# Proactive Environmental Management Of Manufacturing Companies

This paper provides a production planning model considering reactive and proactive environmental management. Based on the traditional production planning model manufacturing companies that choose reactive environmental management, maximize their profit under consideration of emission standards for different pollutants. These state-defined standards are indicated by emission constraints that also include the possibility of investments in filters to reduce the emissions. Proactive environmental behavior leads to an objective function, which minimizes the emissions of the pollutants. Here, the impact of different pollutants is reflected by weights that can be fixed by the company and have a strong impact on the optimal solution. The paper will show under which conditions dual prices can be used as suitable weights.

Key words: reactive environmental management, proactive environmental management, weights, dual prices.

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# 1. Introduction

Industrial production processes are causing serious environmental damages (Hutchinson/Hutchinson 1997). Throughout the last decades environmental protection has been considered more and more in state legislation by defining emission standards and imposing pollution charges. The emission standards usually follow the technological development (dynamic standards) to improve the protection of the environment in the future. Manufacturing companies have to face these standards and adjust their production processes to the current legislation. Besides, there is another incentive to consider the environmental impact of production: the growing environmental awareness of the customers. Building up the image of an eco-friendly company may lead to a competitive advantage.

This paper is structured as follows:
First, basic environmental strategies are described. Then production planning models are presented assuming (Chapter 3) reactive environmental management and proactive environmental management (Chapter 5). To illustrate the models we include numerical examples (Chapter 4 and Chapter 6, respectively).
Chapter 7 provides an approach to solve the proactive production planning model using dual prices as weights, followed by the summary in Chapter 8.

# 2. Environmental Strategies

Basically we can distinguish between two kinds of behavior: **reactive** and **proactive environmental management.**

**Reactive environmental management** means that manufacturing companies just meet the emission standards. The main reason for this behavior is that the companies are not always able to compensate the increasing costs associated with the environmental investments by charging higher consumer prices.
Prevailing strategies of reactive environmental management are:

- to slow down the implementation of environmental investments forced by legislation,
- to substitute polluting materials by others that are also polluting,
- to lower the production rate,
- to shut down certain facilities or plants,
- to move the production site (e.g. to countries with lower emission standards).

Considering short-term goals these strategies could be appropriate to increase profit, but they are unable to assure the long-term existence of a company.

Companies, however, that choose **proactive environmental management,** do not consider environmental protection as a necessary evil but as an economic challenge (Stoner *et al.* 1995). Here, environmental investments are realized side by side with new technological developments, such as improvements of the production process. This may result in higher costs, but in the long run the environmental investments will cause decreasing expenditures that go along with innovations in products or production processes. Thus, proactive environmental management should be part of the strategic management and can be based on the following principles (Pieroth/Wicke 1988):

- Environment protection should be an **established goal**, stated in the company's mission and should be as important as profit making.
- Companies should voluntarily strive for a pollution level below emission standards in order to be ahead of legislation, since the environmental policy of most countries keeps tightening up.
- Companies should acquire environmental competence regarding product design, raw materials, packaging, processing, and distribution to attract eco-oriented customers.

- Environmental measures should be linked to cost cutting measures, especially energy savings, process innovation, and waste disposal.

As in the past, the number of environment oriented customers will further grow, therefore the proactive environmental management may lead to higher sales prospects and to a competitive advantage, which improve the strategic position of a company compared to its competitors.

In the following chapters the basic principles of the reactive and proactive environmental management will be implemented in quantitative production planning models in order to discuss their different consequences in detail.

## *3. Environment Oriented Production Planning*

### *3.1. Assumptions*

Regarding environmental behavior, the traditional production planning model has to be extended by additional variables and constraints. Beside the real variables for the production quantities, we have to introduce binary decision variables to consider the expenses for environmental investments, thus getting a mixed-integer production planning model (Hansmann 1998).
We assume a planning horizon of one year so that the expenditures for the environmental investments have to be split in annuities. The model maximizes the gross profit as chapter 3.2. shows in detail.

In addition, we have to consider the emission standards laid down by legislation which can be kept by investing in filters and other absorbing equipment.
Furthermore the production refuse and its disposal costs must not be neglected.

The production planning model is based on a production process with the following features:

(a) The company produces different products with various processes that differ with respect to costs and pollution.
(b) The company has the option to invest in absorption filters to reduce the emissions.
(c) By using noise reducing measures the company can carry out a night shift and thus enlarge its manufacturing capacity. There is no other opportunity to increase the capacity of the manufacturing plant than the investment in noise protection.
(d) There are no standards given for noise emissions. Thus, the noise protection is only considered within the capacity constraint.
(e) Profit, variable costs, capacity requirements, and the market demand are applied in the same way as in traditional models.
(f) Recycling measures are not considered except disposal costs for production refuse.

### *3.2. The Reactive Production Planning Model*

The symbols used in the model have the following meaning:

**Indices:**

| | |
|---|---|
| z | product |
| i | process |
| j | pollutant |

**Variables:**

| | |
|---|---|
| $x_{zi}$ | production units of product z produced by process i |
| $u_j$ | binary variable for environmental investments<br>(j = 1: investment in noise protection; j = 2, ..., J: investments in absorption filters) |

**Constants:**

$p_z$ price per unit of product z
$k_{zi}$ variable costs per unit of product z produced by process i
$c_{zi}$ capacity requirements per unit of product z produced by process i
$q_z$ disposal costs per unit of production refuse of product z
$r_z$ production refuse (scrap) per unit of product z
$A_j$ annuity of environmental investment j

cap maximum capacity of the plant
$\Delta$ cap additional capacity by investing in noise reducing measures
$M_z$ market demand of product z
$e_{zij}$ emission amount of pollutant j per unit of product z produced by process i
$E_j$ emission standard of pollutant j
$Ab_j$ amount of pollutant j absorbed by invested filters

Mixed-integer production planning model:

$$\textbf{Maximize Profit} = \underbrace{\sum_{zi} p_z \cdot x_{zi}}_{\textit{sales}} - \underbrace{\sum_{zi} k_{zi} \cdot x_{zi}}_{\textit{variable costs}} - \underbrace{\sum_{zi} q_z \cdot r_z \cdot x_{zi}}_{\textit{waste charges}} - \underbrace{\sum_{j} A_j \cdot u_j}_{\textit{environmental investments}} \tag{1}$$

**s.t.:**

**capacity constraint:**

$$\sum_{zi} c_{zi} \cdot x_{zi} - \Delta\text{cap} \cdot u_1 \leq \text{cap} \tag{2}$$

**demand constraints:**

$$\sum_{i} x_{zi} \leq M_z \quad \forall\, z \tag{3}$$

**emission constraints:**

$$\sum_{zi} e_{zij} \cdot x_{zi} - Ab_j \cdot u_j \leq E_j \qquad j = 2, ..., J \tag{4}$$

**binary constraints:**

$$u_j = 0 \text{ or } 1 \qquad \forall\, j \tag{5}$$

**non-negativity constraints:**

$$x_{zi} \geq 0 \qquad \forall\, z, i \tag{6}$$

In the objective function, the gross profit shall be maximized. Equation (2) ensures that the workload does not exceed the available plant capacity. The basic capacity can be enlarged by an investment in noise reduction ($u_1$) that allows additional nightshifts. Equivalent to the traditional production planning model equation (3) guarantees that the production volume does not exceed the market demand of the product. Further, equation (4) makes sure that the pollutants' emissions, affiliated with production, stay within the established emission standards. The binary and non-negativity constraints are given by (5) and (6).

In a reactive setting, the company acts according to the objective of profit maximization, therefore the optimal solution includes the following environmental strategies

- the emission standards given by legislation are just met,
- environmental investments are only realized, if they increase profit.

The conflict between the economic and the ecological targets is solved in favor of the economic goal, while the ecological goal is only considered in the constraints.

## 4. *Numerical Example For The Reactive Production Planning Model*

Suppose a company that produces two products with two different production processes. The variable costs, the emissions, and the capacity requirements of one production unit depend upon the product and the production process applied (see Tab. 1).

The capacity of the manufacturing plant is limited to 500 h per period, but can be increased by 200 h through an investment in noise reducing equipment.

The emissions of $NO_2$ and $SO_2$ are restricted to 4000 and 4500 emission units (EU), respectively, suitable filters are able to absorb 900 EU of $NO_2$ and 1200 EU of $SO_2$.

The investment in noise protection is associated with an annuity of \$ 2000, the investments of the filters amount to annual costs of \$ 1500 ($NO_2$) and \$ 1200 ($SO_2$).

The market demand of the products is restricted to 800 units of product 1 at the price of \$ 180 and 900 units of product 2 at the price of \$ 160.

Tab.1 contains other required numerical data:

*See Table 1*

Using the given data leads to the following objective function:

$$\textbf{Maximize Profit} = 180\,(x_{11} + x_{12}) + 160\,(x_{21} + x_{22}) - 30\,x_{11} - 50\,x_{12} - 35\,x_{21} - 55\,x_{22}$$
$$- 20 \cdot 0.5\,(x_{11} + x_{12}) - 16 \cdot 0.5\,(x_{21} + x_{22})$$
$$- 2000\,u_1 - 1500\,u_2 - 1200\,u_3 \tag{7}$$

**s.t.**

**capacity constraint:**

$$0.3\,x_{11} + 0.6\,x_{12} + 0.4\,x_{21} + 0.8\,x_{22} - 200\,u_1 \leq 500 \tag{8}$$

**demand constraints:**

$$x_{11} + x_{12} \leq 800 \tag{9}$$
$$x_{21} + x_{22} \leq 900 \tag{10}$$

**emission constraints:**

$$\mathbf{NO_2:}\ 5.5\,x_{11} + 4\,x_{12} + 4.5\,x_{21} + 3.5\,x_{22} - 900\,u_2 \leq 4000 \tag{11}$$
$$\mathbf{SO_2:}\ 7.5\,x_{11} + 6\,x_{12} + 6\,x_{21} + 3\,x_{22} - 1200\,u_3 \leq 4500 \tag{12}$$

**binary constraints:**

$$u_1 = 0 \text{ or } 1 \tag{13}$$
$$u_2 = 0 \text{ or } 1 \tag{14}$$
$$u_3 = 0 \text{ or } 1 \tag{15}$$

**variable constraints:**

$$x_{11}, x_{12}, x_{21}, x_{22} \geq 0 \tag{16}$$

The numeric solution of the model leads to the following (rounded) results:

*See Table 2*

The analysis of the results allows the following statements:

- The amount of production units is limited by the maximum capacity and the emission standards.
- The environmental investments in absorption filters for $NO_2$ and $SO_2$ as well as the investment in noise protection are economically justified.

The results of the example are typical of reactive production planning (Hansmann 1998). The company has only the incentive to invest in environmental protection, if the investments increase the profit. In this example each investment has a positive impact on the profit and the emission standards are just met.

## 5. *The Proactive Production Planning Model*

In contrast to the model mentioned above, the master production schedule in a proactive setting is planned according to the goal of minimizing the pollutant emissions provided that a certain minimum profit can be guaranteed (Hansmann 1997).

Now we need a system of weights that specifies the different degrees of harm of the pollutants. Before discussing several approaches to determine these weights (Chapter 6 and 7), we state the proactive model:

| | |
|---|---|
| $g_j$ | weight reflecting the environmental harm of pollutant j |
| $q_z$ | weight reflecting the harm of the production refuse of product z[1] |
| $P_{min}$ | minimum profit demanded by the company |

$$\textbf{Minimize Emission} = \sum_{j=2}^{n} g_j \cdot \left( \sum_{zi} e_{zij} \cdot x_{zi} - Ab_j \cdot u_j \right) + \sum_{zi} q_z \cdot r_z \cdot x_{zi}{}^2 \qquad (17)$$

Noise protection (index j=1) is neglected in the objective function, because it is not sensible to minimize noise for the following reasons:
As mentioned above (p. 3) the noise reducing measures enhance the production capacity by enabling nightshifts, but these additional shifts create additional noise. Thus, we have two "sorts" of noise: dayshift noise which is reduced and nightshift noise which is created. However, noise protection is considered in the capacity constraint.
In the proactive model the constraints (2) to (6) of the reactive model stay in force. Moreover, a **minimum profit constraint** has to be added which ensures that a given minimum profit is reached by the production program:

**Minimum profit constraint:**

$$\sum_{zi} p_z \cdot x_{zi} - \sum_{zi} k_{zi} \cdot x_{zi} - \sum_{zi} q_z \cdot r_z \cdot x_{zi} - \sum_{j} A_j \cdot u_j \geq P_{min} \qquad (18)$$

The solution of the proactive model depends to a large extent on the chosen weights $g_j$. Using these weights offers the opportunity to compare the environmental harm of the different pollutants, but it is extremely difficult to find a system of weights which is consistent and corresponds to the economic and social targets of both the society and the company (Hansmann 1998). Until now, no satisfactory solution has been found, nevertheless the following chapters provide one approach of the literature and one of the authors using dual prices as weights.

## 6. *The Approach Of Schaltegger And Sturm*

Schaltegger and Sturm (Schaltegger/ Sturm 1994) focus on solutions appropriate for practical problems. Therefore they apply emission standards laid down by legislation.
These standards can be interpreted as a compromise between the latest findings of science, the social targets, and the opposing interests of different social groups.

To use the emission standards as weights

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[1] We assume that the weight which reflect the harm of the production refuse of a product is equal to the disposal costs.

[2] Note that the deduction of $Ab_j$ is only allowed, if $\Sigma e_{zij} \cdot x_{zi} \geq Ab_j$. If $u_j = 1$ and $\Sigma e_{zij} \cdot x_{zi} \leq Ab_j$, we have to subtract $\Sigma e_{zij} \cdot x_{zi}$. This aspect is not considered in the model, because it is not relevant in practice.

- they have to be standardized and
- the specific goals and constraints of a company have to be considered.

The second point has been neglected by Schaltegger and Sturm. The standardization results in an equal environmental harm of the two substances mentioned here: $NO_2$ and $SO_2$ (Schaltegger/Sturm 1994). Thus, we assign the value "one" to both weights ($g_2 = 1$; $g_3 = 1$).

We show the consequences of this approach for the proactive model by considering the same situation as in the example of Chapter 4, except using emission minimization instead of profit maximization.

This leads to the new objective function

$$\textbf{Minimize Emission} = 1\,(5.5\,x_{11} + 4\,x_{12} + 4.5\,x_{21} + 3.5\,x_{22} - 900\,u_2) + 1\,(7.5\,x_{11} + 6\,x_{12} + 6\,x_{21} + 3\,x_{22} - 1200\,u_3) + 20 \cdot 0.5\,(x_{11} + x_{12}) + 16 \cdot 0.5\,(x_{21} + x_{22}) \quad (19)$$

We assume that the company wants to get a minimum profit of \$ 100000:

**minimum profit constraint:**

$$180\,(x_{11} + x_{12}) + 160\,(x_{21} + x_{22}) - 30\,x_{11} - 50\,x_{12} - 35\,x_{21} - 55\,x_{22} - 10\,(x_{11} + x_{12}) - 8\,(x_{21} + x_{22}) - 2000\,u_1 - 1500\,u_2 - 1200\,u_3 \geq 100000 \quad (20)$$

The constraints regarding capacity, demand and emissions remain unchanged.

This example leads to the following results:

*See Table 3*

The following overview shows the significant changes in the solution compared to the reactive model and to a proactive model with a minimum profit of \$ 120 000:

*See Table 4*

- The share of the more environmental-friendly product 2 increases from about 52% to almost 80% (minimum profit: \$ 120 000) and to over 96% (minimum profit: \$ 100 000). The market demand of product 2 is fulfilled in both proactive examples.
- The given emission coefficients lead to a higher reduction of the $SO_2$ emission compared to the reduction of the $NO_2$ emission, because of the decreasing production amounts of product 1 and the increasing production amounts of product 2.
- The environmental load is reduced significantly (for the minimum profit of \$ 100 000 it is just 75% of the environmental load of the reactive model).
- The reduction of the environmental load results from a decrease of the profit which is only about 78% of the profit of the reactive model. The example illustrates the conflict between the economic and ecological goals.

## *7. Dual prices As Weights For Pollutants*

As mentioned above, Schaltegger and Sturm neglect the specific situation of the companies which is expressed in the objective function and the constraints. Hence, the following approach tries to combine the economic situation of a company with the environmental harm of pollutants while determining suitable weights.

We know from duality theory (Hastings 1989), that the dual price of a pollutant is the amount by which the profit of a specific company would increase, if that company is allowed to emit one unit more of that pollutant (Hansmann 1998). The dual price will be the higher the more the production program and the profit are restricted by the emission standard of a pollutant. As the emission standard is to be a measure of the harm the pollutant does to the environment,

it will be lower for pollutants with more substantial harm than for other substances. Thus, we can say that the dual price of an emission constraint will be the higher the smaller the emission standard of a pollutant has been laid down by legislation. Consequently, the dual prices indicate in a sense the environmental harm of pollutants within the economic frame of a certain company. In this way, we can favorably combine the environmental targets of society with the economic situation of the manufacturing companies reflected in their production planning models.
We conclude from these thoughts that dual prices are basically suitable as weights for assessing the harm of the pollutants in the proactive model.

To see the effect on the solution, we apply this approach to the numerical example:

In the reactive model both emission standards are fulfilled, the company emits the maximum allowed amount of $NO_2$ and $SO_2$ (slack variables = 0).
Tab. 2 (p. 5) shows the following dual prices of the emission constraints:

- 12.59 for $NO_2$ and
- 7.98 for $SO_2$.

This means that the profit would rise by \$ 12.59 (\$ 7.98), if the company were allowed to emit another unit of $NO_2$ ($SO_2$). Thus, the emission standard for $NO_2$ has a stronger impact on the profit than the standard of $SO_2$.
According to our considerations we use the following weights in the proactive model:

- $g_1 = 12.59$ ($NO_2$) and
- $g_2 = 7.98$ ($SO_2$).

In a similar way, we proceed with the production refuse. As there is no constraint, we use the disposal costs per unit of the production refuse as dual prices. They can serve as weights, because they have an impact on the profit as well:

- $g_3 = 20$ (product 1)
- $g_4 = 16$ (product 2).

This leads to the following objective function:

$$\begin{aligned} \textbf{Minimize Emission} = \; & 12.59\,(5.5\,x_{11} + 4\,x_{12} + 4.5\,x_{21} + 3.5\,x_{22} - 900\,u_2) \\ & + 7.98\,(7.5\,x_{11} + 6\,x_{12} + 6\,x_{21} + 3\,x_{22} - 1200\,u_3) \\ & + 20 \cdot 0.5\,(x_{11} + x_{12}) + 16 \cdot 0.5\,(x_{21} + x_{22}) \end{aligned} \tag{21}$$

Assuming a minimum profit of \$ 100 000 we have the same minimum profit constraint as in the Schaltegger/Sturm-Model, and come to the following results:

*See Table 5*

We compare for a detailed analysis the results of the reactive model to the results of the proactive model assuming first a minimum profit of \$ 120 000 and second of \$ 100 000:

*See Table 6*

First of all, we achieve similar results as Schaltegger/Sturm. The environmental load decreases as long as the minimum profit decreases. As in the first example of Schaltegger/Sturm the production amount of product 2 is growing while less units of product 1 are produced, but here we see a stronger concentration on product 2 produced by process 2 which leads to a higher production amount of product 1 (see tab. 6 and tab. 4). Furthermore, the investment 1 is realized for both profit levels (in contrast to the Schaltegger/Sturm example, where this investment is only carried out for the minimum profit of 100 000 \$).

Finally, we can state that the application of the dual prices leads to a lower environmental load than the application of the weights in the approach of Schaltegger/Sturm.

## 8. Summary

In general, manufacturing companies have two strategies to comply with environmental legislation.
In the reactive environmental management the production program is planned with the objective of maximizing the profit, and emission standards are considered as constraints of the model. Mostly this behavior leads to a production program in which the emission standards are just met.
The second strategy is adopted by companies which follow the proactive environmental management with the objective to minimize the weighted emission of pollutants provided that a pre-defined profit level can be reached. This may lead to a substantial reduction of the emission, but the results strongly depend upon the chosen weights: The application of dual prices results in a different production program and less emissions compared to the Schaltegger/Sturm approach.
Dual prices are basically suitable for the evaluation of pollutants, because they link public emission standards with the economic situation of a company characterized by the marketing and production constraints. On the other hand we face two problems applying dual prices:

1. They are only valid within certain limits and can change abruptly when the production program is modified. This problem can be solved by applying sensitivity analysis (Ravindran *et al.* 1987).
2. If a company emits less pollutants than the emission standard allows, the dual price equals zero and the corresponding pollutant is not considered in the proactive model. This is only justified, if the pollutant does no harm at all, as long as the emissions are lower than the emission standards. This assumption has been partly criticized in the medical community, but the only solution to this problem would be to decrease the emission standards or to construct an environmental damage function dependent on the pollution dose. This requires empirical data on the harm of any emission to the human health which are not available.

Finally we would like to point out some managerial implications of our approach:

- We have seen (p. 3) that a manufacturing company can create competitive advantage by implementing a **proactive** environmental strategy, because the environmental awareness of the customers keeps growing.
- Using our proactive production model the management of a company is able to bring into balance its economic and ecological goals by choosing the desirable profit level. Profit and environmental harm of the business can be compared directly through the dual prices, so that the management knows exactly what lowers emissions cost in terms of profit
- Our proactive model enables the management to choose a strategy which guarantees adequate profits for growth and simultaneously creates competitive advantage and environmental competence in the long run. In addition, the model allows the management to assess the quantitative effects of this strategy with respect to its economic and ecological objectives.

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Tab 1.: Numerical example data

| $x_{zi}$ | $k_{zi}$ | $Q_z$ | $r_{zi}$ | $c_{zi}$ | $e_{zi1}$ ($NO_2$) | $e_{zi2}$ ($SO_2$) |
|---|---|---|---|---|---|---|
| $\mathbf{x_{11}}$ | 30 | 20 | 0.5 | 0.3 | 5.5 | 7.5 |
| $\mathbf{x_{12}}$ | 50 | 20 | 0.5 | 0.6 | 4 | 6 |
| $\mathbf{x_{13}}$ | 35 | 16 | 0.5 | 0.4 | 4.5 | 6 |
| $\mathbf{x_{14}}$ | 55 | 16 | 0.5 | 0.8 | 3.5 | 3 |

Tab. 2: Results of the reactive production planning model

**Maximum Profit: $ 127 862.2**

| **Variables** | | | | **Constraints** | | |
|---|---|---|---|---|---|---|
| ***$x_{zi}$*** | | ***$U_j$*** | | ***Constraint*** | ***Slack*** | ***Dual price*** |
| $x_{11}$ | 384 | $U_1$ | 1 | Capacity | 0 | 36.22 |
| $x_{12}$ | 168 | $U_2$ | 1 | Demand product 1 | 248.65 | 0 |
| $x_{21}$ | 0 | $U_3$ | 1 | Demand product 2 | 294.59 | 0 |
| $x_{22}$ | 605 | | | $NO_2$ | 0 | 12.59 |
| | | | | $SO_2$ | 0 | 7.98 |

Tab. 3: Results of the Schaltegger/Sturm approach

**Minimal emission (environmental load): 72308 points**

| **Variables** | | | | **Constraints** | | |
|---|---|---|---|---|---|---|
| ***$x_{zi}$*** | | ***$u_j$*** | | ***Constraint*** | ***Slack*** | ***Dual price*** |
| $x_{11}$ | 28 | $u_1$ | 0 | Profit | 0 | -0.17 |
| $x_{12}$ | 0 | $u_2$ | 1 | Capacity | 0 | 1.61 |
| $x_{21}$ | 571 | $u_3$ | 1 | Demand product 1 | 772 | 0 |
| $x_{22}$ | 329 | | | Demand product 2 | 0 | 0.48 |
| | | | | $NO_2$ | 1023 | 0 |
| | | | | $SO_2$ | 1073 | |

Tab. 4: Results of the reactive model and the proactive model using the weights of Schaltegger/Sturm

| | ***Reactive*** | ***Proactive I*** | ***Proactive II*** |
|---|---|---|---|
| **Profit** | 127862 | 120000 | 100000 |
| **Prod. 1, Proc. 1** | 384 | 235 | 28 |
| **Prod. 1, Proc. 2** | 168 | 0 | 0 |
| **Prod. 2, Proc. 1** | 0 | 226 | 571 |
| **Prod. 2, Proc. 2** | 605 | 674 | 329 |
| **Investment 1** | Y | Y | N |
| **Investment 2** | Y | Y | Y |
| **Investment 3** | Y | Y | Y |
| **$NO_2$** | 4000 | 3768 | 2977 |
| **$SO_2$** | 4500 | 3940 | 3427 |
| **Environmental load (points)** | 96630 | 88430 | 72308 |

Tab. 5: Results of the approach using dual prices

**Minimal emission (environmental load): 66758 points**

| Variables | | | | Constraints | | |
|---|---|---|---|---|---|---|
| ***$x_{zi}$*** | | ***$u_j$*** | | ***Constraint*** | ***Slack*** | ***Dual price*** |
| $x_{11}$ | 191 | $u_1$ | 1 | Profit | 0 | -1.07 |
| $x_{12}$ | 0 | $u_2$ | 1 | Capacity | 0 | 34.40 |
| $x_{21}$ | 0 | $u_3$ | 1 | Demand product 1 | 609 | 0 |
| $x_{22}$ | 803 | | | Demand product 2 | 97 | 0 |
| | | | | $NO_2$ | 1036 | 0 |
| | | | | $SO_2$ | 1855 | 0 |

Tab 6: Results of the reactive model and the proactive model using the dual prices as weights

| | ***Reactive*** | ***Proactive I*** | ***Proactive II*** |
|---|---|---|---|
| **Profit** | 127862 | 120000 | 100000 |
| **Prod. 1, Proc. 1** | 384 | 384 | 191 |
| **Prod. 1, Proc. 2** | 168 | 0 | 0 |
| **Prod. 2, Proc. 1** | 0 | 0 | 0 |
| **Prod. 2, Proc. 2** | 605 | 731 | 803 |
| **Investment 1** | Y | Y | Y |
| **Investment 2** | Y | Y | Y |
| **Investment 3** | Y | Y | Y |
| **$NO_2$** | 4000 | 3772 | 2964 |
| **$SO_2$** | 4500 | 3875 | 2645 |
| **Environmental load (points)** | 96630 | 88100 | 66758 |