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Conference Article

N.B.: When citing this work, cite the original article.


ISBN: 145630318X

Available at: Linköping University Institutional Repository (DiVA) http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-71876
Timing and sizing of investments in industrial processes – the use of an optimization tool

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Abstract: Investments of different kinds are vital for industries to stay competitive. However, there are several issues that need to be considered before investing, e.g. the timing and size of the investment. In this paper a methodology is presented for analyzing investments from the point of view of optimal size and timing. The energy systems optimization tool reMIND is used as the basis for the modelling, and has been used in several industrial energy systems studies for various purposes. reMIND is based on Mixed Integer Linear Programming (MILP) and has been further developed to consider investments of different kinds. The different constraints needed to model the investment properly are presented together with the variables included in the objective function. A simple case study is also included to illustrate how the method is used. The results from the case study show that the timing and size of the different investments change, depending on the size of the proposed increase in production rate.

Keywords: Energy efficiency, Investments, MILP, Optimization.

1. Introduction

Investments of different kinds are vital for industries to stay competitive. The basis for the investment may for example be to increase productivity, improve quality and replace old processes. Changes in the systems are also needed to reduce environmental impact due to emissions of greenhouse gases [1]. CO2-emissions related to energy use in the industrial sector are considerable and changes in the energy demand in this sector are vital [2]. Reductions in industries’ energy demand can for example be accomplished by investing in processes with low energy demand. When making an investment it is important to consider how processes are process-integrated, i.e. how they are integrated with the rest of the system to achieve a low energy demand overall [3]. It is also important to consider the timing and size of the investment. The decisions that must be made are therefore complicated and tools to provide support are very valuable. Possibilities to reduce energy demand in the industrial sector may be identified by different process integrations methods, e.g. exergy [4], pinch technology [5] and mathematical programming [6]. An energy systems optimization tool called reMIND, based on mathematical programming, has been developed for analyses of industrial energy systems [7, 8] and has been used in several studies focusing on different kinds of question, e.g. operational strategies [9] and the influence on an existing system of different boundary conditions [10]. Different kinds of industry have been analyzed, such as foundries [11], pulp and paper mills [12] and steel works [13]. In these analyses it has been common to calculate the window of investment opportunity, i.e. the maximum cost of an investment. This is a very good approach when, for example, the cost of the investment is not known. However, it does not consider the optimal size or timing of the investment. The aim of this paper is to present a methodology for analyzing investments’ optimal size and timing, where a further developed version of reMIND is used to consider such aspects. The different constraints needed to model the investment properly are presented together with the variables included in the objective function. A simple case study is also included to illustrate how the method is used. The case study includes different scenarios to show how different investments change as regards timing and size. Common investment theory, as found in e.g. [14], has been used as the basis for formulating the investment cost function in reMIND. To handle investments properly in the analysis it must be possible to include some input data. In the improved version of reMIND the rate of return, economic lifetime and technical lifetime can be included. The disposal residual values can
also be entered as fixed values or percentages, where the latter is dependent on the size of the optimal investment.

2. Method

This study uses the energy systems optimization tool reMIND, which is based on the MIND method (Method for analysis of INDustrial energy systems) developed at Linköping University in Sweden [7, 8]. The method has been developed for optimization of dynamic industrial energy systems, but can also be used for other purposes as well. The dynamics of the modelled systems are considered by dividing time into different numbers of time steps, depending on the purpose of the analysis. The structure of the system is modelled using branches that represent different kinds of flow (e.g. materials and electricity), and nodes representing different kinds of process (e.g. separators and boilers). The system to be optimized is compiled in a standardized file, where all limitations and relations in the system are included. The file is optimized using an optimization solver, here CPLEX [15]. The method minimizes the system cost, based on net present value calculations.

As the basis for the optimizations, MILP (Mixed Integer Linear Programming) is used and a MILP problem is defined, in general, according to Equations 1 and 2 [6].

Objective:

$$\min \sum_{v=1}^{V} \sum_{w=1}^{W} \left( c_{1,v} x_v + c_{2,w} y_w \right)$$

subject to:

$$\sum_{v=1}^{V} \sum_{w=1}^{W} \left( c_{1,v} x_v + c_{2,w} y_w \right) \leq C_z, \forall z = 1, 2, ..., Z$$

$$x \geq 0; y \in \{0,1\} \text{ and integer.}$$

2.1. Constraints describing the cost of investments

When investing in any kind of equipment, both the size of the unit and when to invest need to be considered. The constraints generated when using the investment cost functionality extract the largest size of the equipment used in the model, found in any of the time steps, and assign an appropriate price for that size. The investment cost functions may have different shapes and Figures 1 and 2 show two examples of investment cost functions.

Fig. 1. First example of an investment cost

Fig. 2. Second example of an investment cost

Equations 3 to 21 are needed to visualize the function correctly, where Equations 3 to 13 are included as the basis for the investment. The other equations are included if economic and technical lifespan are included and if disposal residual values are inserted. Equations 3 to 5 describe the constraints that determine the maximum flow for the specific investment in all time steps included in the analysis period.

$$\sum_{t=1}^{T} x_{1,t,h} = x_{1,tot}, \forall t$$

$$x_{1,tot} \leq x_{max}, \forall t$$

$$\sum_{t=1}^{T} \sum_{p=1}^{P} x_{2,t,p} = x_{max}$$

$$x_{2,tot}$$ represents the total flow for specific time step t.

$$x_{max}$$ represents the maximum flow the specific flow assigns for all time steps t.
Equations 6 to 10 represent the constraints to determine that only one slope is active for each investment. \( IC_{tot} \) is included in the objective function where multiplied with the factor of internal rate of return \((1+r)^Y\), where \( Y \) is the year the investment is to take place.

\[
P\sum_{p=1}^{p} IC_{t,p} + IC_{t,0} = IC_{tot}, \forall t (6)
\]

\[
c_{i,0} \cdot Y_{i,0} = IC_{t,0}, \forall t (7)
\]

\[
c_{3,t,p} \cdot x_{2,t,p} + c_{4,t,p} \cdot Y_{t,p} = IC_{t,p}, \forall t, p (8)
\]

\[
c_{5,t,p} \cdot Y_{t,p} \leq x_{2,t,p} \leq c_{6,t,p} \cdot Y_{t,p}, \forall t, p (9)
\]

\[
P\sum_{p=1}^{p} Y_{t,p} + Y_{t,0} \leq 1, \forall t (10)
\]

\( IC_{t,0} \) is the price of the equipment unit when there is no flow through the node for the specific time step \( t \). Equations 11 to 13 represent the constraints that ensure that there is no flow through the investment in the time steps that are included in the analysis period before the “investment time step”, i.e. the time step when the investment is made.

\[
P\sum_{p=1}^{p} Y_{t,p} + Y_{t,0} = IH_{1,t}, \forall t (11)
\]

\[
\sum_{i=t}^{H} x_{i,t,b} \leq IH_{2,t} \cdot U, \forall t (12)
\]

\[
IH_{1,t} + IH_{2,(t-IH_{3})} \leq 1, \forall t, IH_{3} (13)
\]

Where

\( IH_{3} = 1, 2, 3, \ldots, T \)

The constraints in Equation 13 are generated as long as \( t-IH_{3} \geq 1 \) \( \forall t, IH_{3} \).

If a technical lifespan is included, Equation 14 is used to ensure that the investment is not active in the time steps after the technical lifespan of the investment. The constraints in Equation 14 are created as long as \( t+IH_{3}+IL \leq IH_{3}, \forall t, IH_{3} \).

\[
IH_{1,t} + IH_{2(t-IH_{3}),2} \leq 1, \forall t, IH_{3} (14)
\]

Where

\( IH_{3} = 0, 1, 2, \ldots, T \)

\( IL_{t} \) is calculated according to the example shown in Figure 3 and the subsequent text, where a technical lifespan of 2 years has been assumed.

The analysis period is 5 years (Year1-Year5) divided into different amounts of time steps:

Year1 = 3, Year2 = 2, Year3 = 2, Year4 = 1 and Year5 = 2.

\[ \begin{array}{c|c|c|c|c|c|c|c}
    \text{Year1} & \text{Year2} & \text{Year3} & \text{Year4} & \text{Year5} \\
    \hline
    \text{IL1} & \text{IL2} & \text{IL3} & \text{IL4} & \text{IL5} \\
\end{array} \]

Fig. 3. Schematic example of the basis for the calculation of the values for \( IL_{t} \).

From Figure 3 it is possible to calculate the corresponding values for \( IL_{t} \) according to the following:

\( IL_{1} = 7 = (Year1 - 0) + Year2 + Year3 = (3 – 0) + 2 + 2 \)

\( IL_{2} = 6 = (Year1 - 1) + Year2 + Year3 = (3 – 1) + 2 + 2 \)

\( IL_{3} = 5 = (Year1 - 2) + Year2 + Year3 = (3 – 2) + 2 + 2 \)

\( IL_{4} = 5 = (Year2 - 0) + Year3 + Year4 = (2 – 0) + 2 + 1 \)

\( IL_{5} = 4 = (Year2 - 2) + Year3 + Year4 = (2 – 2) + 2 + 1 \)

\( IL_{6} = 4 = (Year3 - 0) + Year4 + Year5 = (2 – 0) + 1 + 2 \)

\( IL_{7} = 4 = (Year3 - 1) + Year4 + Year5 = (2 – 1) + 1 + 2 \)

\( IL_{8} \) to \( IL_{10} \) are not valid as the technical lifespan in the example is 2 years and would be outside the analysis period and are therefore not calculated.

If an economic lifespan is included for the investment, Equations 15 and 16 are included as long as \( IE-YA+YT \geq 0 \). \( IR_{tot} \) is included in the objective function.

\[
P\sum_{i=1}^{T} \sum_{p=1}^{P} IR_{i,p} = IR_{tot} (15)
\]

\[
IC_{t,p} \cdot \frac{(IE-YA+YT)}{IE} \cdot (1+r)^Y = IR_{i,p}, \forall t, p (16)
\]

Constraints for \( IR_{t,0} \) are only included in the model when \( IC_{t,0} \neq 0 \). \( YT_{t} \) is calculated according to the example shown in Figure 4 and the subsequent text. The analysis period is 5 years (T1-T5) divided into different numbers of time steps: T1 = 3, T2 = 2, T3 = 2, T4 = 1 and T5 = 2.

\[ \begin{array}{c|c|c|c|c|c|c|c}
    \text{Year1} & \text{Year2} & \text{Year3} & \text{Year4} & \text{Year5} \\
    \hline
    \text{YT1} & \text{YT2} & \text{YT3} & \text{YT4} & \text{YT5} \\
\end{array} \]

Fig. 4. Schematic example of the basis for the calculation of the values for \( YT_{t} \).
From Figure 4 it is possible to calculate the corresponding values for $YT_t$ according to the following, i.e. each $YT_t$ is assigned the same number as the year $YT_t$ is included in: $YT_1 = 1$, $YT_2 = 2$, $YT_3 = 2$, $YT_4 = 1$, $YT_5 = 2$, $YT_6 = 3$, $YT_7 = 3$, $YT_8 = 4$, $YT_9 = 5$, $YT_{10} = 5$

It is possible to choose whether to include a percentage disposal residual value or a fixed disposal residual value. The disposal residual values may be positive or negative depending on whether there is a cost or a profit after shut-down. If a percentage disposal residual value has been entered in the model, the constraints shown in Equations 17 and 18 are included. $IP_{tot}$ is included in the objective function.

$$\sum_{i=1}^{T} \sum_{p=4}^{T} PT_{i,p} = IP_{tot} \quad (17)$$

$$IC_{i,p} \cdot ip \cdot (1 + r)^{-ID_t} = IP_{i,p}, \forall t, p \quad (18)$$

Constraints for $IP_{i,0}$ are only included in the model when $IC_{i,0} \neq 0$. $ID$ is calculated according to the example in Figure 5 and the subsequent text, where a technical lifespan of 2 years has been assumed. The analysis period is 5 years (T1-T5) divided into different numbers of time steps: T1 = 3, T2 = 2, T3 = 2, T4 = 1 and T5 = 2.

![Fig. 5. Schematic example of the basis for the calculation of the values for ID](image)

From Figure 5 it is possible to calculate the corresponding values for $ID_t$ according to the following, i.e. each $ID_t$ is assigned the number of the year that the technical lifespan for the investment ends, depending on what year the investment is made (when the investment is made late in the analysis period the technical lifespan exceeds the timeframe of the analysis and are therefore assigned the number for the last year): $ID_1 = 3$, $ID_2 = 3$, $ID_3 = 3$, $ID_4 = 4$, $ID_5 = 4$, $ID_6 = 5$, $ID_7 = 5$, $ID_8 = 5$, $ID_9 = 5$, $ID_{10} = 5$

If a fixed disposal residual value has been entered in the model the constraints shown in Equation 19 and 20 are included. $IF_{tot}$ is included in the Objective function.

$$\sum_{i=1}^{T} \sum_{p=4}^{T} IF_{i,p} = IF_{tot} \quad (19)$$

$$Y_{i,p} \cdot ip \cdot (1 + r)^{-ID_t} = IF_{i,p}, \forall t, p \quad (20)$$

Constraints for $IF_{i,0}$ are only included in the model when $Y_{i,0} \neq 0$.

A constraint according to Equation 21 is included in the model to supplement the equations stated above to ensure that the solution does not include disposal residual values even though the investment is not in operation.

$$IC_{tot} - IR_{tot} - IP_{tot} - IF_{tot} \geq 0 \quad (21)$$

In Figure 6 and the subsequent text an example is presented of the use of the investment cost functionality.

![Fig. 6. Schematic illustration of the use of the investment cost functionality](image)

As can be seen from Figure 6 the present value of the investment is calculated at the end of the year the investment is made. However, the investment in the example is in operation from time step $t_f$. The economic lifespan is 2 years and the residual value is therefore calculated from Year 3. It should be noted that the economic residual value is zero in this example as the economic lifespan is shorter than the remaining length of the analysis after the year the investment is made. The technical lifespan is set to 6 years, but as the analysis period is 5 years and the there are only 4 years for the investment to be in operation after the “investment time step”, the disposal residual value is calculated...
from Year5. According to investment theory the disposal residual value should be calculated from the end of the last year of the economic lifespan. However, as seen in Figure 6, the present value factor for the disposal residual value is calculated two years after the economic lifespan has ended. Firstly, this is made possible in the tool due to the possibility for the investment to continue working during the entire technical lifespan and, secondly, due to the complexity of estimating extra costs, e.g. maintenance cost, after the economic lifespan have been completed. If setting the same economic and technical lifespan a situation according to investment theory is possible to achieve. However, the way the constraints from the above presented equations are created, allows modelling of real industrial situations, e.g. when investing in large process equipment that is used after the economic lifespan has ended. It should be noted that the residual values are calculated as a linear depreciation and that the economic lifespan is always shorter than or equal to the technical lifespan. The interest rate for the different investment alternatives may also have different values compared to the analysis as a whole.

3. Case study model description

The energy systems optimization tool reMIND is used to model the system. The modelled system in this case study represents a fictive company that is planning to increase its production capacity and the production rate gradually every year. The company therefore plans to invest in new processes to meet the increased demand. To produce the product, raw materials are processed in different processes and change states to result in a finished product, see Figure 7. Process I is an existing process and Processes II and III are new processes in which the company plans to invest. The different processes have different electricity demand and different efficiency. Processes II and III also have different economic lifespan, technical lifespan and residual disposal value. The input data for the processes are shown in Table 1. The investment cost for Process II rises sharply and is a function of production flow as shown in Figure 2. In Process III two different sizes of the investment are possible, depending on production capacity, as shown in Figure 1. In this study, 10 production years were modelled using 10 time steps. A discount rate of 6% is used. Both electricity and material prices are assumed to fluctuate over the analysed period, as shown in Figure 8. The prices are fictive and are used here to illustrate the use of the investment cost functionality. The system cost of the model considers costs for investments, energy and raw materials.

<table>
<thead>
<tr>
<th>Table 1. The input data for the processes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process I</td>
</tr>
<tr>
<td>Electricity demand (kWh/ton)</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Technical lifespan</td>
</tr>
<tr>
<td>Economic lifespan</td>
</tr>
<tr>
<td>Residual disposal value</td>
</tr>
</tbody>
</table>

Fig. 7. A schematic outline of the modelled system derived from reMIND. The arrows represent different flows of electricity, raw material and finished product.

Fig. 8. Electricity and raw material prices over the analysed period.
4. Case study scenarios
In order to investigate the usefulness of using reMIND for investment decision support, two different scenarios were devised. In Scenario 1, the company increased its production rate by 5% each year and in Scenario 2 by 10% each year.

5. Case study results
In Scenario 1, when the company increases its production capacity by 5% each year, the size of Process II and Process III differs. The optimization result from Figure 9 shows that the company should invest in Process III the first year. Process III should be used from the second year to the sixth year. The optimization result also shows that the optimal size for Process III can handle production flows up to 900 tons/year, i.e. the investment that costs 2,500 EUR (see Figure 1). The company should also invest in Process II during year 6 and use this investment for the rest of the analyzed period, i.e. from year 7 to year 10. The optimal size for Process II can handle up to 1,086 tons/year, i.e. the investment costs 2,172 EUR (see Figure 2). Scenario 1 therefore gives the lowest cost using Process III when the amount of produced unit per year is less than 900 tons, until year 5, and using Process II during the rest of the analyzed period, when the quantity of produced unit per year is more than 900 tons.

In Scenario 2, the company increases its production capacity by 10% each year and in the same way as in Scenario 1 different investment sizes are also used for both Process II and Process III. While in Scenario 1 the optimization results indicated that the company should start to invest in Process III, Scenario 2 shows that the company should begin by investing in Process II, see Figure 10. Process II is invested in during the first year and operates from the second year to the fifth year. The optimal size for this investment is slightly smaller than in Scenario 1 and can handle production flows up to 1,025 tons/year, i.e. the investment amount to 2,050 EUR (see Figure 2). The remainder of the analyzed period, i.e. from year 6 to year 10, the company should operate Process III by making the investment in year 5. The optimal size for Process III is much larger than in Scenario 1 and is capable of handling up to 2,000 tons/year, i.e. the investment costs 3,700 EUR (see Figure 1). Scenario 2 therefore gives the lowest cost using Process II when the amount of produced unit per year is less than 1,025 tons, until year 5, and using Process III during the rest of the analyzed period, when the quantity of produced unit per year is more than 1,025 tons.

5. Concluding discussion
As the case study indicates it is difficult to know when to make different investments. When the production rate is increased by 5%, Process III is invested in and used during the years before investment in Process II. When the production rate is increased by 10%, the first investment is Process II, which is used during the first years of the analysis period, before investing in Process III. In this simple case study, only one future change is included, i.e. the production rate change. In more
complex situations there may be several different future changes to consider, which complicates the analysis.

The size of the investment is yet another complicating factor, which is indicated by the simple case study, as the size of the investments depends on what investment to make and when to make it. As for the timing of the investment, more complex situations than the one shown in the simple case study in this paper will complicate the analysis of the sizing of the investment.

Both the timing and sizes of investments are difficult issues to deal with. This indicates a need for tools that consider investments accurately to provide a solid foundation for investment decisions.

Using a window of investment opportunity is a good way to estimate the maximum cost of an investment, especially when the investment cost is unknown. However, when investment cost functions for different processes are known the possibility to calculate the timing and size of investments enhances the use of the results. Also, it is not possible to use the window of investment opportunity method when more than one investment alternative is potentially included in the solution, as is the situation in the case study in this paper. The complicating factor is the technical lifespan, which can not be considered in the window of investment opportunity method and therefore a comparison between such an analysis and including an investment functionality is not shown in this paper.

The possibility to include an economic and technical lifespan, including fixed or percentage disposal residual value, enhances the use of the results from the analysis and more intricate problems may be analyzed with this method. The simple case study in this paper is only included to show the use of the method.

One drawback of including the investment cost functionality is that large numbers of constraints are needed to picture the investments correctly. Integers are also needed for the functionality, which might lead to longer solution times. This simple case study has a solution time of approximately 0.2 seconds. However, including more time steps and representing the investments with more information, e.g. more steps in the investment function, will increase solution time.

### Nomenclature

#### Parameters

- $c$: a coefficient: represents e.g. (1) a slope of a function [slope] and (2) a step in a function [step] (real)
- $C$: a constant (real)
- $h$: flow included as basis for the investment cost (integer)
- $H$: total number of flows included as the basis for the investment cost (integer)
- $if$: fixed disposal residual value of an investment (real)
- $ip$: percentage disposal residual value of an investment (real)
- $ID$: represents a parameter stating the year the technical lifespan for a specific investment ends (integer)
- $IE$: represents the economic lifespan of an investment (integer)
- $IL$: represents a parameter stating the number of time steps an investment is in operation after the time step the specific investment is made (integer)
- $p$: a slope within the function (integer) ($p=0$ represents the point when the production flow, as shown in Figure 1, is exactly zero. Slope 1 begins when the production flow is larger than zero)
- $P$: total number of slopes within a function (integer)
- $r$: interest rate (real)
- $t$: time step (integer)
- $T$: total amount of time steps (integer)
- $U$: a large number (real)
- $v$: the number of a specific real variable
- $V$: the total number of real variables in the problem
- $w$: the number of a specific integer variable
- $W$: the total number of integer variables
- $YA$: specifies the amount of years in the analysis
- $YT$: specifies the year a specific time step is included (integer)
- $z$: the number of a specific constraint (integer)
- $Z$: total number of constraints (integer)
Variables

x represents a flow of any kind (real)
Y (binary) (only attaining the values 0 or 1)
IC represents the investment cost (real)
IH represents a help variable (integer)
IF represents the fixed disposal residual value of an investment (real)
IP represents the percentage disposal residual value of an investment (real)
IR represents the economic residual value of an investment (real)
IY represents the year the investment takes place (integer)

References


Acknowledgments: We kindly thank the Swedish Energy Agency (SEA) for their financial support.