

“Cost-effective Variety” Can Reduce Variety In Real World
: Diversity in Water Infrastructure System

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1. Vulnerability of water-related disasters
2. Cost-effective variety for enhancing resilience
3. Framework of cost-effective variety (CEV) method
4. Examples: Drought case
5. Conclusion

Growing Water-related Disasters

- ❖ Rapid increase in intensity, frequency and damage of climate extremes and water-related disasters
 - * The frequency and damage of water-related disasters in the last decade are reported to account for approximately 40 and 50% of them occurred over the past 100 years, respectively (EM-DAT)
- ❖ More vulnerable urban area to the water-related disasters by risk propagation



Disturbances and Counteractions

A variety of disturbances



- Increased frequency
- Growing intensity



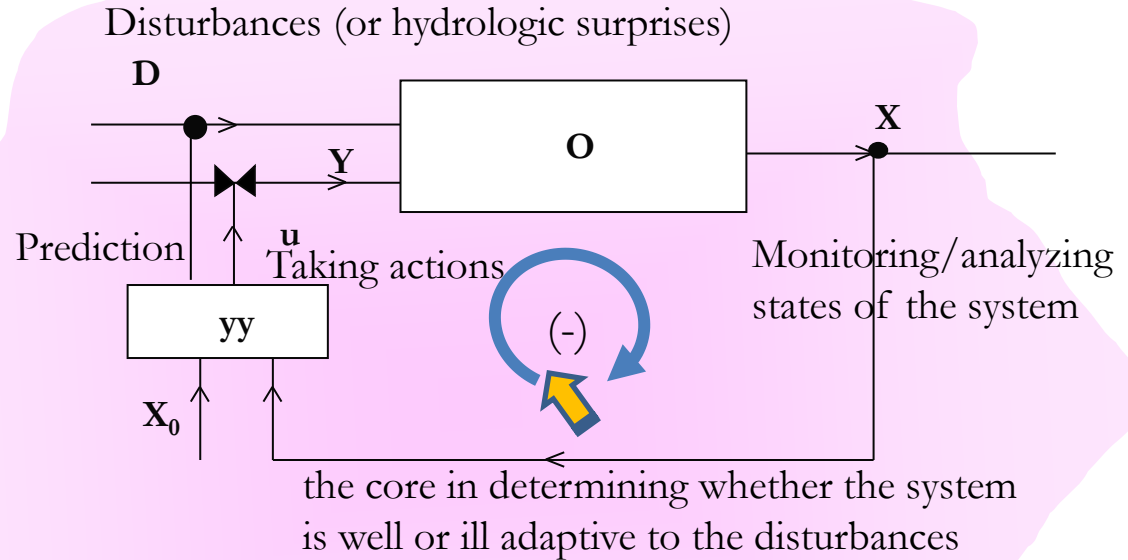
- High uncertainty
- Catastrophic impact

Human lives

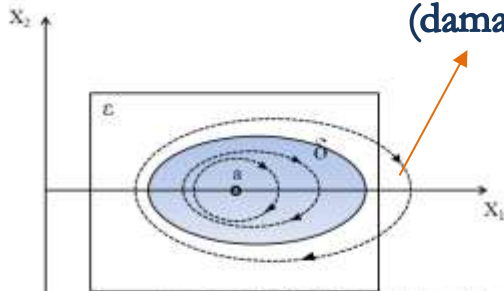


Examples of Current counteractions





System failure
(damage)

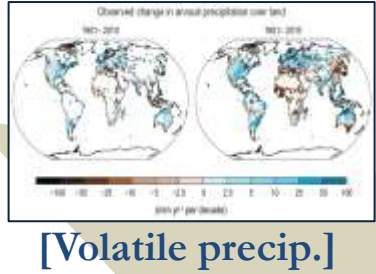
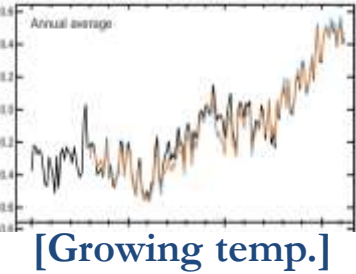


- a : an immobile Point of equilibrium state of a system
- ϵ : domain of permissible deviations from the equilibrium state of a system
- δ : domain includes the equilibrium state

Variety of Disturbances (VOD)

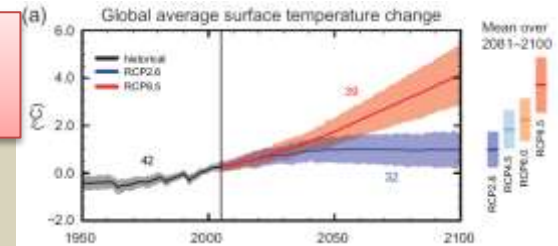
Drivers 1: Climate Change

Drivers 2: Growing extremity and variability



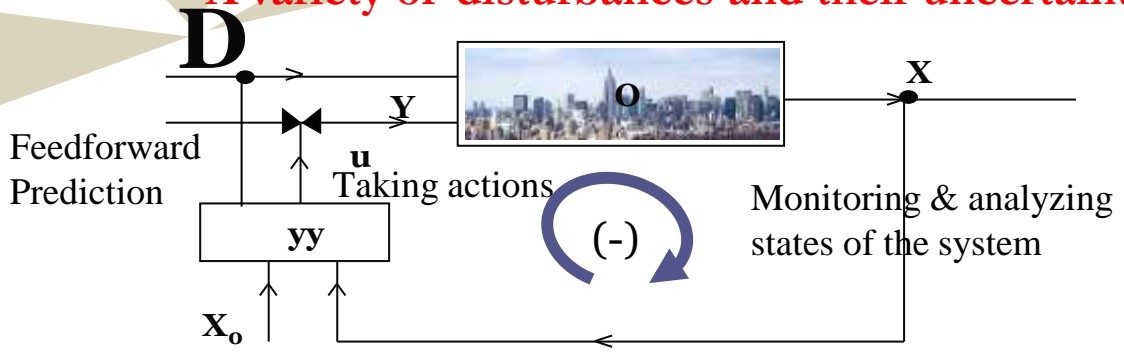
Drivers 3

Drivers 4: Uncertainty



- * Demography, Economy and security,
- Technology, Water resources,
- Water infrastructure,
- Environmental (including agriculture),
- Society, ethics and culture,
- Governance and institutions, Politics

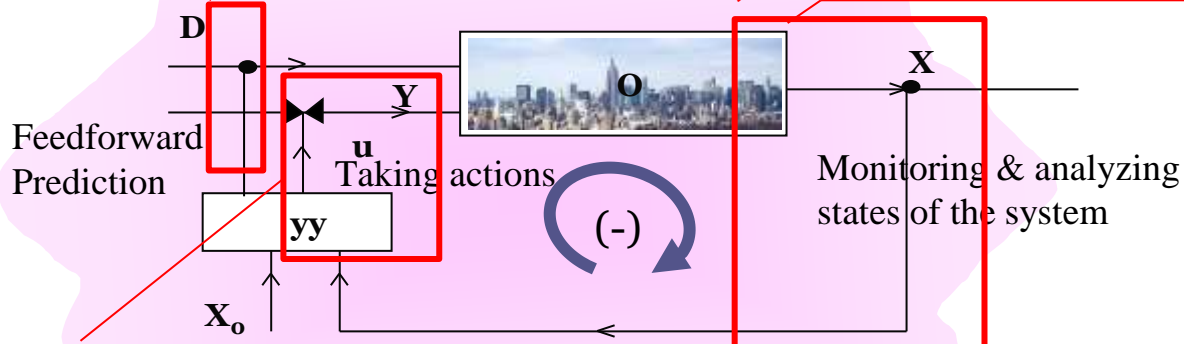
A variety of disturbances and their uncertainty



Variety of Responses (VOR)

1) PRINCIPLE OF ACCURACY

2) PRINCIPLE OF SUFFICIENCY



3) PRINCIPLE OF ADEQUACY

		Options
VARIETY	• ACCURACY	<ul style="list-style-type: none"> • Build the risk map by using historical records and forecasts • Analyze climatologic/socio-economic variables with improved prediction models • Collect much information by using big-data and data-mining technologies
	• SUFFICIENCY	<p>VOD >>> VOR (what if test)</p> <ul style="list-style-type: none"> • Develop system planning & design methods • Monitor the short-term trend of hydrologies by using the RS technologies
	• ADEQUACY	<ul style="list-style-type: none"> • Increase structural capacity • Design the drainage system sharing flood intensity over the watershed basin • Increase connectivity of storm water infrastructure • Build the emergency aid & action plans • Manage water level of river in a more reliable way during the wet season

Two ideal ways to deal with variety

1. ALEXANDER AND THE GORDIAN KNOT



2. The law of Requisite Variety (by W. Ross Ashby, 1957)

- * If a system is to be stable,
of states of its control mechanism \geq # the number of states in the system being controlled.
- * Ashby states the Law as "variety can destroy variety"

❖ “Only variety can destroy variety”(Ashby, 1957)

		Y		
		Y ₁	Y ₂	Y ₃
D	d ₁	f	f	k
	d ₂	k	e	f
	d ₃	m	k	a
	d ₄	b	b	b
	d ₅	o	g	o
	d ₆	h	h	m
	d ₇	j	a	a
	d ₈	a	p	j
	d ₉	i	n	h

* $VOR \geq VOD$

* Impossible to make VOR larger than VOD, especially with infrastructure



Law of “Sūn Wùkōng(孫悟空) in Buddha’s Palm”

Who can make the Buddha’s Palm to control 孫悟空?

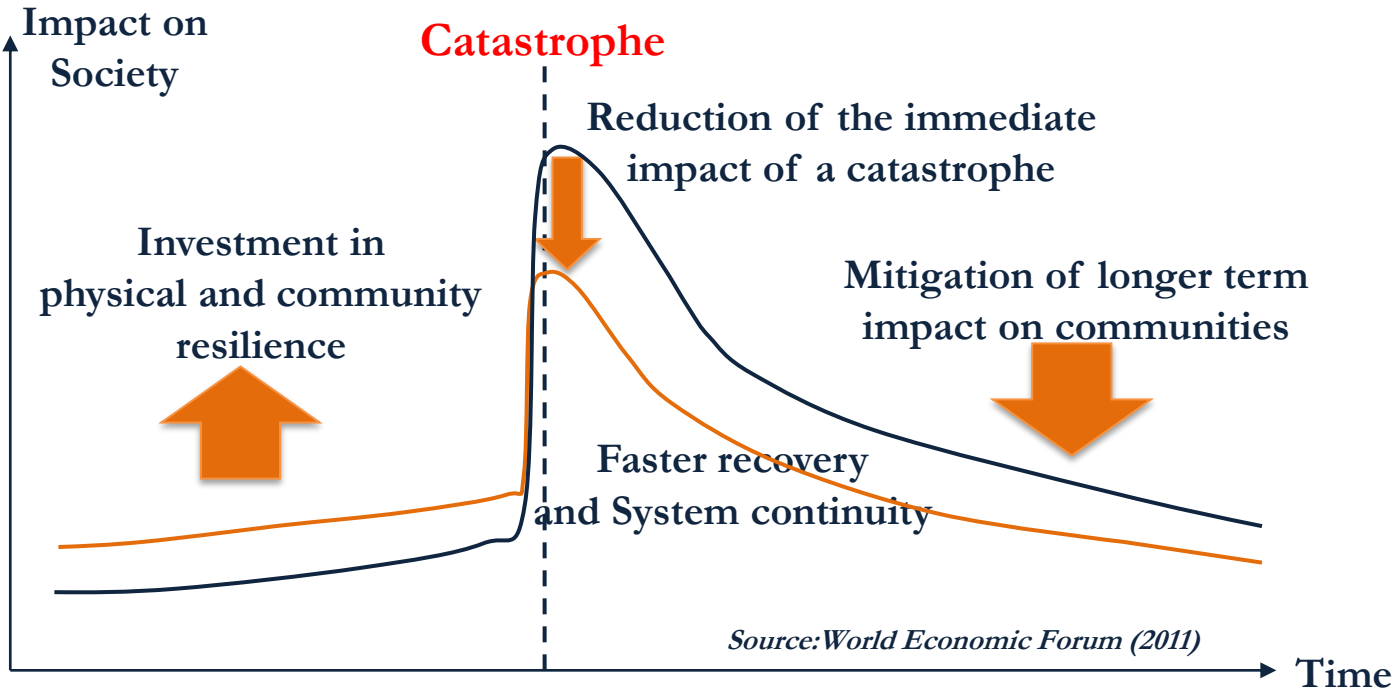
Two ideal ways to deal with variety

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Impossible to prevent disasters!!!



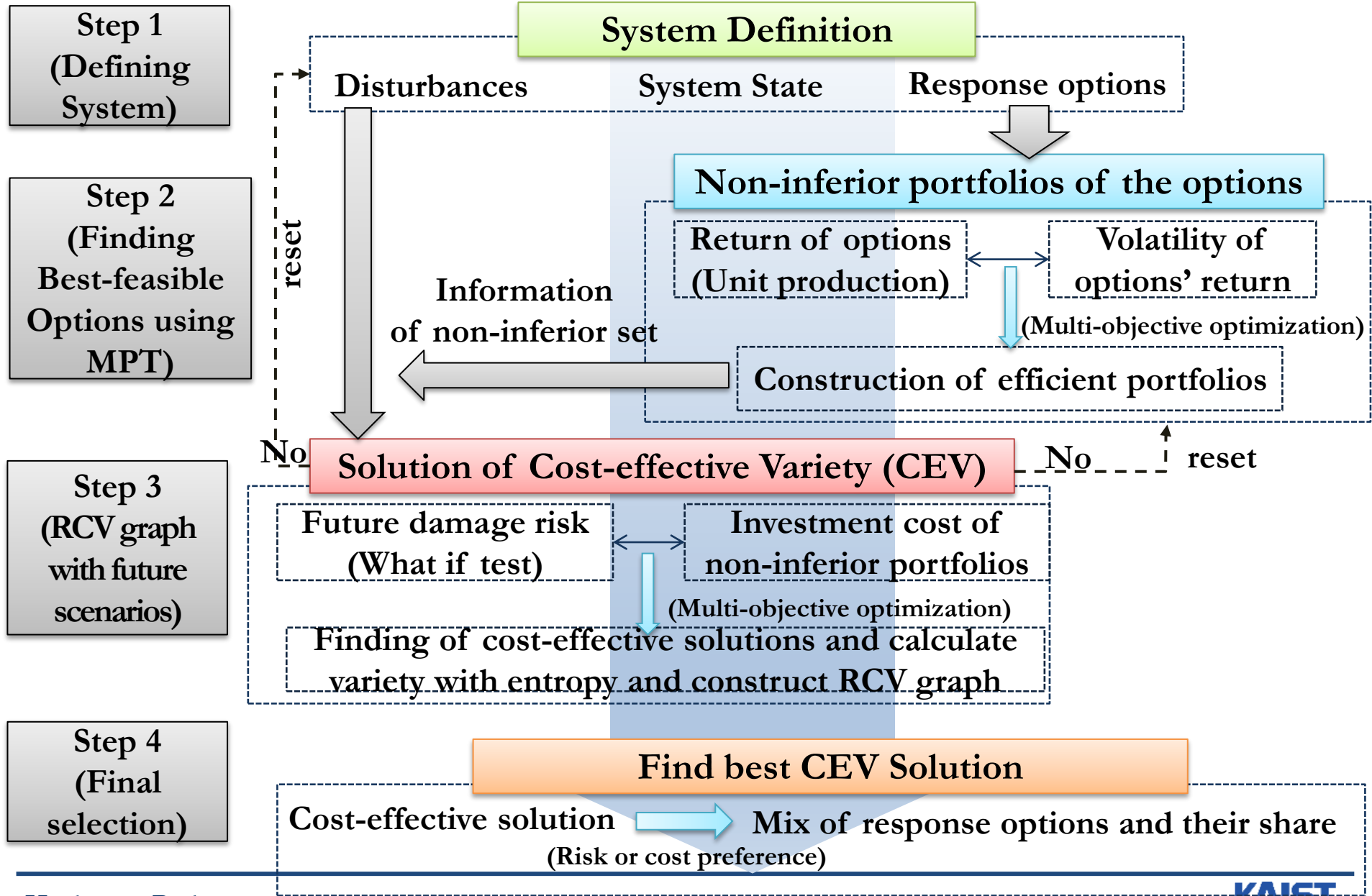
All we can do is “reduction” of disasters



“**Cost-Effective Variety (CEV)**” **reduce** the variety of disasters in this world

Framework of Cost-Effective Variety (CEV) Method

- to find best sets of response options for given economic constraints or risks.



❖ Background



❖ A water supply dam reservoir

- * 3 service regions in a service area
- * Dependence on a dam for water supply

	Region 1	Region 2	Region 3
Service area	100%	15%	3%

❖ Drought & the dam reservoir

- * Unexpectedly low inflow (due to much decrease of rainfall)
- * Water storage: staged restriction of water intake to 50%

Object of the study:

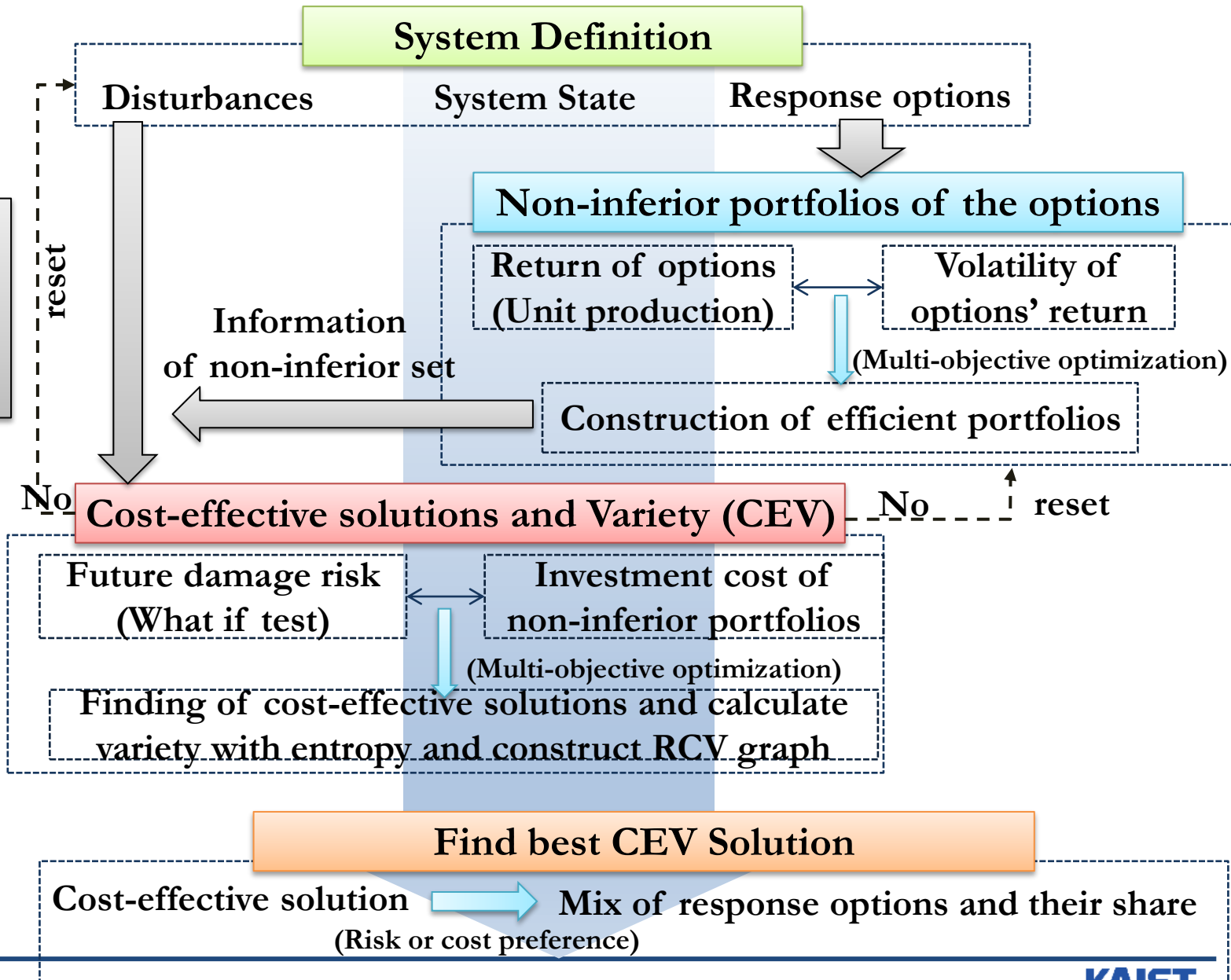
- Find a combination of water supply options against all the possible droughts in Yrs 2010~2050.

Step 1
(Defining System)

Step 2
(Finding Best-Feasible Options using MPT)

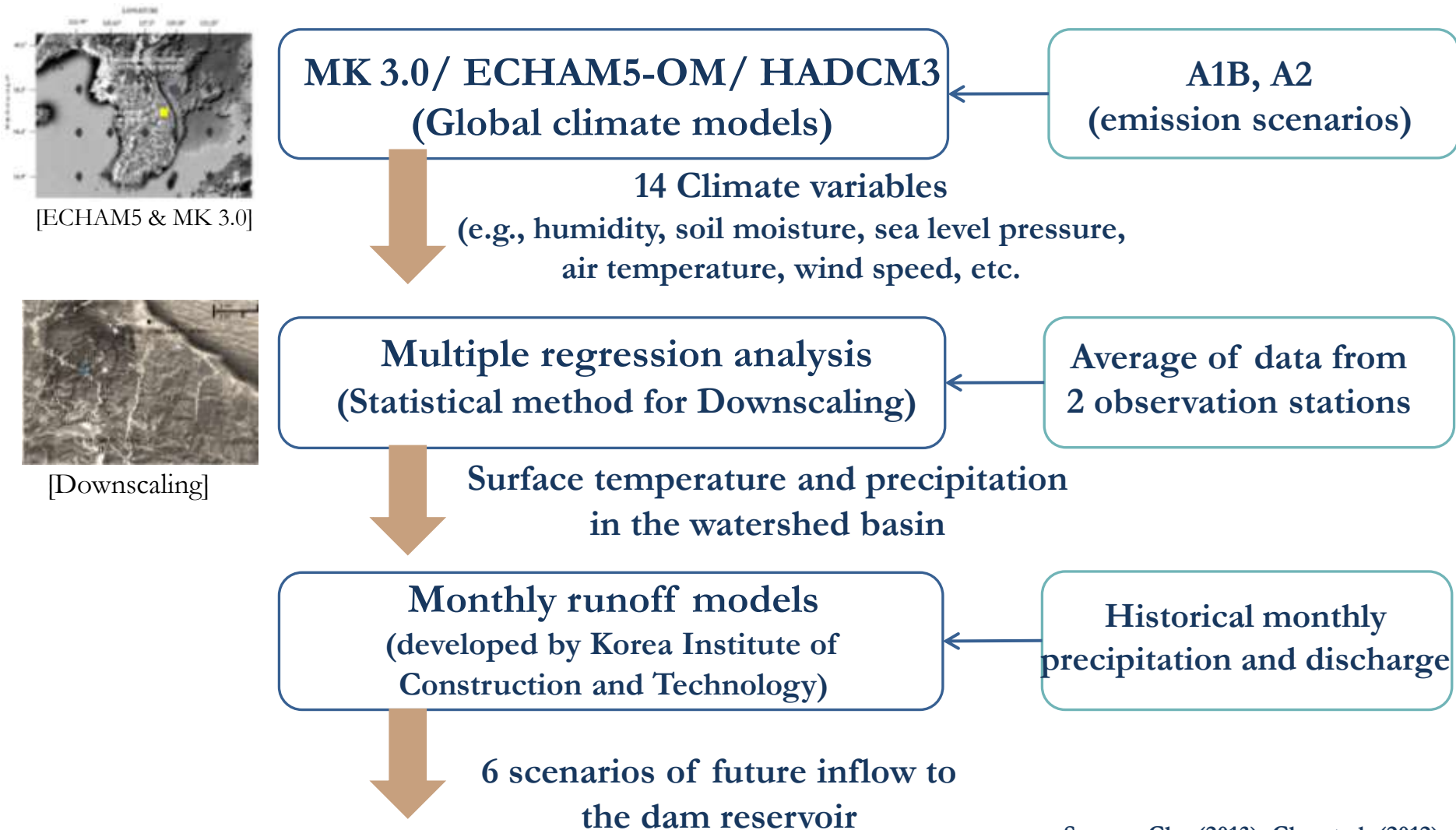
Step 3
(RCV graph with future scenarios)

Step 4
(Final selection)



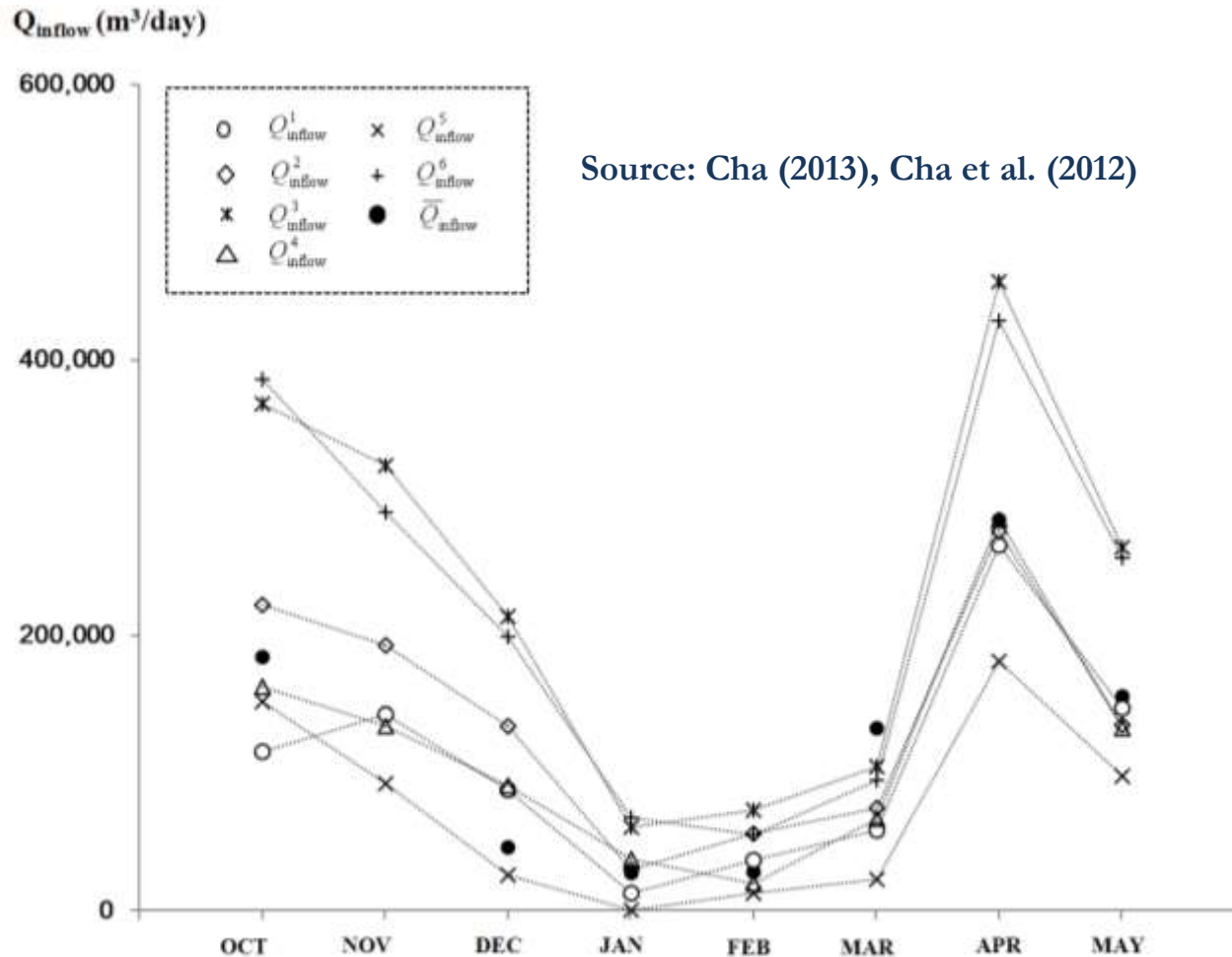
Step 1-1: Analyzing system disturbances (1/3) 16

❖ Disturbance 1: climate change influencing inflow to the Dam reservoir



Source: Cha (2013), Cha et al. (2012)

❖ Disturbance 1: climate change influencing inflow to the Dam reservoir



[Inflow to the Dam by climate change in Yr 2050]

❖ Disturbance 2: Service population change influencing water requirement

[Water requirement by service population change]

	Region 1	Region 2	Region 3
change 1	▲	▲	▲
change 2	▲	▼	▼
change 3	▼	▲	▼
change 4	▼	▼	▲
change 5	▼	▲	▲
change 6	▲	▼	▲
change 7	▲	▲	▼
change 8	▼	▼	▼

* Assuming increase and decrease with 3%

❖ Total 48 scenarios from climate change and service population change

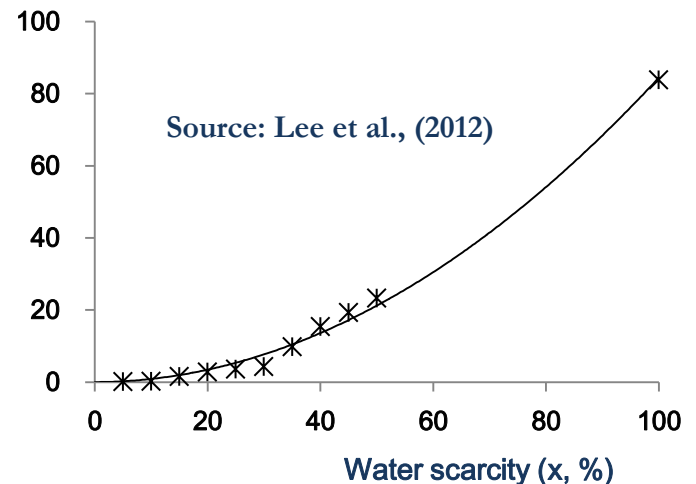
❖ System state

$$* \text{ Water scarcity} = 1 - \frac{\text{Total amount of supplied water}}{\text{Total water requirement}} (\%)$$

$$= \text{water shortage} / \text{total water requirement} (\%)$$

❖ Economic damage due to water scarcity

Damage costs per capita (USD/day)



❖ Water resources for water supply as response options



[Dam water]



[Reclaimed water]



[Rain water]



[Desalinated water]

❖ **Diversification of water resources** $H(Y) = \sum_{i=1}^N p(y_i) \ln \frac{1}{p(y_i)} = - \sum_{i=1}^N p(y_i) \ln p(y_i)$

* Option A: Dam reservoir / B: Reclaimed water / C: Rain water / D: Desalinated water

	A	B	C	D	H(Y)
Case 1 (A)	1.00 ¹⁾	-	-	-	0.000
Case 2 (A+B) ²⁾	0.50	0.50	-	-	0.693
Case 3 (A+B+C)	0.33	0.33	0.33	-	1.099
Case 4 (A+B+C+D)	0.25	0.25	0.25	0.25	1.386

H(Y)
Increase

1) The values represented probability for estimation of entropy. The probability was assumed as dependence on the options for achievement of system goal. The probabilities for all options were assumed to be equal for only examining diversification.

❖ Decentralization of the options

	A	B	C	D	H(Y)
Case 1 ¹⁾	0.70	0.05	0.05	0.20	0.871
Case 2 ²⁾	0.60	0.10	0.10	0.20	1.089
Case 3 ²⁾	0.45	0.15	0.15	0.25	1.275
Case 4 ⁴⁾	0.25	0.25	0.25	0.25	1.386

H(Y)
Increase

1) Case 1 described the case of heavily relying on option A for achieving system goal.

2) Case 2 and 3 described the cases of reducing dependence on option A and increasing dependence on the others.

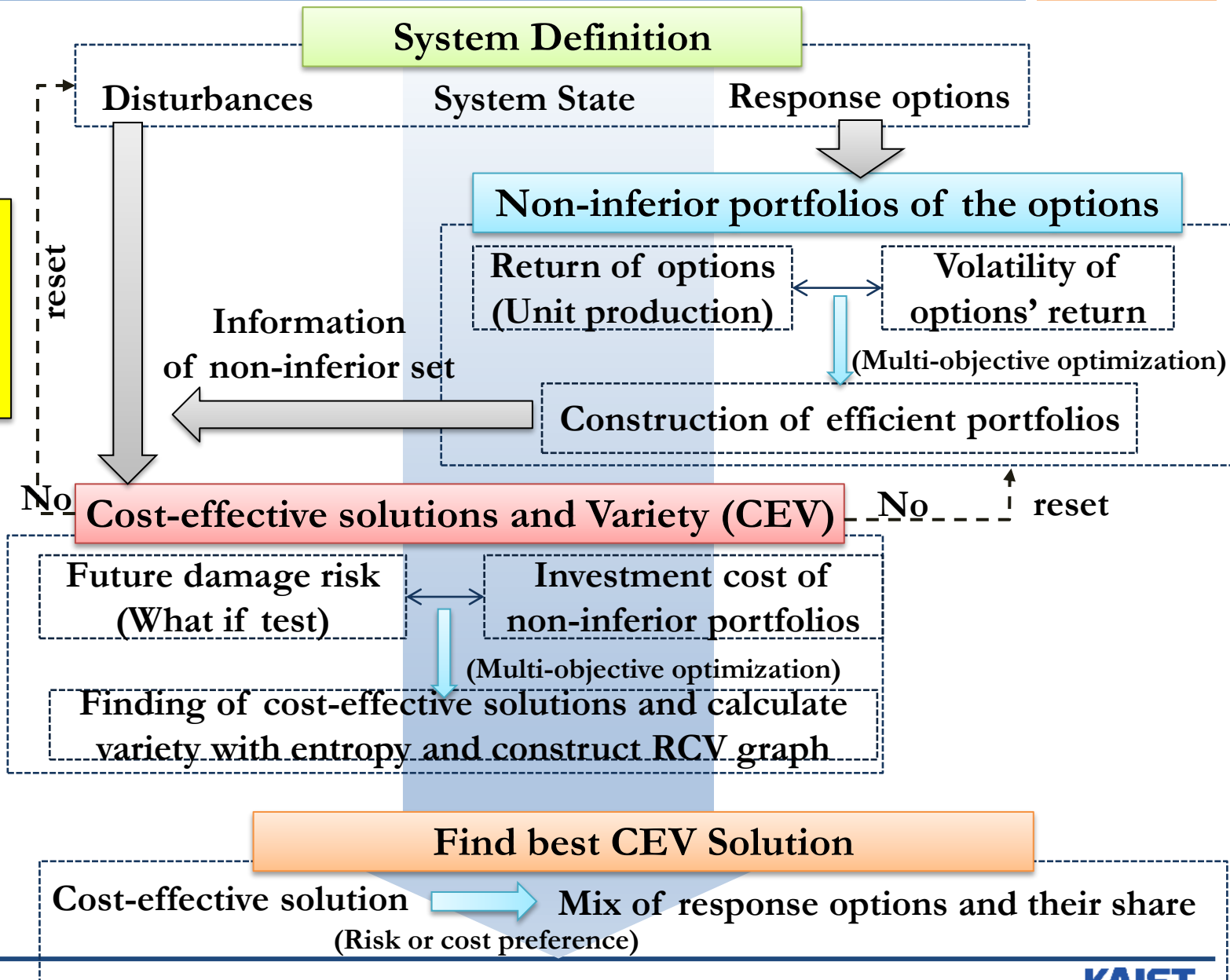
3) Case 4 described the case of uniformly relying on the each option.

Step 1
(Defining System)

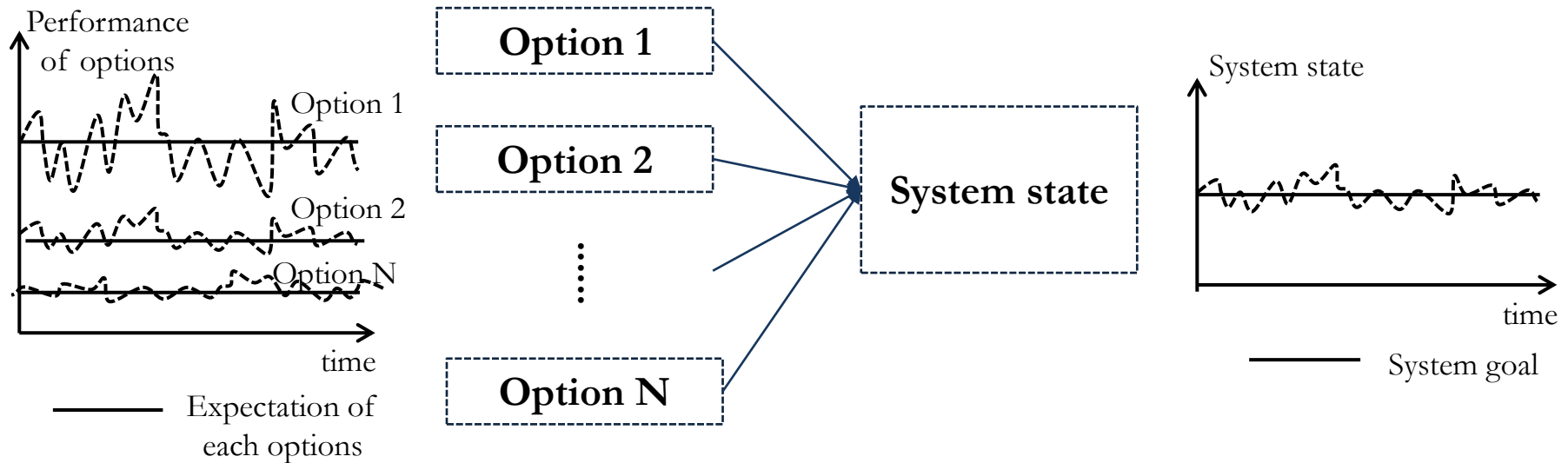
Step 2
(Finding Best-Feasible w/ MPT)

Step 3
(RCV graph with future scenarios)

Step 4
(Final selection)



- ❖ Many response options and their combinations → Which one is best?
- ❖ MPT (Modern Portfolio Theory) : Best portfolio of response options
 - * Return = benefit associated with an investment (← perspective of cost-effectiveness)
 - * Risk due to volatility of the options (← perspective of system state)
- ➔ MPT: Find best portfolios of response options which generate the largest return for a given risk or lowest risk for a given return



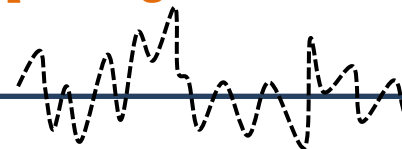
❖ Return

- * Production rate of a portfolio ($\text{m}^3/\text{month}/\text{USD}$)
- * historical data for a recent decade (2001~2010) from the Water Management Information System (WAMIS) and Statistics of water works
- * Estimate investment cost by power law rule (using data from previous literatures)

	Dam water	Reclaimed water	Rain water	Desalinated water
unit production cost (USD/ m^3/month)	0.364	0.632	1.552	3.05

❖ Volatility

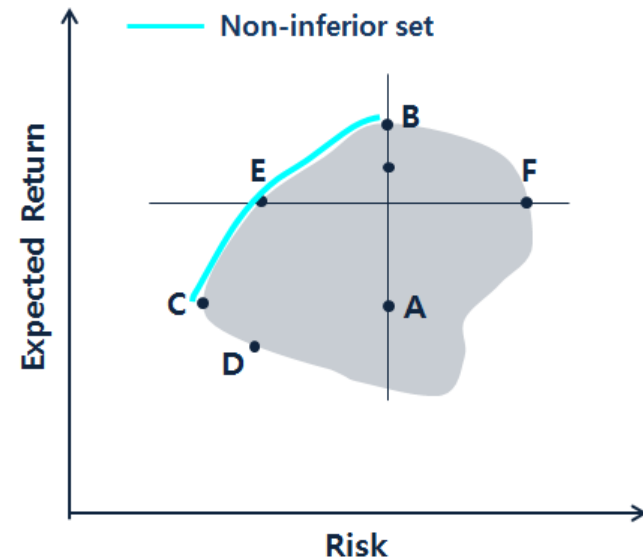
- * The semivariance (downside volatility relative to expected goal of return on each options)



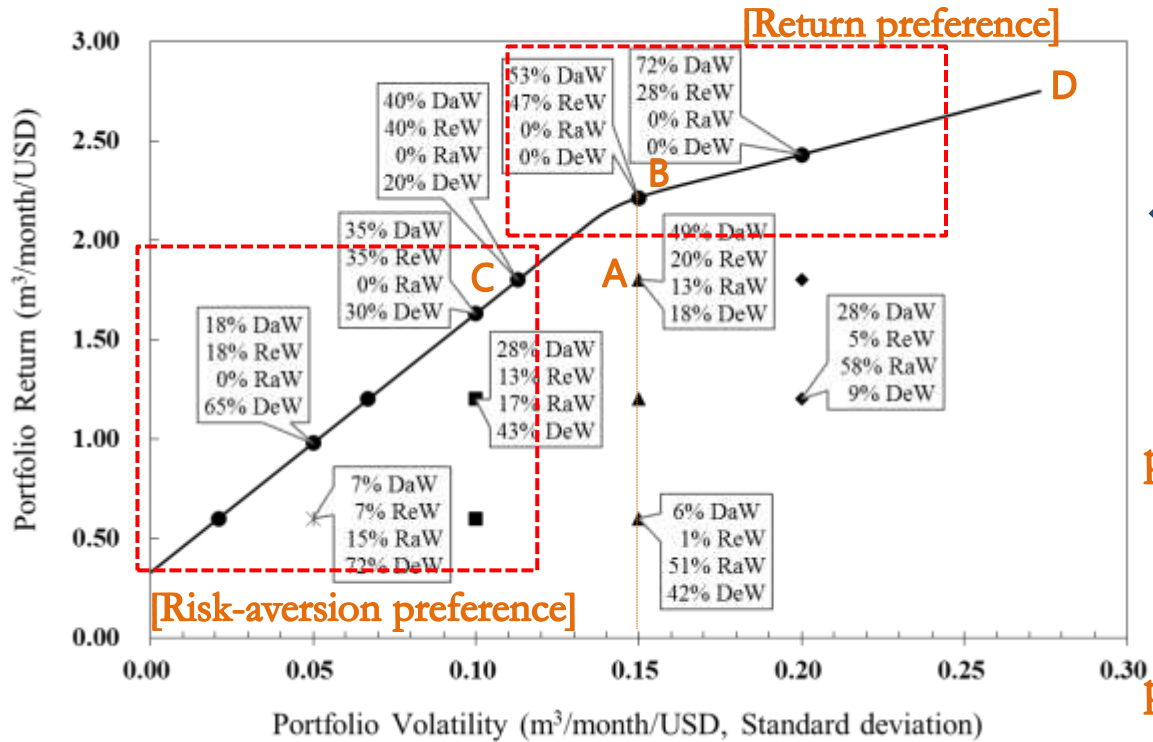
[Return and risk of individual water resources in thenCase study area]

Assets	Goal: Expected return	Volatility (SD)
Dam water	2.7481	0.2732
Reclaimed water	1.6005	0.0330
Rain water	0.5477	0.2865
Desalinated water	0.3277	0.0000

Non-inferior portfolios



Step 2-2: Deriving non-inferior portfolios of options 26



❖ From current D portfolio (single option of Dam water)

* Set of largest variety → A portfolio

* Efficient set → (return preference) B portfolio

→ (volatility preference) C portfolio

[Estimation of entropy for A, B, C and D portfolios]

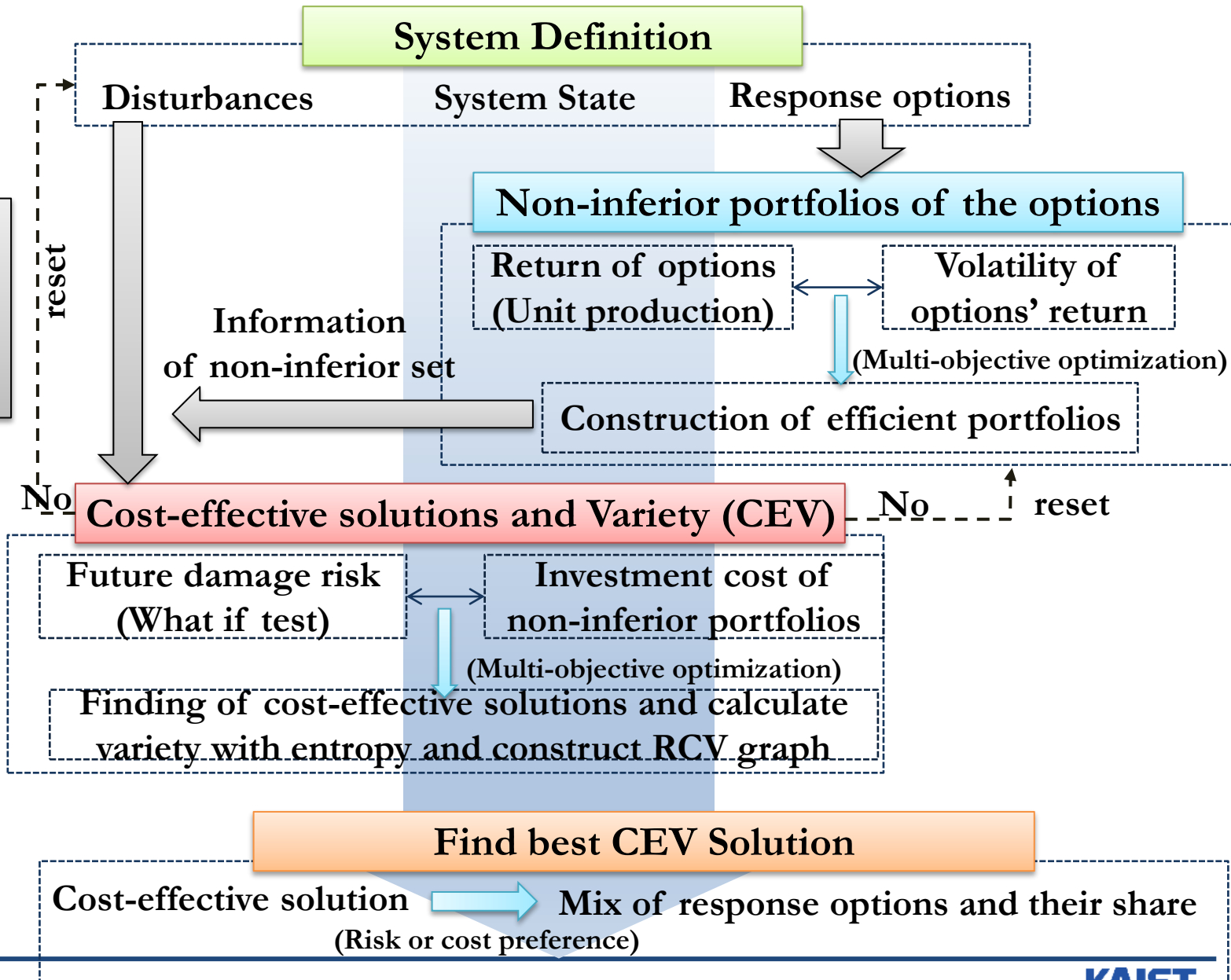
Portfolio	A point	B point	C point	D point
Entropy	1.25	0.69	1.10	0.00

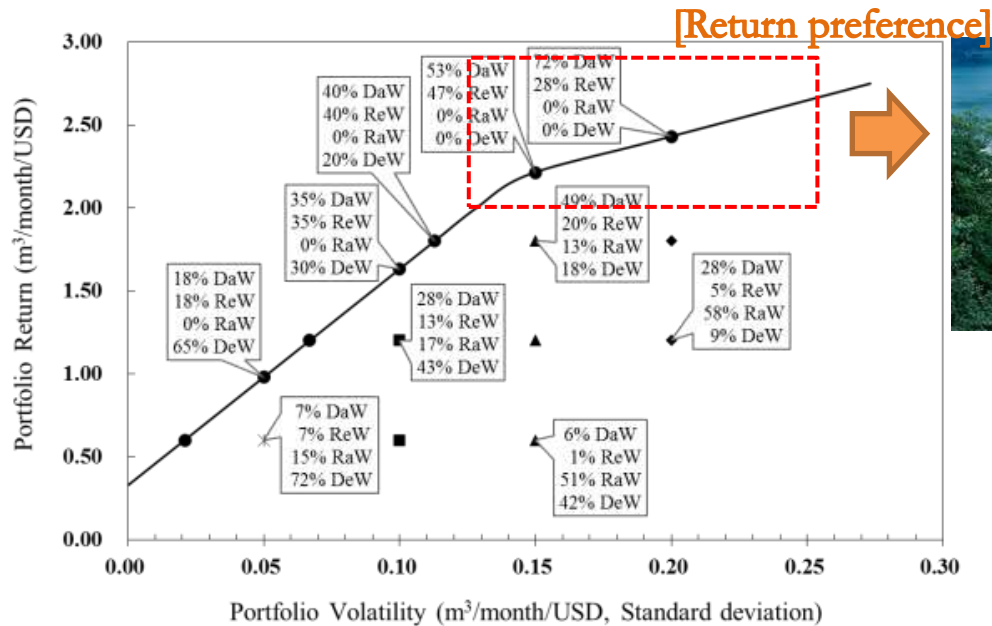
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[Dam water]

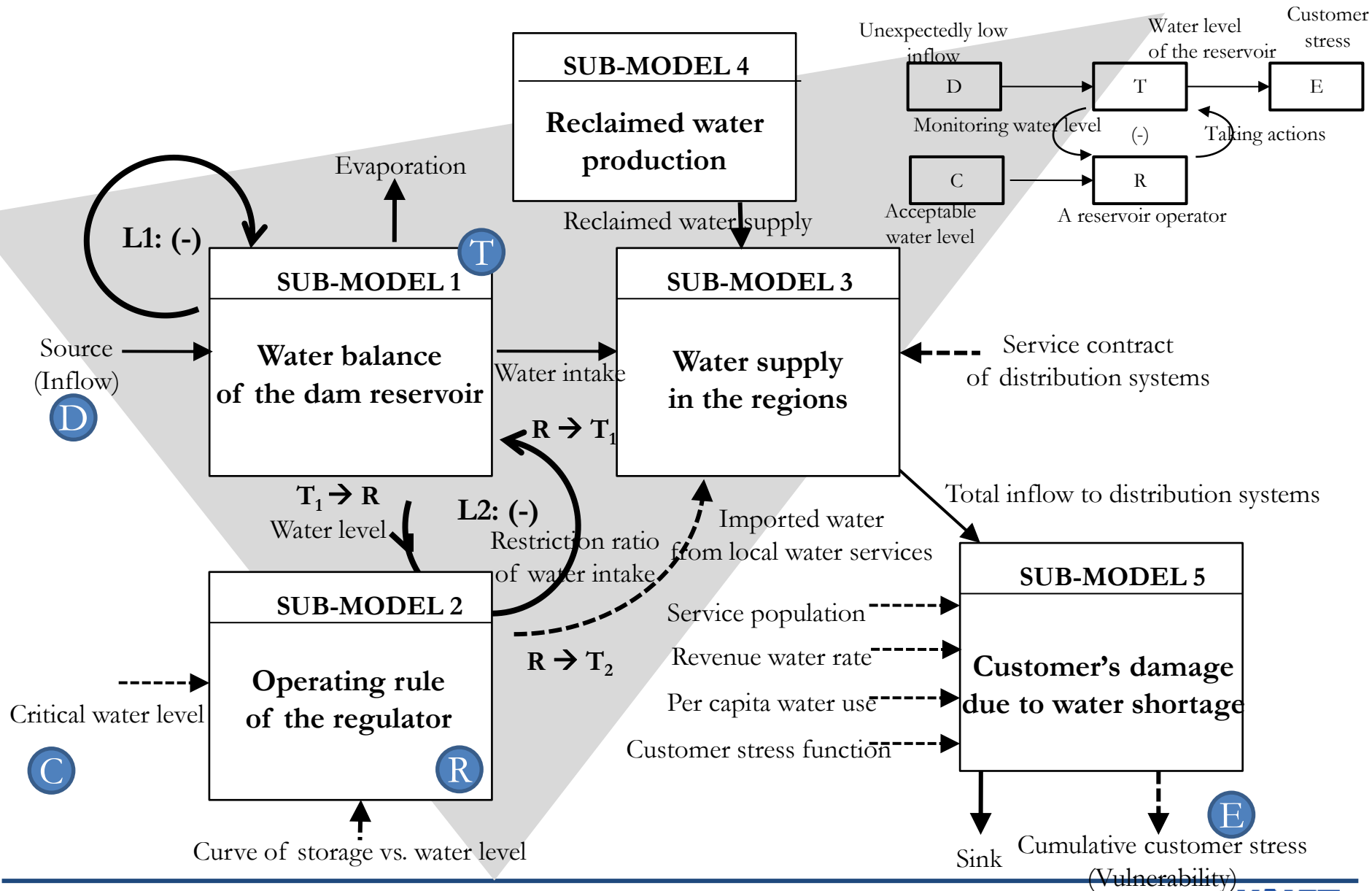


[Reclaimed water]

[A Portfolio with Different Shares: for what if test]

	Dam water	Reclaimed water	Entropy H(Y)
Case 0 (status quo)	100 %	0 %	0.000
Case 1	90 %	10 %	0.325
Case 2	80 %	20 %	0.500
Case 3	70 %	30 %	0.611
Case 4	60 %	40 %	0.673
Case 5	50 %	50 %	0.693

Step 3-2: Analyzing risk with future scenarios (1/5) 29



❖ System state

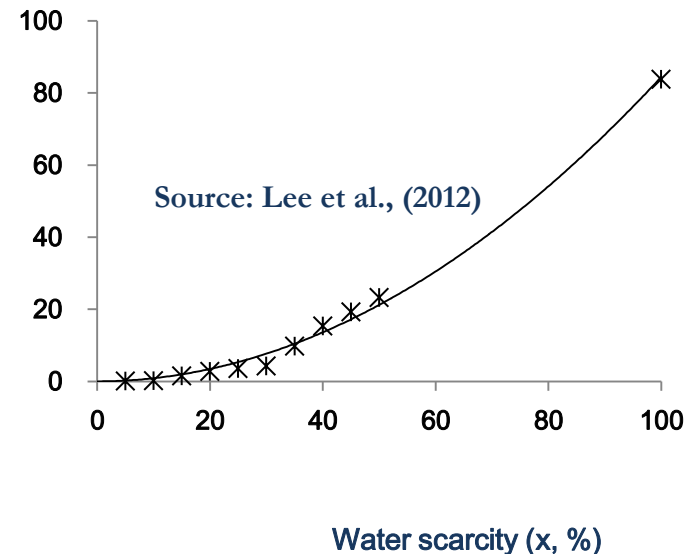
$$* \text{ Water scarcity} = 1 - \frac{\text{Total amount of supplied water}}{\text{Total water requirement}} (\%)$$

$$= \text{water shortage} / \text{total water requirement} (\%)$$

❖ Risk = Expected economic damage due to water scarcity

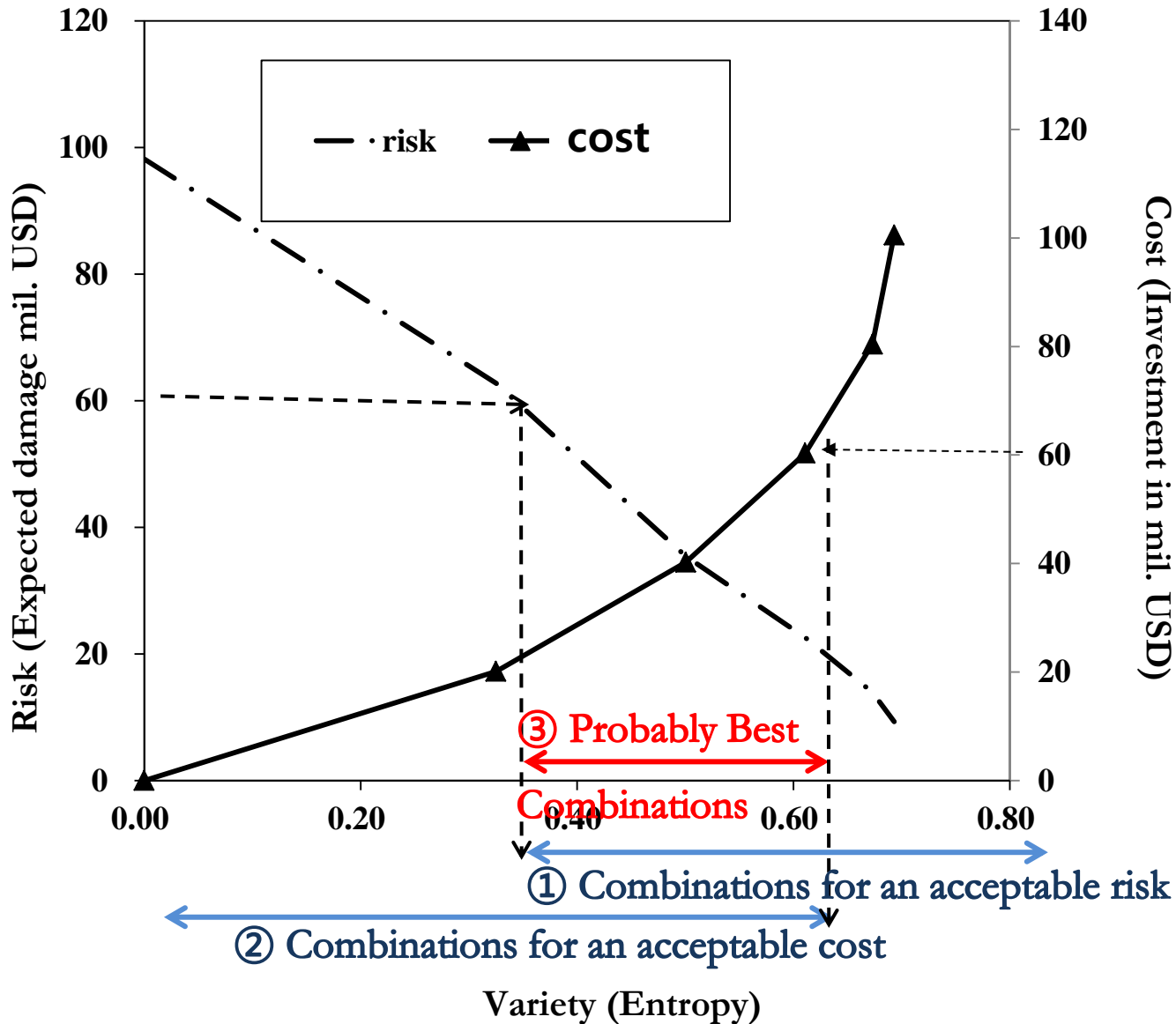
- The occurrence probabilities of individual scenarios = equal
→ uniform distribution
("equal likelihood criterion" by unpredictability, Gigch, 1974)

Damage costs per capita (USD/day)

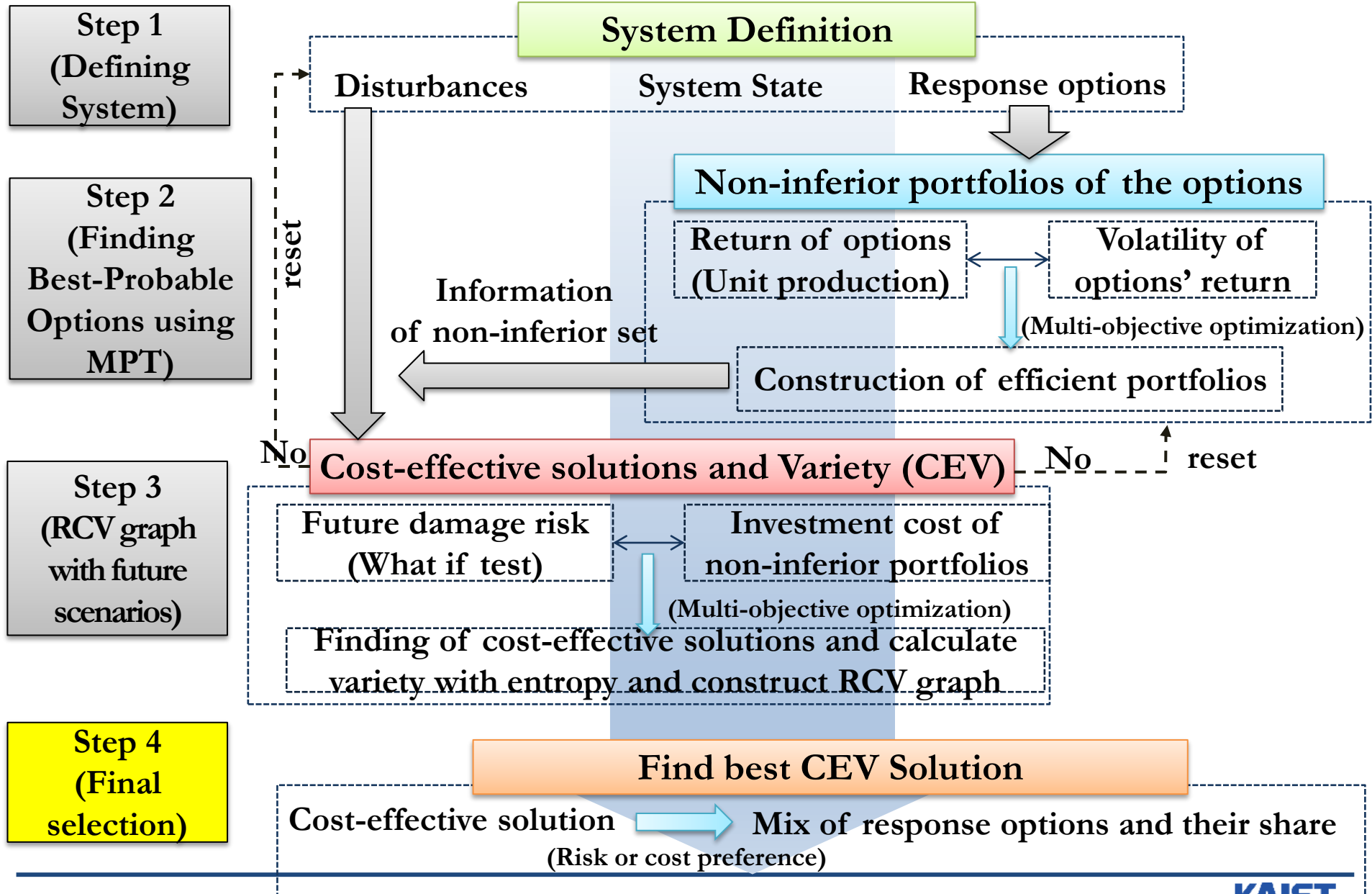


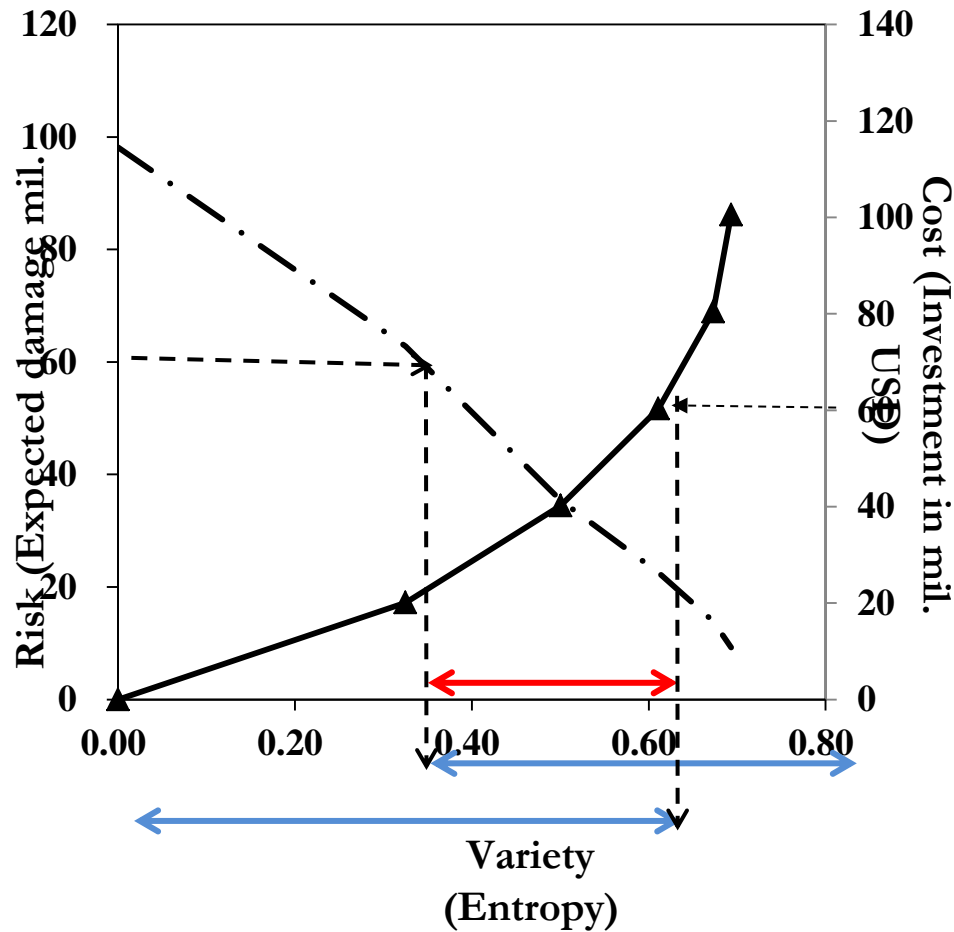
Water scarcity (x, %)

Step 3-3: Creating RCV Graph



	Dam w ater	Reclai med wa ter	H(C)
Case 0	100 %	0 %	0.00
Case 1	90 %	10 %	0.32
Case 2	80 %	20 %	0.50
Case 3	70 %	30 %	0.60
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❖ Step 4:

Selecting a portfolio of the options and their shares in the range

-
- ❖ A great deal of variety of disasters and uncertainty

- * We, engineers, need cost-effective securement of variety in infrastructure system to realistically apply the “law of requisite variety” for effective controlling various and highly uncertain disasters (“Cost-effective variety can reduce variety”).

-
- ❖ The CEV method including the MPT framework and RCV curve can be an effective tool to quantitatively devise out, with various constraints in real world, a combination of infrastructure options for future disturbances and their uncertainty.



Thank you