Economic and technical representation of investments: A basic planning model example

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This document aims at illustrating how investments can be represented in a multi-year planning model and can as such be used as a basis for discussion of how we tackle these things within SPINE. First, this document shows how one can correctly value future cashflows (investment, FOM, VOM and generation costs) in the objective function. Second, we look at the technical representation of investment retirements in a multi-year planning model.

1 Economic representation of multi-year investments

To correctly value future cashflows, a series of discount factors is used. In this section, all relevant discount factors are defined and explained.

In what follows, it is assumed that the planning horizon is split up in different investment periods that each are assigned a milestone year (one characteristic year that is assumed to be operationally representative for the entire period). Figure 1 provides a graphical illustration of the planning horizon structure. The set of milestone years are indexed by $y \in \mathcal{Y}$.

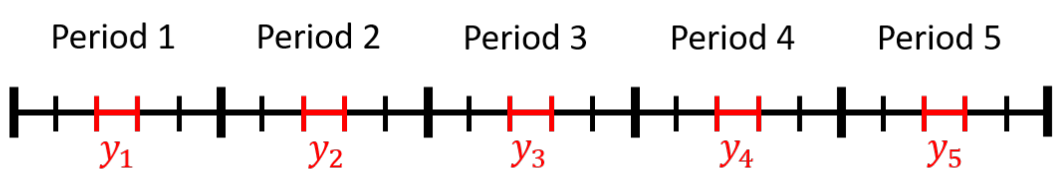

Figure 1: Graphical illustration of the planning horizon.

1.1 Discounting of period costs to the discount year

The objective function should reflect the total costs incurred over the entire planning horizon expressed as a monetary value at a single point in time. In order to do this, we need to a priori define a discount year (DY) to which all period costs are discounted. Figure 2 depicts a graphical

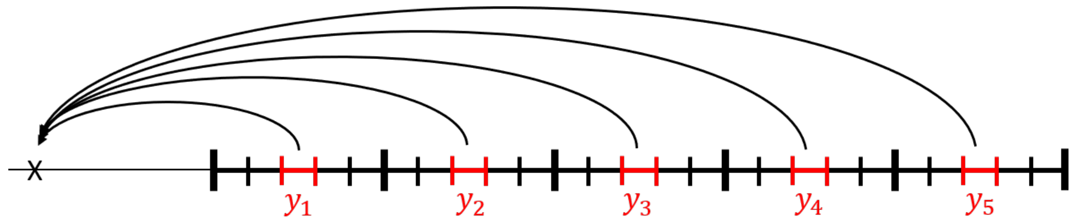

Figure 2: Graphical illustration of discounting of period costs. The discount year is represented by X.

illustration of the discounting of period costs to a specific discount year.

With period costs we refer to all cost incurred in a specific period (characterized by its milestone year y). These costs include the investment costs associated with that period, the fixed O&M costs of the investments made in that period and all operational costs associated with that period (variable O&M costs, generation costs and ENS costs).

$$periodcost_y = c_y^{inv} + c_y^{fom} + c_y^{vom} + c_y^{gen} + c_y^{ens}$$

Since period costs are incurred during the milestone year y associated with that period, the discount factor for a specific period (DF_y) can be expressed as:

$$DF_y = \frac{1}{(1+r)^{y-DY}} \tag{1}$$

1.2 Economic representation of investment costs

1.2.1 Correctly accounting for annuities

When an investment is made in a particular period, we assume that the investment decision is taken during the first year of that period. Therefore, the payments for the investments begin in the period's start year (PS_y). To distribute the annuities of investment costs over the economic lifetime of the investment, we assume that the these annuities increase linearly over the investment's lead time and decrease linearly at the end of the economic lifetime of the investments (see Figure 3). Other distributions exist (the TIMES documentation part II, p 153 onwards lists 4 investment cases), but I think this is a commonly used one.

The distribution of the annuities has an impact on the costs associated with an investment. To account for this we can introduce a markup factor by which we can multiply the total overnight investment costs to obtain the correct discounted cost. This markup factor can be expressed as:

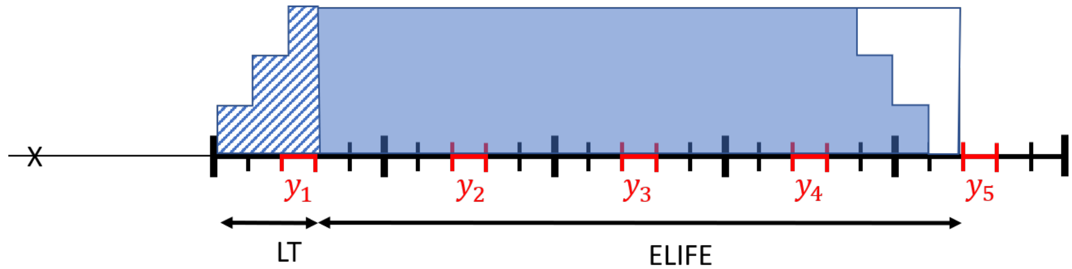

Figure 3: Graphical illustration of the Lead time mark up.

$$MARKUP^{AN}_{g,y} = CRF^r_g \cdot \sum_{j \in PY_{g,y}} \frac{1}{(1+r)^{j-y}} \cdot p^{frac}_{g,y,j} \tag{2}$$

with:

- CRF^r_g: the capital recovery factor associated with technology g and discount rate r. The capital recovery factor is the ratio between the annuity and the present value of an investment and can be calculated as:

$$CRF^r_g = \frac{r(1+r)^{ELIFE_g}}{(1+r)^{ELIFE_g} - 1}$$

- $PY_{g,y}$: the set containing all payment years for an investment made for technology g in the period associated with milestone year y. This set can be expressed by following interval.

$$[PS_y, PS_y + LT_g + ELIFE_g - 1] \tag{3}$$

- $p^{frac}_{g,y,j}$: the fraction of the annuity for technology g with vintage year y that needs to be paid in payment year j. This fraction can be calculated via:

$$p^{frac}_{g,y,j} = max\left(\frac{UP_{g,y,j} - DOWN_{g,y,j} + 1}{LT_g}, 0\right)$$

with:

  - $UP_{g,y,j}$: $min\,(PS_y + LT_g - 1, j)$
  - $DOWN_{g,y,j}$: $max\,(PS_y, j - ELIFE_g + 1)$

1.2.2 Salvage fraction

If an investment's economic lifetime exceeds the model horizon, we need to subtract the value of the investment at the end of the model horizon from th eobjective function. As such, a salvage fraction can be defined for an investment in technology g in milestone year y. The salvage fraction parameter can be defined as follows:

$$SF_{g,y} = max\left[\frac{\sum\limits_{j=EOH+1}^{PS_y+LT_g+ELIFE_g} \frac{1}{(1+r)^{j-y}} \cdot p^{frac}_{g,y,j}}{\sum\limits_{j\in PY_{g,y}} \frac{1}{(1+r)^{j-y}} \cdot p^{frac}_{g,y,j}}, 0\right] \tag{4}$$

with:

- PS_y: the period start year of the period with milestone year y.
- LT_g: the lead time of technology g.
- $ELIFE_g$: the economic lifetime time of technology g.
- EOH: the end of the planning horizon.
- $p^{frac}_{g,y,j}$: the fraction of the annuity for technology g with vintage year y that needs to be paid in payment year j. This fraction can be calculated via:

  $$p^{frac}_{g,y,j} = max\left(\frac{UP_{g,y,j} - DOWN_{g,y,j} + 1}{LT_g}, 0\right)$$

  with:

  - $UP_{g,y,j}$: $min\left(PS_y + LT_g - 1, j\right)$
  - $DOWN_{g,y,j}$: $max\left(PS_y, j - ELIFE_g + 1\right)$

1.2.3 Technology-specific discount rates

A useful feature of an investment model is to allow technology-specific discount rates to be assigned to, e.g., more risky investments.

$$MARKUP^{DR}_g = \frac{CRF^r_g}{CRF^{r'}_g} \tag{5}$$

with:

- CRF^r_g: the capital recovery factor associated with technology g if the common discount rate r is used.

- $CRF_g^{r'}$: the capital recovery factor associated with technology g if the technology-specific discount rate r' is used.

$$CRF_g^{r'} = \frac{r'(1+r')^{ELIFE_g}}{(1+r')^{ELIFE_g} - 1}$$

1.3 Discounting of FOM costs to period costs

Fixed O&M costs are incurred during each year in which the investment is operational. As such, we need a discount factor that discounts every operational year back to the milestone year of the period in which the investment is made. Figure 4 illustrates the discounting of fixed O&M costs.

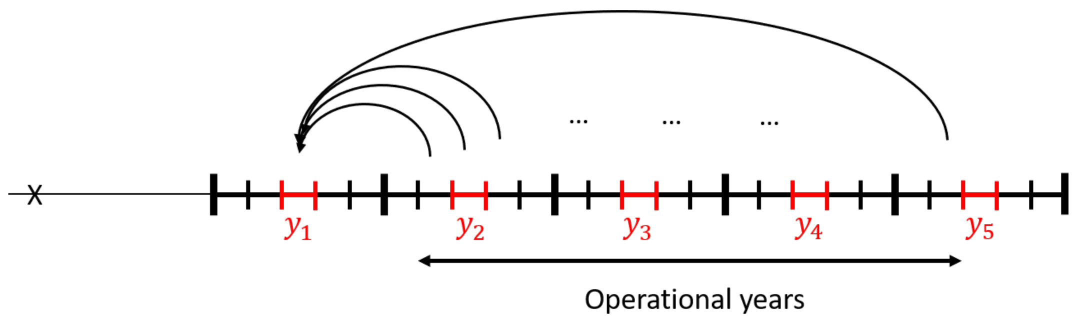

Figure 4: Graphical illustration of the discounting of investment costs (occurring in the first year of the period) to the period costs.

Summing all the discount factors for all the operational years gives the factor by which we must multiply the annual fixed O&M cost to obtain the total fixed O&M cost for a particular investment. This factor can also be interpreted as the total number of operational years compensated for discounting effects.

$$D_{g,y}^{OY} = \sum_{j \in OY_{g,y}} \frac{1}{(1+r)^{j-y}} \tag{6}$$

The set of operational years of an investment in technology g in milestone year y is denoted by $OY_{g,y}$. and can be expressed by the following interval.

$$[PS_y + LT_g, min(PS_y + LT_g + TLIFE_g - 1, EOH)] \tag{7}$$

with:

- PS_y: the period start year of the period with milestone year y.
- LT_g: the lead time of technology g.

- $ELIFE_g$: the (economic) lifetime time of technology g.
- EOH: the end of the planning horizon.

1.4 Discounting of operational costs to period costs

The operational costs associated with a milestone year are assumed to be representative for every year in the period. As such, we need to multiply the milestone year operational costs by the period duration compensated for discounting effects. Figure 5 illustrates the discounted period duration.

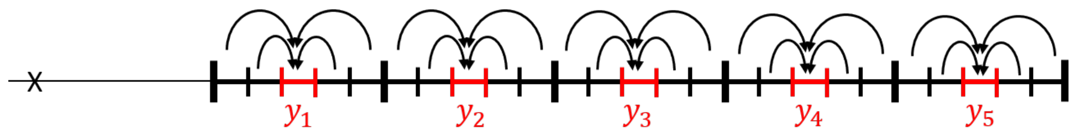

Figure 5: Graphical illustration of the discounting of operational costs to the period costs.

Let $\mathcal{J}(y)$ denote the set of all the years included in the period associated with milestone year y. Then the discounted period duration associated with milestone year y (DD_y) can be expressed mathematically as:

$$DD_y = \sum_{j \in \mathcal{J}(y)} \frac{1}{(1+r)^{j-y}} \tag{8}$$

2 Technical representation of multi-year investment availability

To account for multi-year investments' availability, a distinction needs to be made between investment decision variables, i.e., variables that represent the decision to invest in a technology at a specific point in time, and investment availability variables, i.e., variables that reflect the available capacity of an investment at a particular point in time. These variables are related through a capacity transfer factor that defines the fraction of an investment in technology g during vintage year v that is still available in year y. This capacity transfer parameter CPT can be calculated as:

$$CPT_{g,v,y} = \begin{cases} 0 & PE_y < PS_v + LT_g \\ max\left[min\left(1 - \frac{PS_v + LT_g - PS_y}{DUR_y}, 1\right), 0\right] & PS_y \leq PS_v + LT_g < PE_y \\ max\left[min\left(1 - \frac{PS_v + LT_g + TLIFE_g - PS_y}{DUR_y}, 1\right), 0\right] & otherwise \end{cases}$$

The first case expresses that for every investment decision with vintage year v the available fraction is zero for year y if the final year of the period containing y comes before the year during which the investment becomes available ($PS_v + LT_g$). The second case represents the case for which the investment becomes available during the period containing y. The final case defines CPT for all other cases.

3 Planning model example

3.1 Objective function

The objective function expresses a minimization of the discounted total system costs, which consists of investment costs, fixed operation and maintenance (FOM) costs, variable operation and maintenance (VOM) costs, generation costs, and load-shedding costs.

$$Min \sum_{y \in \mathcal{Y}} DF_y \cdot \left(c_y^{inv} + c_y^{fom} + c_y^{vom} + c_y^{gen} + c_y^{ens} \right) \tag{9}$$

The investment costs are a function of the investment variables for generation technologies. The investment costs take into account the salvage fraction (SF) of each investment, i.e., the fraction that reflects the remaining value of the investments at the end of the planning horizon. Furthermore, we assume that the investment decision occurs at the start of each investment period so that these costs need to be discounted from the start of the period, to the period's milestone year DF_y^{SM}.

$$c_y^{inv} = \sum_{g \in \mathcal{G}} (1 - SF_{g,y}) \cdot C_{g,y}^{INV} \cdot cap_{g,y} \cdot MARKUP_{g,y}^{AN} \cdot MARKUP_{g,y}^{DR} \quad \forall y \in \mathcal{Y} \tag{10}$$

A similar expression is obtained for the FOM costs. However, to obtain the total FOM costs of an investment decision the annual FOM cost is multiplied by the discounted number of operating years (D^{OY}).

$$c_y^{fom} = \sum_{g \in \mathcal{G}} D_{g,y}^{OY} \cdot C_{g,y}^{FOM} \cdot cap_{g,y} \qquad \forall y \in \mathcal{Y} \tag{11}$$

The operational costs include the VOM costs, the generation costs and the load-shedding costs. These costs are calculated based on the representative days used to represent a model year. Each representative day is assumed to be repeated W_i times within a model year, and as such, the operational costs associated with that representative day are multiplied by W_i. Furthermore, to obtain the total operational costs, the annual operational costs are multiplied by the discounted duration of the associated investment period (DD_y).

$$c_y^{vom} = DD_y \cdot \sum_{i \in \mathcal{I}} W_i \cdot \left(\sum_{t \in \mathcal{T}} \sum_{g \in \mathcal{G}} \sum_{v \in \mathcal{V}} C_{g,v}^{VOM} \cdot gen_{g,v,y,i,t} \cdot \Delta \right) \quad \forall y \in \mathcal{Y} \tag{12}$$

The generation costs contain both the fuel as well as the emission costs associated with generating electricity.

$$c_y^{gen} = DD_y \cdot \sum_{i \in \mathcal{I}} W_i \left[\sum_{t \in \mathcal{T}} \sum_{g \in \mathcal{G}} \sum_{v \in \mathcal{V}} \left(\frac{C_{g,y}^{FUEL}}{\eta_{g,v}} + \frac{C^{GHG} \cdot EF_g}{\eta_{g,v}} \right) \cdot gen_{g,v,y,i,t} \cdot \Delta \right] \quad \forall y \in \mathcal{Y} \tag{13}$$

The load shedding cost are directly proportional to the assumed value of lost load (VOLL).

$$c_y^{ens} = DD_y \cdot \sum_{i \in \mathcal{I}} W_i \cdot \left(\sum_{t \in \mathcal{T}} VOLL \cdot ens_{y,i,t} \cdot \Delta \right) \quad \forall y \in \mathcal{Y} \tag{14}$$

3.2 Power balance constraint

Eq. (15) expresses the balance between supply and demand.

$$\sum_{g \in \mathcal{G}} \sum_{v \in \mathcal{V}} gen_{g,v,y,i,t} + ens_{y,i,t} = D_{y,i,t} \qquad \forall y \in \mathcal{Y}; i \in \mathcal{I}; t \in \mathcal{T} \tag{15}$$

3.3 Capacity transfer constraints

To translate investment variables into available capacity variables, capacity transfer constraints are used. The available capacity for year y of an investment characterized by a technology g and a vintage year v is equal to the investment decision variable times a CPT-factor. The CPT-factor is a parameter that reflects the fraction of an investment that is still available in year y and depends on the lifetime and the leadtime of the investment.

$$cap_{g,v,y}^{av} = CPT_{g,v,y} \cdot cap_{g,v} \qquad \forall g \in \mathcal{G}^{new}; v \in \mathcal{V}; y \in \mathcal{Y} \tag{16}$$

3.4 Generation constraints

Eq. (17) reflects the generation limits for newly installed dispatchable capacities.

$$gen_{g,v,y,i,t} \leq cap^{av}_{g,v,y} \qquad \forall g \in \mathcal{G}^{new}_{D}; v \in \mathcal{V}; y \in \mathcal{Y}; i \in I; t \in \mathcal{T} \tag{17}$$

For iRES technologies, the generation limits for new investments are reflected by Eq. (18).

$$\begin{aligned} gen_{g,v,y,i,t} + curt_{g,v,y,i,t} =& CF_{g,i,t} \cdot cap^{av}_{g,v,y} \\ & \forall g \in \mathcal{G}^{new}_{R}; v \in \mathcal{V}; y \in \mathcal{Y}; t \in \mathcal{T}; i \in \mathcal{T} \end{aligned} \tag{18}$$

4 Summary for potential integration is Spine

User-defined parameters

- Inter-annual temporal structure: (How does this type of temporal structure relate to the Spine temporal structure?)
  - Model years (milestone years)
  - Periods associated with a model year (period start, period end, period duration)
  - End of model horizon
- Economic/technical lifetime of units, connections and storage(?)
- Lead times of investments in units, connections and storage(?)
- Discount year(what about rolling horizon?)
- Discount rates (general and technology specific)

Calculated model parameters

- Discount factors
  - DF_y: discount factor of model year y
  - DD_y: discounted duration of the period containing model year y
  - $D^{OY}_{g,y}$: discounted number of operating years of an investment in technology g in year y.
- Investment parameters
  - $SF_{g,y}$: salvage fraction of an investment in technology g in year y.
  - $MARKUP^{AN}_{g,y}$: Markup to account for the annualization of investment costs
  - $MARKUP^{DR}_{g,y}$: Markup to account for technology specific interest rates
- $CPT_{g,v,y}$: Capacity transfer parameters