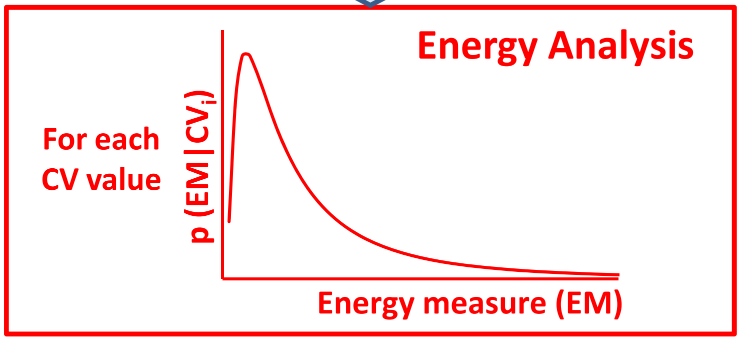
CSV: Cost/Saving Variable, e.g. Ratio initial cost/savings during lifecycle

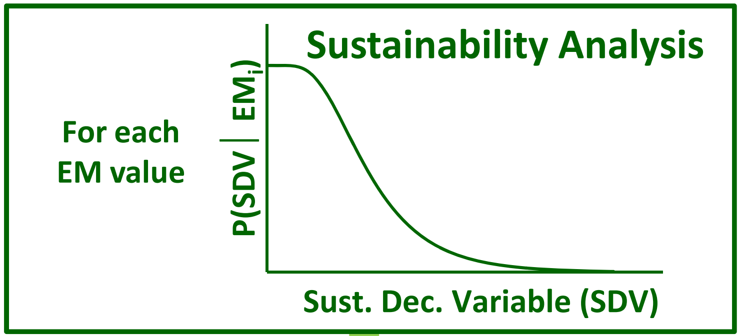
EM: Energy measure, e.g. Energy consumption

CV: Climate Variable, e.g. Temperature change

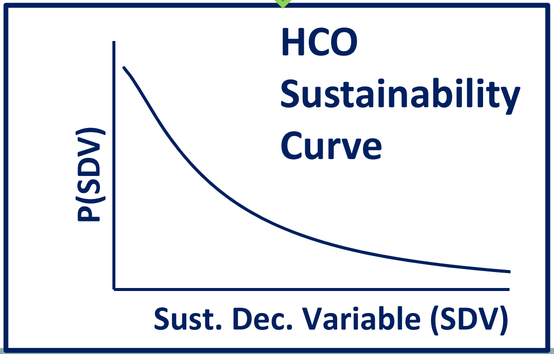
Extended Framework: Human Comfort Objective (HCO): Sustainability







$$P(SDV) = \iint P(SDV\,|\,EM)\,p(EM\,|\,CV)\,p(CV)\,\boldsymbol{dCVdEM}$$



Extended Framework: Human Comfort Objective (HCO): Sustainability

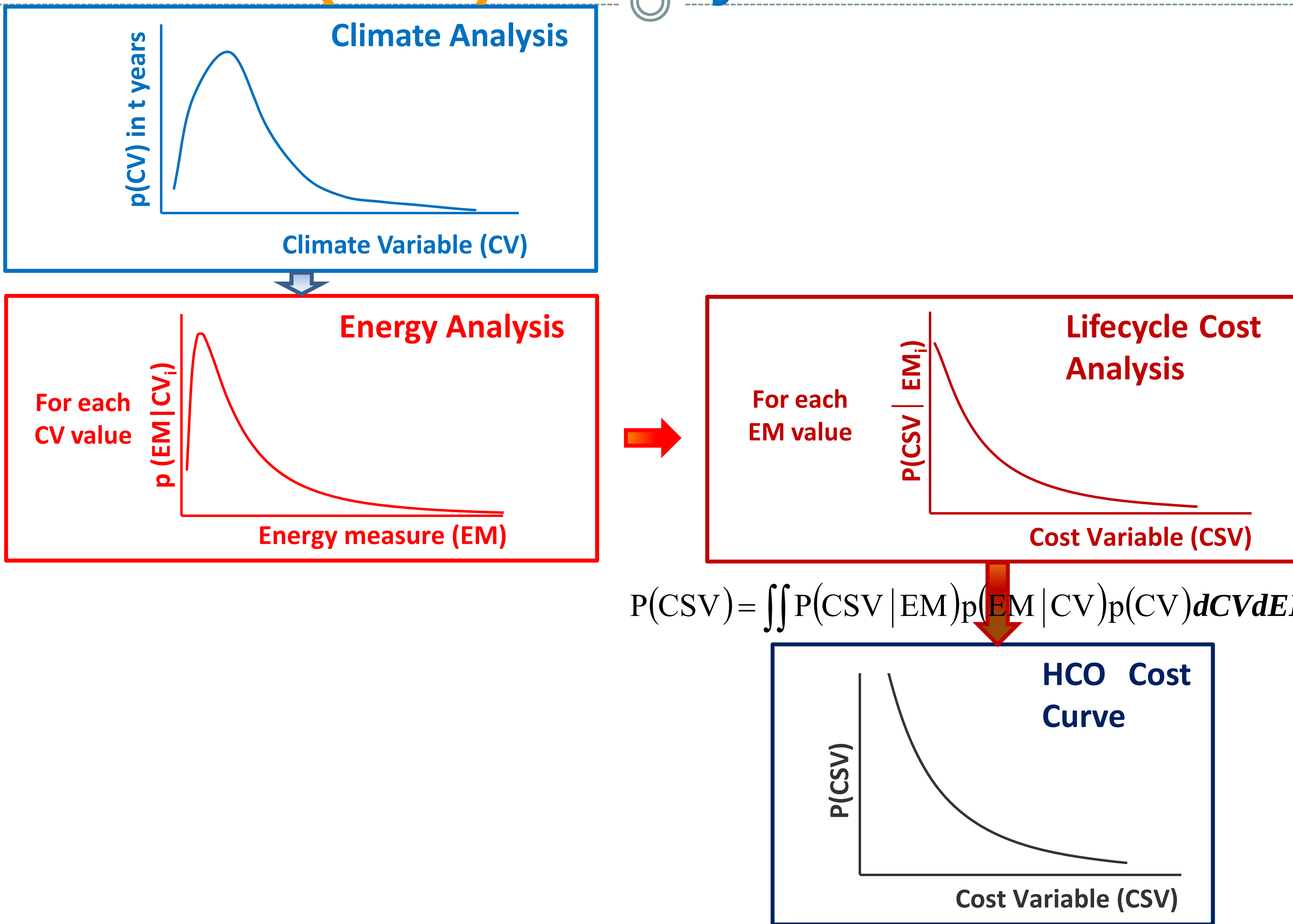
$$P(SDV) = \iint \underbrace{P(SDV|EM)}_{\text{Sustainability Analysis}} \underbrace{p(EM|CV)}_{\text{Energy Analysis}} \underbrace{p(CV)}_{\text{Climate Analysis}} \boldsymbol{dCVdEM}$$

SDV : Sustainability Decision Variable, e.g. Human productivity

EM : Energy measure, e.g. Energy consumption

CV : Climate Variable, e.g. Temperature change

Extended Framework: Human Comfort Objective (HCO): Life Cycle Cost



$$P(CSV) = \iint P(CSV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$

Extended Framework: Human Comfort Objective (HCO): Life Cycle Cost

$$P(CSV) = \iint P(CSV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$

CSV : Cost/Saving Variable, e.g. Ratio initial cost/savings during lifecycle

EM : Energy measure, e.g. Energy consumption

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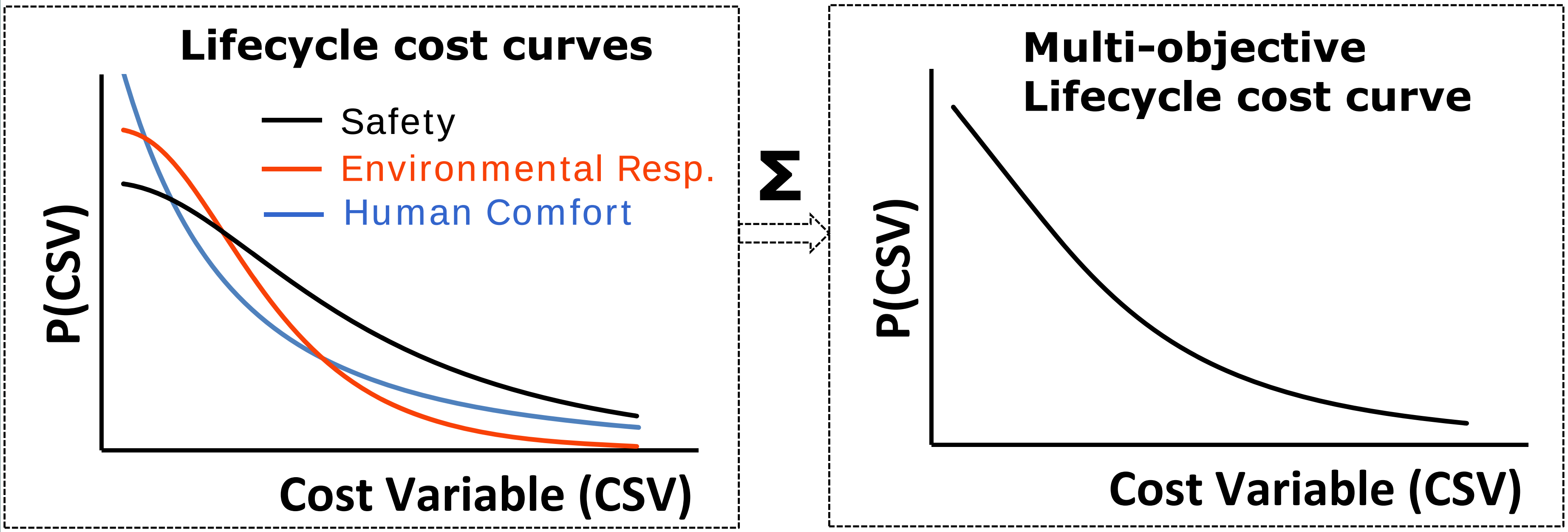
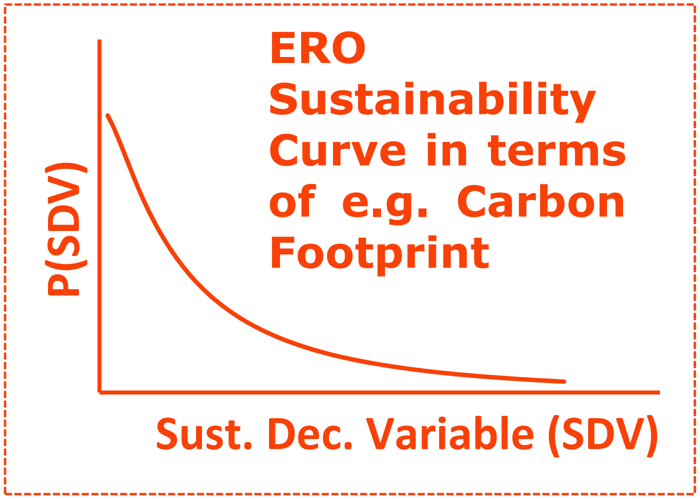
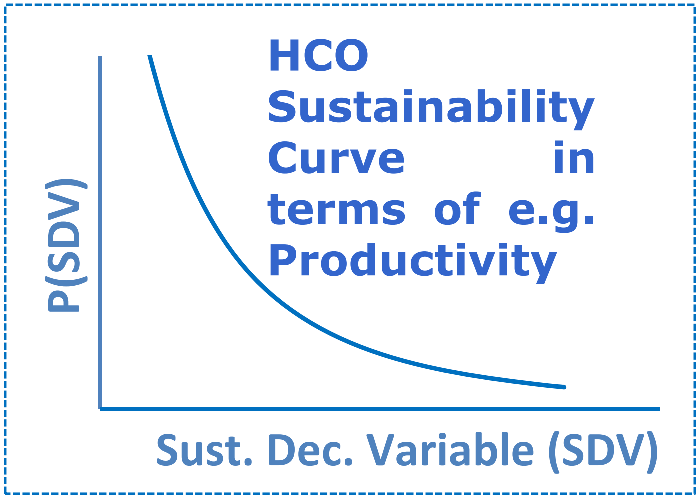
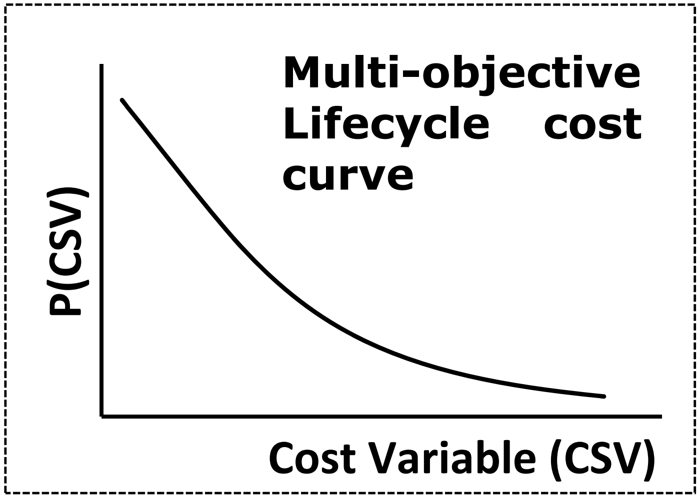
Extended Framework: Multi-objective Life Cycle Cost



Extended Framework: Decision Tools







Extended Framework: **Systematic Decision**

Obtained products (previous slide) can be used in a systematic manner for decision making

- **Decision-Making Systems**
  - Is preference information required?
  - Is preference information presented as relative weights?
  - Will the weights be generated during the process?

- **MIVES (Model for Integration of Values for Evaluation of Sustainability): Decision-Making Process**
  - Tree Construction
  - Value Function
  - Weight Assignment
  - Overall Evaluation and Selection of the Best Solution

Extended Framework: Systematic Decision

❑ MIVES: Decision-Making Process

- **Tree Construction**

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

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

Iyengar (2012)

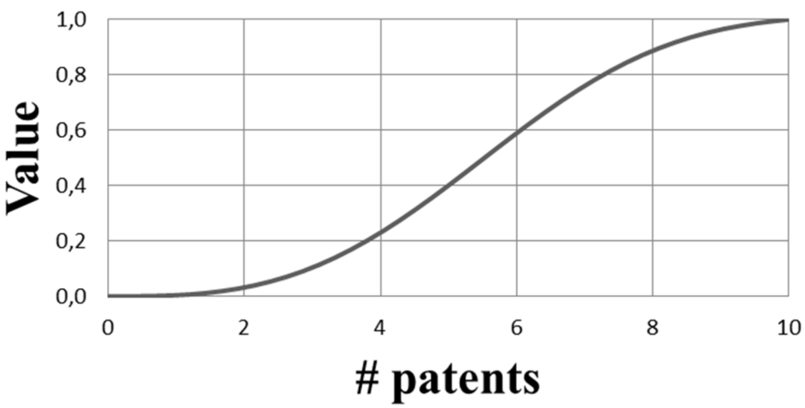
✓ Cut: Use 3 levels of unfolded branches, and every branch to have 5 sub-branches or less in the successive unfolding steps;
✓ Concretize: Use indicators that experts and stakeholders can understand;
✓ Categorize: Use more categories and fewer choices; and
✓ Gradually increase the complexity.

Extended Framework: Systematic Decision

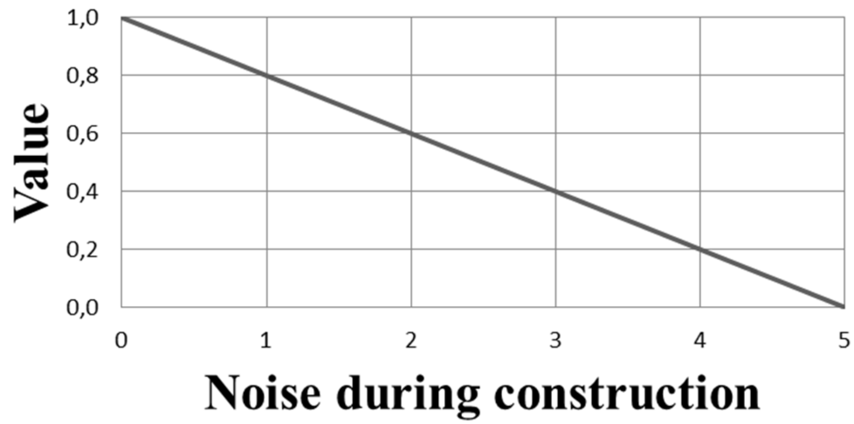
MIVES: Decision-making Process

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

Examples



Number of new patents used in building design



Annoyance to neighbours (noise) during construction

Extended Framework: Systematic 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
		⋮	⋮	⋮	⋮	⋮	⋮

See slide 4

Extended Framework: Systematic Decision

❑ MIVES: Decision-making Process

- **Selection Amongst Alternatives**

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

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

Weights — Value function

✓ The 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.

Extended Framework: Systematic Decision

PBE approach: PBE-MIVES

- **Multiple Indicators in a Direct Probabilistic Manner**

Assume **3** indicators DV_{CO2}, DV_E and DV_{ST} are considered and corresponding PDFs are:

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

For weights w_{CO2}, w_E and w_{ST}, the overall value for the indicators is:

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

If DV_{CO2}, DV_E, and DV_{ST} (with value functions u_{CO2}, u_E, and u_{ST}) are **mutually independent**, the joint PDF is:

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

else,

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

Therefore, **the conditional probability distribution** should be defined.

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

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

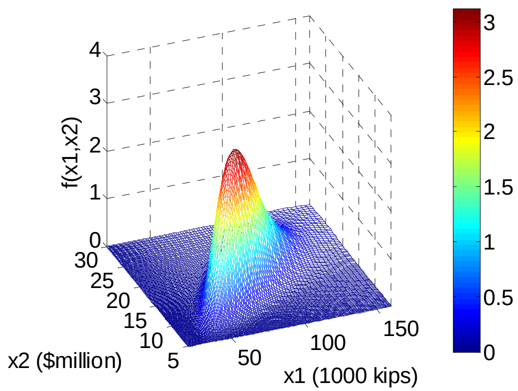
Extended Framework: Systematic Decision

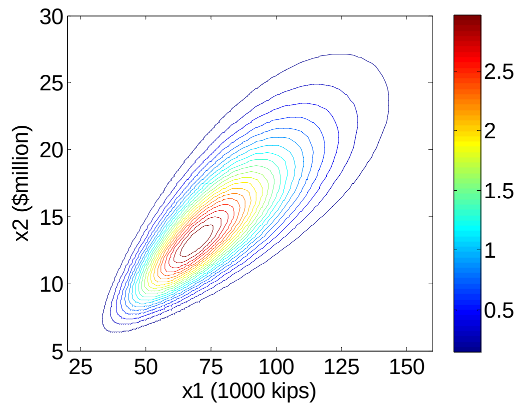
❑ PBE approach: PBE-MIVES

▪ Application to the UCS Building

- ✓ Two alternatives with different fuel consumption (in Btu) ratios

  Electricity : Natural gas = 5 : 2 (Plan 1), Electricity only (Plan 2)
- ✓ 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 was assumed as 0.8.





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

Extended Framework: Systematic Decision

❑ PBE approach: PBE-MIVES

- **Application to the UCS Building**

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

Linearly decreasing value functions

$$u(x) = 1.0 \quad if \ x \le x_a$$
$$= 1.0 - (x - x_a)/(x_b - x_a) \quad if \ x_a < x \le x_b$$
$$= 0.0 \quad if \ x > x_b$$

→ The following was computed to compare Plans 1 and 2:

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

Expected value of an alternative → rank different alternatives

<u>If no loss, i.e. $x_3 = 0$</u>

Case 1: $0 \le x_1 \le 80$, $0 \le x_2 \le 15$

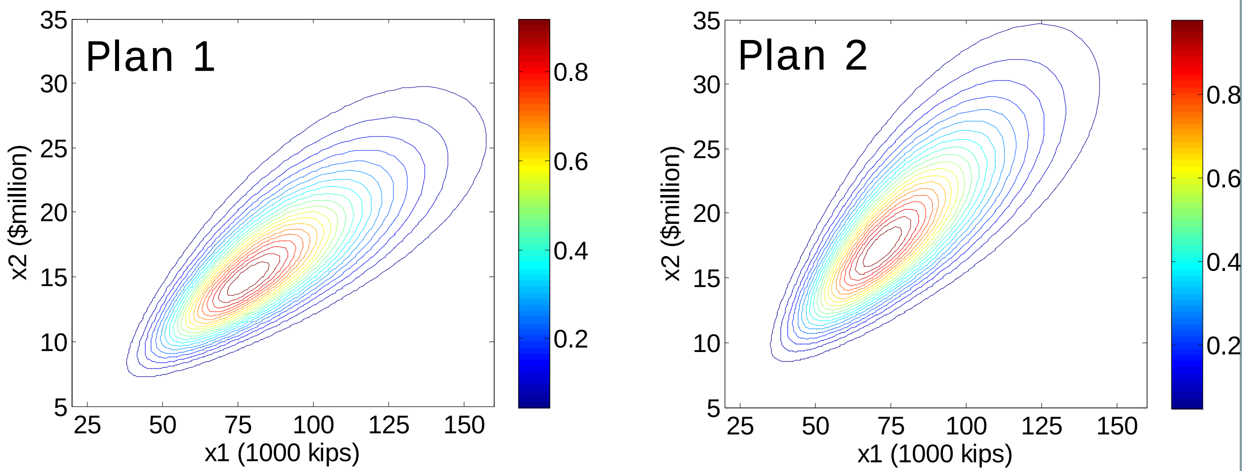
✓ <u>Plan 1: $V_{prob} = 309.52$</u>

Plan 2: $V_{prob} = 223.56$

Case 2: $0 \le x_1 \le 80$, $0 \le x_2 \le 20$

Plan 1: $V_{prob} = 393.95$

✓ <u>Plan 2: $V_{prob} = 449.61$</u>



Contours of Vf of energy expenditures (x_1) and CO_2 emissions (x_2) for Plans 1 and 2 of the UCS example building

[Monetary loss due to structural damages $x_3 = 0$]

Extended Framework: Systematic Decision

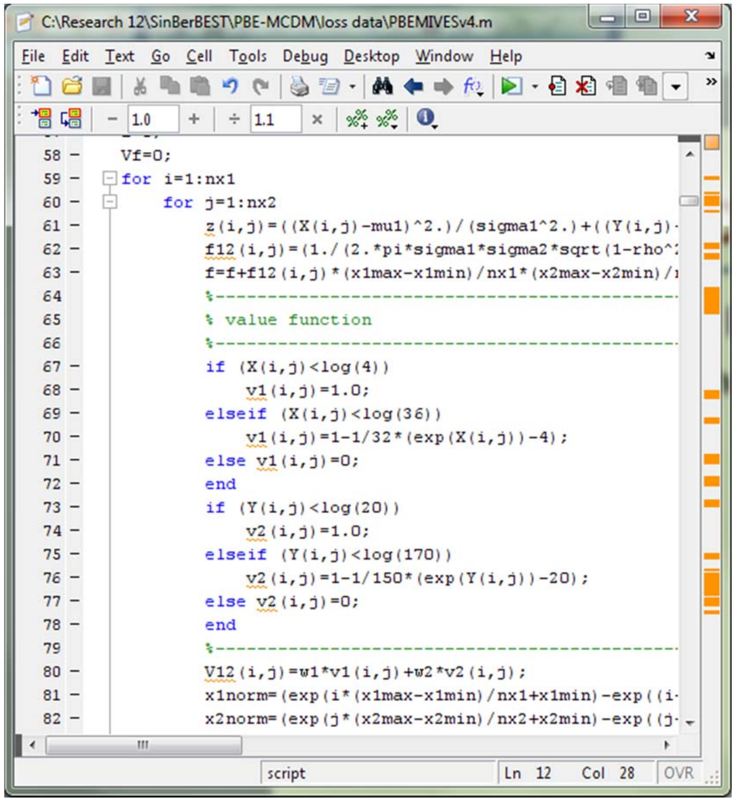
❑ PBE approach: PBE-MIVES

- ✓ 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.

- ✓ 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.

- ✓ As shown in the comparison of V_{prob} in the UCS example building, 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.

Matlab code for PBE-MIVES



Thank you