Probabilistic production cost simulation (PPC)

- Development started in the late 1960:th
- Analytical calculations
- A fast method but limitations concerning possibilities to include market details.

**Calculating of system index**

**Basic idea**

- Assume a system where all power plants are 100% available.
- In this system it is easy to calculate the system indices from the load duration curve, LDC

**Example**

- Load duration curve, LDC
- Two power stations (300 MW, always available, incremental operation cost $\beta_1$ and $\beta_2$ respectively, $\beta_1 \leq \beta_2$)
Calculation of system index - Basic idea

LOLP = LDC(600) = 876 h/year = 10%

Calculation of system index - Basic idea

\[ ENS = \int_{600}^{\infty} LDC(x) \, dx \]

Load model

- We only study the total load in the system
- We assume that the load is price independent
- The load is represented by a scenarioparameter, D, which has a probability distribution which is data for the simulations
- In probabilistic simulation (PPC) the load is represented with the load duration curve.
Load model

- How to determine the load duration curve?
- It can not be calculated but it has to be estimated from historical data and forecasts.
- **Alternative 1**: Select a standardized function (e.g. normal distribution) and fit historical data + forecast to this one.
- **Alternative 2**: Calculate an LDC directly from available data + forecasts.

Load model – Alternative 2

**Definition 6.11.** The load curve, \( D(k) \), states the mean load per hour during a specified time period: \( k = 1, \ldots, T \).
\[
D(k) = \text{load hour } k \ [\text{MWh/h}]
\]

**Definition 6.12.** The real load duration curve, \( L_{DCR}(k) \), states the load level which is exceeded during \( k \) hours.
\[
L_{DCR}(K) = \text{load level that is exceeded during } k \text{ hours} \ [\text{MWh/h}]
\]

Load model – Alternative 2

**Example 6.7**

The expected value of the load corresponds to the area below the curve.

The area below the real LDC is as large as the area below the load curve.

Information is lost when an LDC is created!
Load model – Alternative 2

- **Definition 6.13.** The inverted load duration curve, $LDC(x)$, states how many hours a certain load level $x$ is exceeded.

$$LDC(x) = \text{number of hours when the load level } x \text{ is exceeded} \quad [\text{h}]$$

By dividing $LDC(x)$ with the length of the studied time period, the normalized $LDC$ is obtained.

The normalized $LDC$ shows the probability distribution of the load during the studied period.

Load model – Alternative 2

Example 6.8:
The area below the curve is still the same since only axes are changed.

Load model – Practical aspect

- In reality the load is a continuous stochastic variable.
- To be able to calculate expected energy values, it is necessary to integrate the load duration curve, which means that some numerical methods have to be applied.
- It is therefore suitable to use a discrete approximation of the $LDC$. 

Example 6.8:
The area is now changed since the $y$-axes is divided with $T$. To get the correct expected value, the area has to be multiplied with $T$. 

The area below the curve is still the same since only axes are changed.

$E[D] = 12\,600 \text{ MWh/day}$
Thermal power station model

The model of the thermal power stations include:

- Installed capacity, \( \hat{G}_g \).
- Production cost, \( C_{Gg}(G_g) = \alpha + \beta G_g \).

This means that we assume that the incremental production cost is independent of the production level, i.e., constant efficiency.

- Availability, \( p_g \).

Thermal power station model

- A thermal power station is represented by a scenario parameter, \( \hat{G}_g \) (available production capacity), with a distribution which is used as data for the simulation.

- In probabilistic simulation a two state model is used for available capacity.

Thermal power station model

- The availability of a thermal power station can not be calculated, but has to be estimated from historical data and forecasts of the future.
**Definition 6.14.** The Mean Time To Failure is calculated by

\[
MTTF = \frac{1}{K} \sum_{k=1}^{K} t_u(k),
\]

where \(K\) is the number of periods when the power plant is available and \(t_u(k)\) is the duration of each of these periods.

**Definition 6.15.** The Mean Time To Repair is calculated by

\[
MTTR = \frac{1}{K} \sum_{k=1}^{K} t_d(k),
\]

where \(K\) is the number of periods when the power plant is not available and \(t_d(k)\) is the duration of each of these periods.

**Definition 6.16.** The failure rate \(\lambda\) is the probability that an available unit will fail. The failure rate can be estimated as

\[
\lambda = \frac{1}{MTTF}.
\]

**Definition 6.17.** The repair rate \(\mu\) is the probability that an unavailable unit will be repaired. The repair rate can be estimated as

\[
\mu = \frac{1}{MTTR}.
\]
**Definition 6.18.** The availability is the probability that a power plant is available. This probability can be estimated as the part of a longer period that the unit is available:

\[ p = \frac{MTTF}{MTTF + MTTR} = \frac{\mu}{\mu + \lambda}. \]

**Example 6.11 (availability in a power plant).** Table 6.4 shows the operation log of a power plant. Calculate the failure rate, repair rate and unavailability of this unit.

<table>
<thead>
<tr>
<th>Event</th>
<th>Time [week]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>20 60 70 101</td>
</tr>
<tr>
<td>Repair</td>
<td>0 23 62 74 104</td>
</tr>
</tbody>
</table>

**Definition 6.19.** The unavailability is the probability that a power plant is unavailable, which can be estimated by

\[ q = 1 - p = \frac{MTTR}{MTTF + MTTR} = \frac{\lambda}{\mu + \lambda}. \]

**Thermal power station model - Practical considerations**

- How the availability is estimated depends on available data. Is, e.g., MTTF and MTTR available or not?
- Remember that availability is not the same as utilization! If a power plant is available, does not mean that it is used! A plant is only used when it is available and needed! Needed means that the load is high enough and the plant is competitive.
Probabilistic production cost simulation (PPC)

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PPC model

Assume
- Perfect competition
- Perfect information
- Load is not price sensitive
- Neglect grid losses and limitations
- All scenario parameters can be treated as independent

Some of these assumption can be treated with some specific methods.

Calculation of system index
- Basic idea
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Example
- Load duration curve, LDC
- Two power stations (300 MW, always available, incremental operation cost $\beta_1$ and $\beta_2$ respectively, $\beta_1 \leq \beta_2$)
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Calculation of system index - Basic idea

\[
\text{LOLP} = \text{LDC}(600) = 876 \text{ h/year} = 10%
\]

Calculation of system index- Basic idea

\[ EENS = \int_{0}^{\infty} LDC(x) dx \]

Calculation of system index- Basic idea

\[
EENS = \int_{0}^{\infty} \text{LDC}(x) dx
\]

Calculation of system index - Basic idea

\[ ETOC = \beta_1 E_G_1 + \beta_2 E_G_2 \]

Load model – Alternative 2

Example 6.8:

The area is now changed since the y-axes is divided with T. To get the correct expected value, the area has to be multiplied with T.
Thermal power station model

- The availability of a thermal power station can not be calculated, but has to be estimated from historical data and forecasts of the future.

Equivalent load

**Definition 6.10.** The equivalent load is given by

\[ E_g = D + \sum_{k=1}^{g} O_k, \]

where

- \( E_g \) = equivalent load for the power plant next to be dispatched after unit \( g \),
- \( D \) = actual load,
- \( O_k \) = outage in unit \( k \).

- We have seen that it is simple to calculate the system indices in a system where all power plants are 100% available.
- How is this performed when this is not the case?
- **PPC-method:** Consider outages in power stations as load increase instead of reduced available production capacity.

Equivalent load - example

A capacity deficit problem (LOLO) occurs when:

- Available capacity < demand
  \( \Rightarrow \)
  Installed capacity – outages < demand
  \( \Rightarrow \)
  Installed capacity < demand + outages
  \( \Rightarrow \)
  Installed capacity < equivalent load
**Equivalent load - example**

**Calculation of system indices**

- From the equivalent load duration curve, $\tilde{F}_g(x)$, it is possible to calculate the system indices.

- Total available capacity:
  $$\tilde{G}_g^{\text{tot}} = \sum_{k=1}^{g} \tilde{G}_k$$

- Total installed capacity:
  $$\hat{G}_g^{\text{tot}} = \sum_{k=1}^{g} \hat{G}_k$$

- Total outage:
  $$O_g^{\text{tot}} = \sum_{k=1}^{g} O_k$$

**Calculation of system indices**

- Risk of capacity deficit = Loss of load probability. Capacity deficit occurs when the demand exceeds available production capacity, i.e.

  $$\text{LOLP}_g = P(D > \tilde{G}_g^{\text{tot}}) = P(D > \hat{G}_g^{\text{tot}} - O_g^{\text{tot}})$$
  $$= P(D + O_g^{\text{tot}} > \hat{G}_g^{\text{tot}}) = P(E_g > \hat{G}_g^{\text{tot}})$$
  $$= \tilde{F}_g(\hat{G}_g^{\text{tot}}).$$

- Expected Energy Not Served, EENS: This means energy that cannot be delivered depending on capacity deficit, i.e., equivalent load > installed capacity

  $$\text{EENS}_g = T \int \tilde{F}_g(x) dx.$$
Calculation of system indices

• Expected energy production in power plants, $EG$: Assume that we do not have unit $g$. Then the expected unserved energy is $EENS_g - 1$. When unit $g$ is then installed the expected unserved energy decreases to $EENS_g$. The difference is expected energy production in the unit.

$$EG_g = EENS_g - 1 - EENS_g.$$ 

Calculation of system indices

• Expected production cost. If energy production in each unit is available, then it is easy to calculate the production cost.

$$ETOC_g = \sum_{k=1}^{g} \beta_k E G_k$$

• It is also possible to include the cost of disconnected consumers

$$ETOC_g = \sum_{k=1}^{g} \beta_k E G_k + \beta_U EENS_g$$

Calculation of system indices

• Example 6.3-6.6. In a simple system the load is constantly 200 kW. The system is supplied by a 200 kW power plant having an availability of 80% and the operation cost 1 \$/kWh. Calculate the $EENS$, $LOLP$ and $ETOC$ of the system.

[Figure 6.2: Calculation of system indices directly from the load duration curve.]

Calculation of system indices

• Example 6.4. Study the same system as in example 6.3. What does the equivalent load duration curve look like?

• The definition of the equivalent load is:

$$E_g = D + \sum_{k=1}^{g} O_k.$$

• This means convolution since the equivalent load is a sum of independent stochastic variables.
Calculation of equivalent load duration curve, ELDC

- General formula:
  \[ \tilde{F}_g(x) = p_g \cdot \tilde{F}_{g-1}(x) + q_g \cdot \tilde{F}_{g-1}(x - \hat{G}_g). \]

- Assume an LDC and one power plant with availability \( p_1 \) ⇒ ELDC:
  \[ \tilde{F}_1(x) = p_1 \cdot \tilde{F}_0(x) + q_1 \cdot \tilde{F}_0(x - \hat{G}_1). \]

- The equivalent load is > \( x \), when
  - unit available, load is > \( x \), probability \( p_1 \)
  - outage of \( G_1 \), load > \( x - G_1 \), probability \( q_1 \)

Calculation of system indices

- Example 6.4-6.5. Study the same system as in example 6.3. What does the equivalent load duration curve look like?

Calculation of system indices

- Example 6.6. Calculate the unserved energy, loss of load probability and expected operation cost per hour in the system described in figure 6.3.
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Example 6.6
Power Generation Operation and Planning, EG2200

Probabilistic production cost simulation of electricity markets – lecture 14

Lennart Söder
Professor in Electric Power Systems

PPC model

Assume
- Perfect competition
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Some of these assumptions can be treated with some specific methods.

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\[ EENS = \int_{0}^{\infty} LDC(x) dx \]

\[ 600 \]

h/year LDC

LOLP

8760

200 400 600 800 MW

x

h/year LDC

EENS

8760

200 400 600 800 MW

x
Calculation of system index
- Basic idea

\[ ETOC = \beta_1 E_1 + \beta_2 E_2 \]

Perfect competition ⇒ Unit 1 is used first, since \( \beta_1 \leq \beta_2 \)

\[ \text{h/year} \quad \text{LDC} \]

8 760

Load model – Alternative 2

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  \[
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  \]

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- The definition of the equivalent load is:

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  E_g = D + \sum_{k=1}^{g} O_k,
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  This means convolution since the equivalent load is a sum of independent stochastic variables.
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  \[ \tilde{F}_g(x) = p_g \cdot \tilde{F}_{g-1}(x) + q_g \cdot \tilde{F}_{g-1}(x - \tilde{G}_g) \]

- Assume an LDC and one power plant with availability \(p_1\) \(\Rightarrow\) ELDC:
  \[ \tilde{F}_1(x) = p_1 \cdot \tilde{F}_0(x) + q_1 \cdot \tilde{F}_0(x - \tilde{G}_1) \]

- The equivalent load is > \(x\), when
  - unit available, load is > \(x\), probability \(p_1\)
  - outage of \(G_1\), load > \(x - G_1\), probability \(q_1\)

Model of a wind power station

The production varies when the wind varies

- The wind varies

Model of a wind turbine

- There is one discrete probability that the wind power plant will not produce anything, i.e. When there is too little wind, too much wind or there is an outage.
- There is one discrete probability that the wind power plant will produce installed capacity, i.e. When the wind is higher than rated wind speed and lower than cut-off wind speed, and there is no outage.
- During the rest of the time there is a continuous distribution between 0 MW and installed capacity
Model of a wind turbine

Wind power probability function

Thermal power probability function

Model of many wind turbines

- The production in several wind power plants can not be treated as independent variables, since high wind in one place normally means high winds in neighbouring regions.

Model of many wind turbines

- Since PPC is based on independence between unit variation (outages) in different power plants, all wind power has to be treated as one source.
- Compared to one unit pdf, the discrete probabilities are much smaller.

Model of wind power

- Available wind power capacity is a continous stochastic variable ⇒ use discrete approximation.
Model of wind power

- Thermal power is treated with two states: Installed capacity or zero.
- Total wind power is treated with a multi-state unit:
- ELDC Convolution with thermal power:
  \[ \tilde{F}_g(x) = p_g \cdot \tilde{F}_g - 1(x) + q_g \cdot \tilde{F}_g - 1(x - \hat{G}_g). \]
  \[ N_g \]
- Wind power:
  \[ \tilde{F}_g(x) = \sum_{i=1}^{N_g} p_{g,i} \tilde{F}_g - 1(x - x_{g,i}), \]
  \[ N_g = \text{number of states in power plant } g, \]
  \[ p_{g,i} = f_{Wg}(\bar{W} - x_{g,i}) = \text{probability of state } i, \]

PPC model

Assume
- Perfect competition
- Perfect information
- Load is not price sensitive
- Neglect grid losses and limitations
- All scenario parameters can be treated as independent

Some of these assumptions can be treated with some specific methods.

Wind power in PPC

- “All scenario parameters can be treated as independent”
- Outages in thermal power plant can be considered to be independent on wind speed
- There is often a common variation between load and wind:
  - **time coupling**: treat as independent in each period
  - **special couplings** (e.g. low wind when it is extremely cold): treat as independent in each period

Example 6.13 (the power system in a small island): The small island Kobben is not connected to the national grid, but there is a local grid which is powered by a small wind power plant (installed capacity 200 kW) and a diesel generator set. The diesel generator set has a maximal capacity of 200 kW and the availability is 95%. A simplified model of the wind power plant is stated in table 6.5. The load duration curve is shown in figure 6.12. Calculate the risk of power deficit in this system.
Example 6.13

**Power market simulations**
- **Capacity credit of a plant**

  - **Definition:** Capacity credit means the possibility of a power plant to increase the reliability (decrease in LOLP) of a plant
  - **Question:** Is there any capacity credit for wind power?

Table 6.5 Model of the wind power plant in example 6.13.

<table>
<thead>
<tr>
<th>Outage [kW]</th>
<th>Probability during the day [%]</th>
<th>Probability during the night [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>200</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 6.12 The load for the small island in example 6.13.

Example 6.13

**Solution:** We start by calculating the system LOLP during day time. The total installed capacity is 400 kW; hence, we get

\[
\text{LOLP}_{\text{day}} = \frac{\tilde{F}_{\text{day}}}{2} \cdot (400) = 0.95 \tilde{F}_{\text{day}} (400) + 0.05 \tilde{F}_{\text{day}} (400 - 200) = \\
= 0.95 \cdot (0.3 \tilde{F}_{\text{day}} (400 - 0) + 0.4 \tilde{F}_{\text{day}} (400 - 100) + 0.3 \tilde{F}_{\text{day}} (400 - 200)) + \\
+ 0.05 \cdot (0.3 \tilde{F}_{\text{day}} (200 - 0) + 0.4 \tilde{F}_{\text{day}} (200 - 100) + 0.3 \tilde{F}_{\text{day}} (200 - 200)) = \\
= 0.95(0.3 \cdot 0 + 0.4 \cdot 0 + 0.3 \cdot 0.1) + 0.05(0.3 \cdot 0.1 + 0.4 \cdot 0.7 + 0.3 \cdot 1) = 5.9\%.
\]

In the same way we can calculate the night time LOLP:

\[
\text{LOLP}_{\text{night}} = 0.95(0.1 \cdot 0 + 0.5 \cdot 0 + 0.4 \cdot 0) + \\
+ 0.05(0.1 \cdot 0 + 0.5 \cdot 0.2 + 0.4 \cdot 1) = 2.5\%.
\]

To calculate the total system LOLP we use the weighted average of these two values:

\[
\text{LOLP} = \frac{14}{24} \text{LOLP}_{\text{day}} + \frac{10}{24} \text{LOLP}_{\text{night}} \approx 4.5\%.
\]

Wind Power Capacity Credit
(expressed as equivalent load increase)

How much can the consumption increase when the amount of wind power increases and the risk of power deficit is kept constant?
Wind power capacity credit - 1

No wind power

Wind power capacity credit - 2

With wind power

Wind power capacity credit - 3

With wind power, load + 300 MW

Capacity credit of wind power

• **"True" value**: Considers the possibility of wind power increase the reliability of the power system, ≈ 20% of installed capacity.

• **Market value**: High market prices when there is a risk for power deficit.