Implied efficiency curves from analysis of operational patterns

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Goals

- We are investigate how hydropower production planners produce above and below the best efficiency point of the turbines

- Want to establish an empirical model for hydropower operations
  - Based on observed time series
  - Assuming operators were acting rationally

- Develop a method for estimating water values from time series of production, inflow and prices, and technical hydropower plant data

Method: Structural Estimation

- We develop an estimable dynamic programming approach to a hydropower planning problem
- Maximum likelihood estimation with an SDP as a constraint
- Use observed decisions to estimate economic primitives: managers perceived cost of deviating from BEP

Bellman Equation

Value of future profits

$$V(x) := \max_{d \in D} \mathbb{E}_d \left(\sum_{t=0}^{\infty} \beta^t g(X_t, d_t) \middle| X_0 = x \right)$$

Can write it as

$$V(x) = \max_{d \in D} \left(g(x, d) + \beta \mathbb{E}_d \left(V(X_{t+1}) \middle| X_t = x \right) \right)$$

Assuming stationarity

$$V(x) = \max_{d \in D} \left(g(x; d) + \beta \mathbb{E}_d \left(V(X_1) \middle| X_0 = x \right) \right)$$

- Idiosyncratic shock, ε(d), observed by decision maker, but not by the analyst

$$g(x, \varepsilon; d) = g(x; d) + \varepsilon(d)$$

- Define value function

$$v(x,d) := \mathbb{E}_d \left(\int V(X_1, \varepsilon_1) \mathcal{E}(\mathrm{d}\varepsilon_1 | X_1) \middle| X_0 = x \right)$$

$$v(x,d) = \mathbb{E}_d \left(\int \max_{d \in D} \{ g(X_1; d) + \varepsilon_1(d) + \beta \cdot v(X_1) \} \mathcal{E}(\mathrm{d}\varepsilon_1 | X_1) \middle| X_0 = x \right)$$

Structural Estimation Problem

- Maximum likelihood estimation problem
  - Based on original algorithm (NFXP) by Rust(1987)
  - We use NLP approach suggested by Su and Judd (2012)

$$\underset{\theta}{maximize} \quad L(\theta, v_\theta, (X_n, d_n)_{n=1}^{N})$$
$$s.t. \quad v_\theta = t_\theta(v_\theta)$$

- Likelihood function

$$L(\theta, v_\theta, (X_n, d_n)_{n=0}^{N}) = \sum_{n=1}^{N} log(P_v(d_n|X_n)),$$

Hydropower

	Energy Coefficient $[KWh/m^3]$	Production Capacity $[MW]$	Reservoir Capacity $[Mm^3]$	Average Inflow $[m^3/s]$
A	0.94268	10	35	3
B	1.2385	128	180	15

A: 1 turbine
B: 2

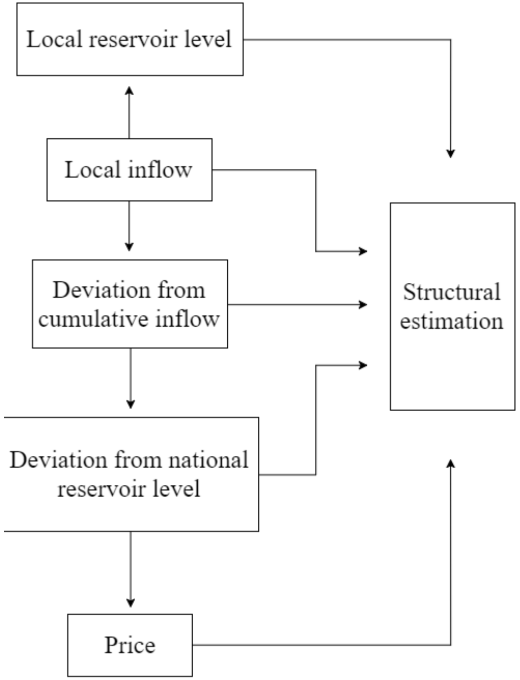
- Hydropower planning assumptions:
  - One reservoir
  - Sufficient reservoir flexibility
  - Sufficient production capacity
  - Price taker
  - No marginal production cost
  - Insignificant start-up and shutdown cost

State Space

- Have five state variables
  - Inflow, *I*
  - Deviation from normal cumulative local inflow, *C*
  - Deviation from normal aggregate system reservoir level in Norway, *R*
  - Spot price, *P*
  - Storage (reservoir level), *S*

  - Connection between inflow and price!

- Weekly resolution



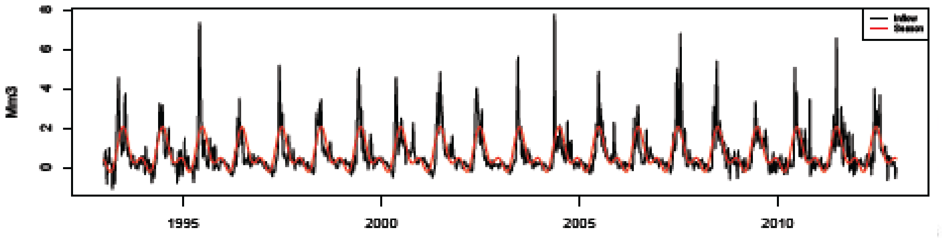
Inflow Process

- Seasonal and base process

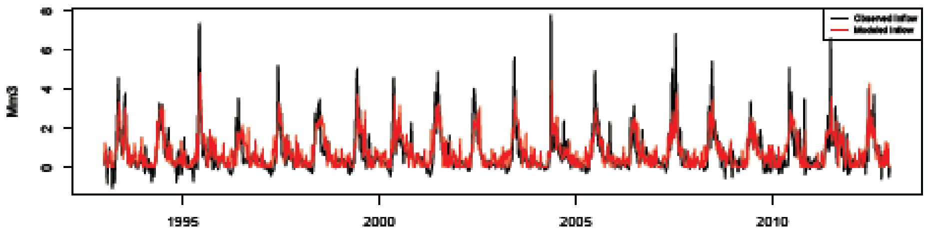
$$I_t = f^I(t) + X_t^I$$

- AR base process
  - Only one lag, since Markovian

$$X_t^I = \gamma X_{t-1}^I + \varepsilon_t^I$$



Observed inflow time series (black) and seasonal component (red)



Observed inflow time series (black) and simulated inflow (red)

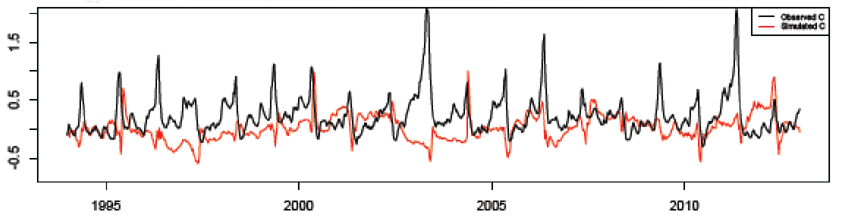
Cumulative Inflow and Aggregate System Reservoir Level

- Cumulative inflow

$$i_t = I_{t-1} + \rho i_{t-1}$$

- Deviation from normal cumulative inflow

$$C_t := \frac{i_t - \bar{i}_t}{\bar{i}_t}$$



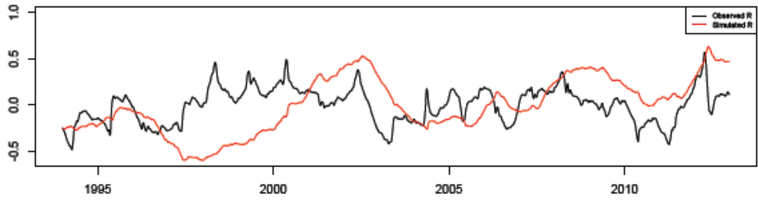
Deviation from normal cumulative local inflow, observed time series (bl) and simulation (red)

- Deviation from normal aggregate system reservoir level

$$R_t := \frac{r_t - \bar{r}_t}{\bar{r}_t}$$

- Autoregressive process, also dependent on *C*

$$R_t = \beta_1 R_{t-1} + \beta_2 C_{t-1} + \varepsilon_t^R$$



Simulated and observed deviation from aggregate system reservoir level

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Price Process

- Seasonal and base process

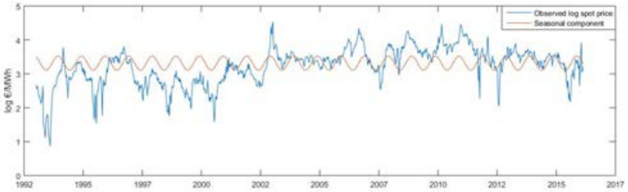
$$P_t := f^P(t) + Y_t^P$$

- Base process has mean reverting level depending on R

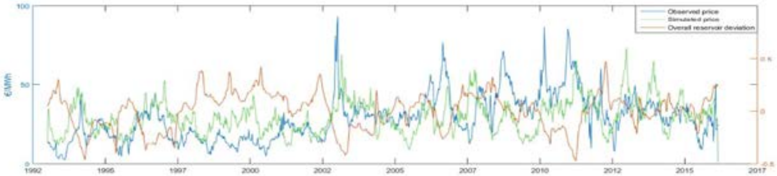
$$Y_t^P = X_t^P + \eta R_t$$

- Underlying autoregressive process

$$X_t^P = \delta X_{t-1}^P + \varepsilon_t^P$$



Observed log price time series (blue) and seasonal component of the log price (red)



Observed price time series (blue), simulated price (green) and overall reservoir devi-aiton (red)

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Descriptive Statistics

I: Inflow, C: cumulative inflow, R: System reservoir deviation, P: Price

Power plant A		Mean	St.dev.	Min.	Max.	Median
I	Observed	0,7151472	1,064891	-1,07798	7,766352	0,342648
	Simulated	0,751687	0,843074	0	4,373952	0,5568258
C	Observed	0,01462579	0,2187709	-0,5969365	1,003681	-0,00486093
	Simulated	0,227499	0,3268673	-0,3029207	2,104676	0,1476972
R	Observed	0,00E+00	0,1887571	-0,4811746	0,5708791	0,0308818
	Simulated	0,0156275	0,2160682	-0,5664131	0,7145599	-0,000471952
P	Observed	3,138499	0,5256082	1,427228	4.425137	3.204928
	Simulated	3,082369	0,3152591	2,346197	3,752814	3.064955

Table A.1: Descriptive statistics for the state variables processes for power plant A

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Efficiency curves

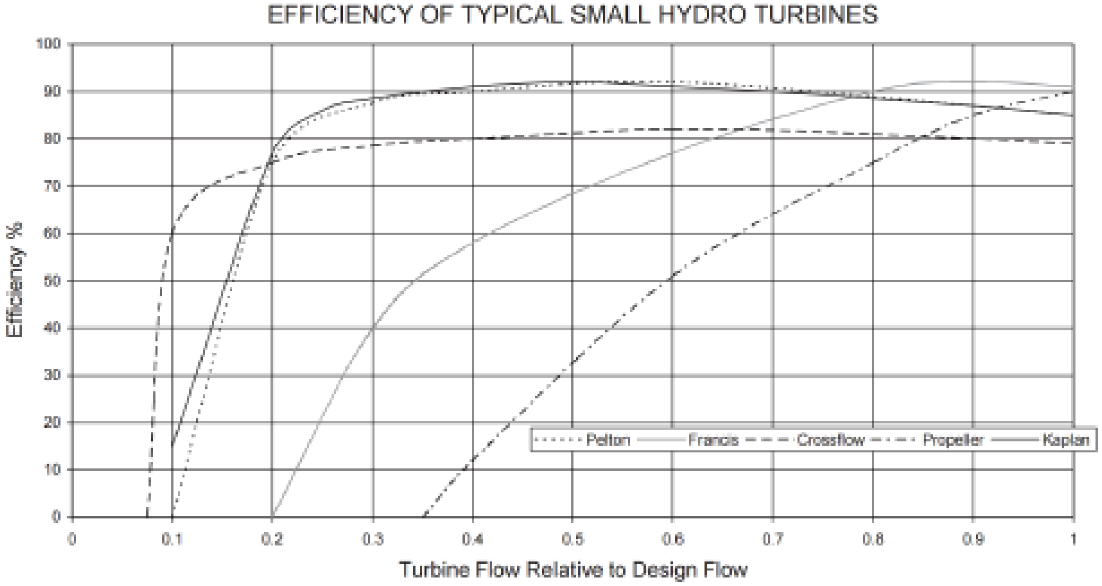


Figure 2.3: Efficiency curves for different turbines (Okot, 2012)

- Release function
  - Discrete decisions

$$u(X_t, d_t) = min\{S_t - S^{min} + I_t, d_t Q\}$$

- Profit function: price times production
  - Price taker
  - No cost

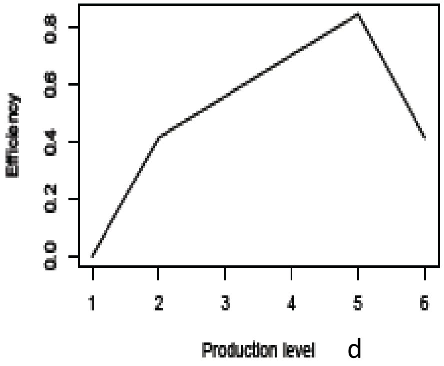
$$g(X_t; d_t) := P_t u(X_t, d_t)$$

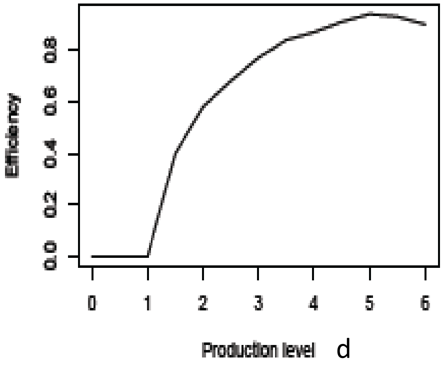
Structural Estimation for a Hydropower Producer

- Within-week generation depends linearly on the efficiency function *E*(), which is specified to capture the power operator's resistance to deviating from the best efficiency point (BEP). The efficiency function is dependent on three factors: the BEP, ξ, the efficiency for production levels beneath the BEP, θ_1, and the efficiency for production levels above the BEP, θ_2.
- For production levels (coded in the parameter *d*) below the BEP, $d < \xi$, the following equation applies:
- $E(\theta_1, \xi) = 1 - (\xi - d)\theta_1$
- and for production levels above the BEP, the efficiency function is:
- $E(\theta_2, \xi) = 1 - (d - \xi)\theta_2$

Results

- The results indicate that the reservoir managers require a 51% higher reward for producing at 100% instead of 83% of maximum production (83% is the BEP). They require a 17% higher reward for producing at 67% of maximum production, i.e. below BEP. Further, since the relationship is assumed to be linear, they require a 2·17% = 34% higher reward for producing at 50% of maximum production, and so on.





Changes in operational pattern over time

Table 1. Changing values of θ_1 and θ_2 for the power plant over time

	First half of the sample (20 years)	Second half
θ_1	0.5456	0.0794
θ_2	1	0.398
Log-likelihood	-579.69	-676.54

- Increased willingness to deviate from BEP over time
  - Unbserved gains? Less fear of cavitation wear?
- Recall efficiency model $E(\theta_1, \xi) = 1 - (\xi - d)\theta_1$ (below BEP), and
- $E(\theta_2, \xi) = 1 - (d - \xi)\theta_2$ (above BEP)

Results – Water Values

- Able to calculate water values!
- Similar shape
- Do not capture the extremes
- Good indication that our model works

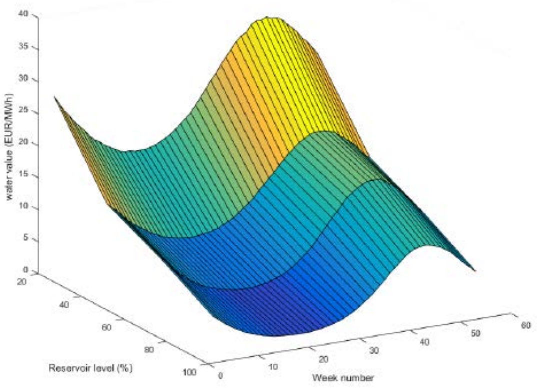
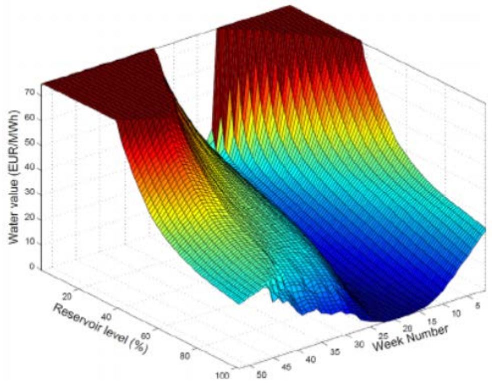


Figure 5.5: Marginal water values



(b) Water values from the EMPS model for a reservoir in south of Norway (Gebrekiros et al., 2013)

Further Studies

- Validate model further by simulating decision process and use as input to the model
- Apply model to a general sample of hydropower producers
- Reduce memory usage

Conclusion

- Have developed a working structural estimation model for a hydropower producer
- Willingness to produce below BEP rather than above
  - Cavitation
- Last 10 years: more willingness to produce both above and below BEP
- Work in progress. Need further studies to validate and improve model

Thanks!