Aalto-yliopisto
Perustieteiden korkeakoulu

How problem formulation influences total costs in multi-stage energy capacity planning

Aleksander Heino

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Supervisor: Fabricio Oliveira

Instructor: Olli Herrala

Systeemianalyysin laboratorio

Agenda

1. Background
   1. Capacity expansion
   2. SDDP
2. Implementation
   1. Uncertainty
   2. Models
   3. Data
3. Results

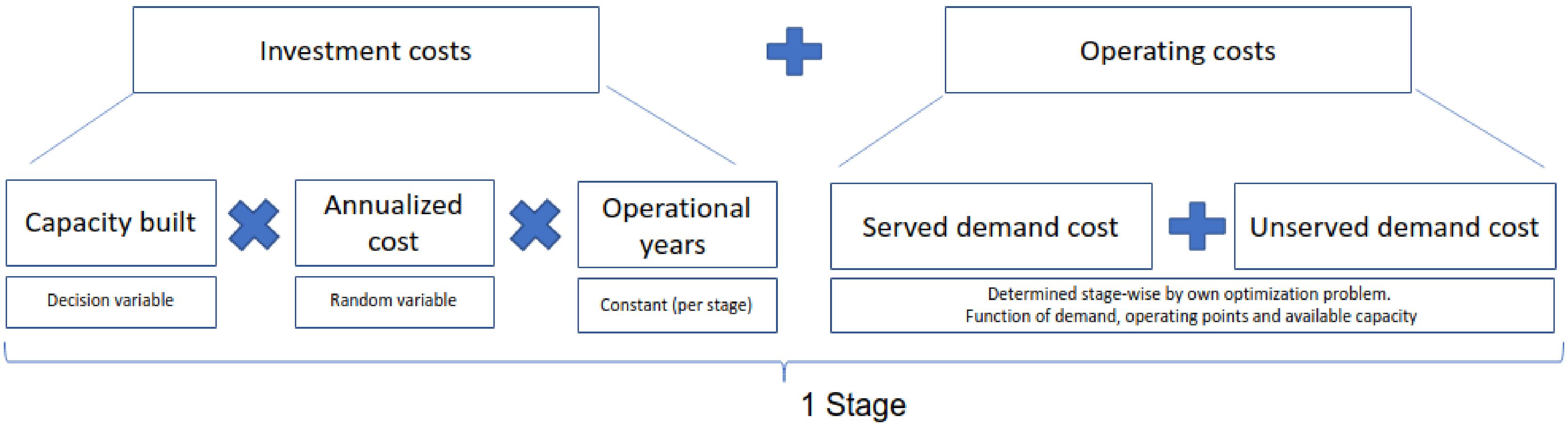
Capacity expansion is relevant in multiple areas

- Electricity grid expansion
- Goods production
- Wastewater treatment capacity

…under uncertain parameters

Capacity expansion aims to minimize costs while meeting demand goals

$$\underset{x_t(\tilde{\xi}_{t-1}),\, y_t(\tilde{\xi}_t)}{\text{Minimize}} \; E_{\tilde{\xi}}\left\{ \sum_{t=1}^{T} \left[\tilde{C}_t^{I^\top} x_t\left(\tilde{\xi}_{t-1}\right) + C_t^{O^\top} y_t\left(\tilde{\xi}_t\right) \right] \right\}$$



However, the models can be hard to solve

1. Exponential growth in scenarios if classic "tree structure" is used
   - How can we reduce the exponential growth?
2. Effect of imperfect uncertainty modeling on solution quality is unknown
   - How big is this effect?
3. Effect of modeling granurality on solution quality unknown
   - How do we know if solutions change because of uncertainty revealing vs. Modeling being more granular?
   - What is the relative magnitude of these effects?

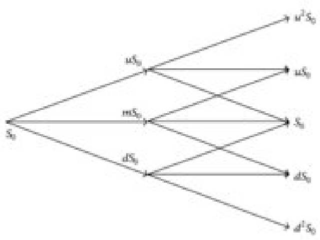
Uncertainty modeled with scenario lattice to reduce complexity growth

Demand growth

Trinomial tree

N(t) = t

N= T(T-1)/2

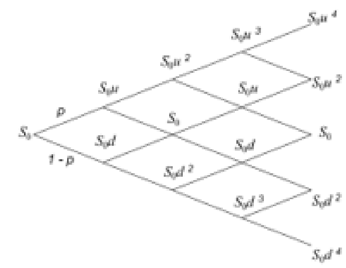


Price reduction

Binomial tree

N(t) = 2t-1

N= T^2



Node characteristics:

Total nodes per stage = 2t^2-t = O(t^2)
Total nodes = T^3(T-1)/2 = O(T^4)
Scenarios = 6^T

Randomness Characterization

$$D_{s,n,o} = D_{n_0} c_s d_o$$

$$c_s\,(n,t) = (1+u)^{\,n \cdot T}\, g_e^t$$

Motivation & Results:

- Number of nodes reduced from 6^T to O(T^4)
- Cuts can now be modeled for each node separately
- **No stage-independent randomness** is included in the model
- Only way to model exponential trends in SDDP
- Way of overcoming problem with product of decision variable and random variable

3 different models considered, each isolating one more source of result bias

Model 1

Operating points per investment decision: **1**

Result is influenced by:

- Ability to do more informed decisions
- More granular uncertainty modeling
- Inability to create plans for building

Model 2

Operating points per investment decision: **Arbitrary**

Result is influenced by:

- Ability to do more informed decisions
- Inability to create plans for building
- ~~More granular uncertainty modeling~~

Model 3

Operating points per investment decision: **Arbitrary**

At each investment stage, capacity to be built for each of following operating stages is defined

Result is influenced by:

- Ability to do more informed decisions
- ~~Inability to create plans for building~~
- ~~More granular uncertainty modeling~~

Data

- Open-source data
- IEEE standard electricity grid
- Electricity data from literature

Hypotheses

- H1: Model 1 will see largest decline in costs with increase in decision stages
- H2: Model 2 is expected to result in lower investment and operational costs compared to Model 1.
- H3: Model 3, with its capacity-building plans and ability to build capacity according to those plans, will likely have the lowest investment costs but higher operational costs compared to Model 2. T
- H4: As the number of stages increases, the differences in costs between the three models are expected to decrease.

Total cost per model supports H1 and H4

	Investment stages		
	1	**2**	**4**
Model 1	72643	39542	21971
Model 2	47767	27784	21971
Model 3	23831	22028	21971

- Model 1 sees sharpest decline in costs as number of stages increases
- All models converge to same cost with 4 investment stages
- Of total improvement 49% was caused by better modeling of operating points, 47% by being able to create investment plans and only 4% by better decisions through uncertainty
- Being able to take into account uncertainty when making decisions (1 vs 4 investment stages) accounted for 8% of total costs.

Operational & Investment costs support H2 & H3

Operational costs

	Investment stages		
	1	**2**	**4**
Model 1	8726	11307	9269
Model 2	8849	8863	9269
Model 3	9191	9398	9269

Investment costs

	Investment stages		
	1	**2**	**4**
Model 1	62890	28235	12385
Model 2	35204	18069	12385
Model 3	13966	12304	12385

– Model 1 sees highest investment costs

– Model 3 sees higher operational but lower investment costs

Recap

1. An improved scenario structure was created to reduce computational complexity of capacity expansion problems
2. Three formulations were proposed, each isolating a single source of result bias.
3. Each model formulation was found to behave as expected with increase in number of operational and investment stages
4. Effect of revelation of uncertainty on total cost was 8% of total cost and 4% of total improvement created (4 stages vs 1 stage)