Life Cycle Cost Minimization for Cement Production under Various Constraints

Hakob Avetisyan

Department of Civil and Environmental Engineering, A. James Clark School of Engineering, University of Maryland, College Park, Maryland

KEYWORDS: Cement, Sustainability, Life Cycle Cost, Economic Model, Optimization, Pollution, Emission and Resource Constraints.

ABSTRACT

The world consumption of cement is rising at an increasing rate, resulting in significant levels of pollution. Therefore, cement production is considered one of the major contributors to environmental pollution, requiring implementation of more efficient sustainability practices. The main driving forces for sustainability practices are environmental, material and energy constraints, which limit the operation of a particular plant in certain geographic areas. Such constraints force the cement companies to make investments in the development of emission reduction technologies. Production of 1,000kg of cement requires 1,500-1,700kg input of raw material. The rest of the material is considered by-product, which goes to the atmosphere in the form of emissions. These emissions vary depending on the plant type and the country. In this research the economic-mathematical model of cement production is developed, which minimizes the Life Cycle Cost (LCC) of the cement plant, while satisfying the forecasted demand and various constraints. The economic-mathematical model, developed in this research, is useful for existing cement plants and for those that will be built in the future. The model computes the optimal amounts of cement production that will provide minimum LCC during the projected period. The main decision variables represent the optimal production of cement by each producing unit within the plant.

INTRODUCTION

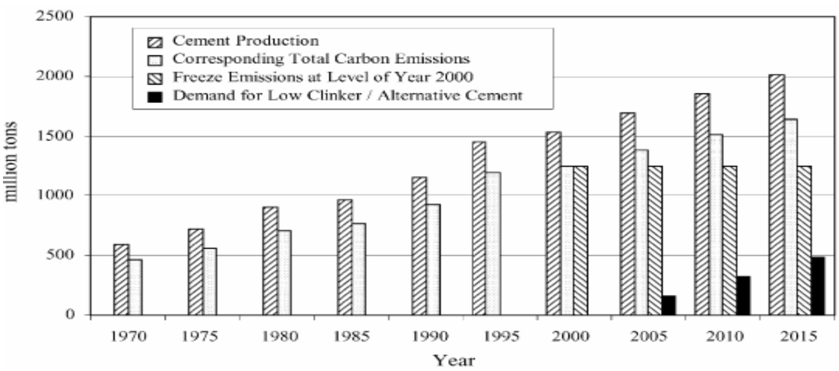
The implementation of sustainability practices is a subject that is of interest to many people, but it is particularly of interest to members of firms that are polluting the environment (Avetisyan, 2008). Industrial construction projects generate pollution and the members of the cement industry would benefit from information about how to improve their business practices and incorporate sustainability concepts during both the design stage as well as during the operation period of cement production. It is difficult for members of the cement industry to make more informed decisions on whether to implement sustainable practices on projects, to determine the economic impact of implementing sustainable practices, to determine the social and environmental benefits, and to determine whether they will have a positive effect on reputation management, since existing research does not provide detailed and complete information, which will consider all aspects of operation in this area.

Construction projects, especially in the area of industrial construction, contain various activities that are larger in scale in comparison to building construction. Accordingly the environmental, economic and social impacts from the mistakes or from inappropriate design of those structures or construction processes and operation will be much bigger than from smaller projects. Therefore, one of the major tasks for people involved in design and in operation of projects is to make sure that the design and operation procedures of a project satisfy the existing standards for environmental issues as well.
The ability of a firm to secure investments, or receive preferential treatment on bids, could be affected by environmental and social credibility.

The use of sustainability practices in cement production could benefit projects, especially in the area of materials, if designers take into consideration the selection of materials that could be reused or that use fewer resources during their production, or the transportation stage, or that could be recycled, or in fuel choice. Sustainability practices are helping to reduce energy consumption during construction and operation or the use of renewable energy alternative technologies during the construction and operation of projects. Pollution reduction could involve having less toxic materials in the products used in production and technological changes reducing noise and spatial pollution. According to Worrell et al. (2001), the cement industry contributes approximately 5% to global anthropogenic CO_2 emissions. Therefore, the cement industry should be one of the target sectors for CO_2 emission mitigation strategies. The dominating portion of CO_2 emissions comes from limestone calcinations, combustion of fuels in the kiln, and electricity generation required for cement production (Worrell et al., 2001). According to the authors, only process emissions are available. Their estimates show that in 1994 total carbon emissions from cement manufacture was 307 million metric tons of carbon (MtC). In particular, 160 MtC out of the mentioned 307 MtC were from process carbon emissions, and 147 MtC from energy use in the cement industry. In 1994, the top 10 cement producing countries generated 63% of world carbon emissions generated by cement industry. The emissions abatement strategies, discussed in Worrell et al., incorporate improvement of energy efficiency, new more efficient processes, use of low carbon fuels, possible use of waste fuels, extensive use of additives in cement production, alternative cements, and CO_2 emissions reduction from flue gases coming from clinker kilns (Worrell et al., 2001). With the conventional Portland cement process, relatively high volumes of CO_2, NO_x and SO_x are being generated. Despite this the blended cements are more practical and meet current requirements through incorporating various mineral mixes, industrial by-products and wastes, hence partially substituting clinker, rising bulk production and conserving energy (Worrell et al., 2001).

As mentioned by Arikan, if CO_2 emissions “frozen” by EC and USA equal to the level of year 2000, Portland cement share in the market will be reduced significantly (up to 25%) by the year of 2015 (Arikan, 2004, p. 1125). In his paper Arikan presents a figure, which illustrates forecasts of emissions and expected share of low-clinker cement in market (Arikan, 2004).

As illustrated in **Figure 1.1**, the market share of low-clinker cement is increasing drastically justifying the construction of new cement producing facilities, which, in turn, create a need for additional power plants that will supply energy to cement producers. From the ecological perspective, the use of high performance cement is more desirable, since it uses about 50% less clinker compared to traditional cement (Arikan, 2004).



Source: Arikan, 2004, Building and Environment, vol. 39

Figure 1.1 Prediction of Emissions and Expected Market Share of Low-Clinker Cement.

The Chartered Institute of Building (CIOB) in their report on “Sustainability and Construction” states that as a first step all members of the construction industry, who wish to move toward sustainability as a business opportunity, must consider their operations in the following four key areas (CIOB, 2004, p. 2):

- **Energy:** Reduce energy consumption, be more energy efficient and use renewable energy as well as “alternative technologies”.
- **Materials:** Choose, use, re-use and/or recycle materials during the design, manufacture, construction or maintenance of a structure.
- **Waste:** Produce as little waste as possible and recycle more.
- **Pollution:** Produce less toxic materials to reduce water and spatial pollution.

Some programs were developed in order to promote environmentally friendly production worldwide.

Sustainability Reporting

For all industries particularly for cement industry is preferable to be involved in sustainable practices, which in turn have a positive effect on firms’ reputation as a company with high values caring not only for profits but also for environment and the health of people in general. For this purpose many activities start and develop programs initiating activities for emission minimization and quality improvement of products. Already many firms are adopting these approaches and improving their performance. Such opportunity was created through Sustainability Reporting. The benefits of a company from sustainability reporting are better financial performance, enhanced stakeholder relationships, improved risk management, as well as improved investor relations as mentioned by KPMG (Klynveld, Peat, Marwick, Goerdeler (KPMG), United Nations Environment Program (UNEP), 2006). Currently Sustainability Reporting is performed on a voluntary basis. Sustainability Reporting is a reporting system on environmental performance or on a broader range of sustainability issues. It helps companies to quantify current impacts, formulate targets for development, and communicate with customers, communities, governments, financial markets, and other stakeholders about sustainability issues (Andrews and Slater, 2002, p. 86). Many of these reports are formulated according to the *Sustainability Reporting Guidelines* presented by the Global Reporting Initiative (GRI) and released in June of 2000 (Andrews and Slater, 2002, p. 86). According to Andrews and Slater, sustainability reporting should be part of a long-term commitment that incorporates sustainability processes. Many of the companies that are actively engaged in sustainability reporting have many years of experience in environmental reporting (Andrews and Slater, 2002, p. 86).

According to Howard Klee and "World Business Council for Sustainable Development in Switzerland", 11 cement producing companies have spent large amounts of money on the "Sustainable Cement Project". They spent $4 million on the process itself. In particular, they mention that the World Business Council for Sustainable Development (WBCSD) sponsored the two-year initiative and trying to determine how the cement industry can operate more sustainable, underline key sustainable development issues of the cement industry, report the present performance of the cement industry (Klee and WBCSD, 2007). The 11 companies that funded the project are Cemex (Mexico), Cimpor (Portugal), Heidelberg Cement (Germany), Holcim (Switzerland), Italcementi (Italy), Lafarge (France), RMC (UK), Siam Cement (Thailand), Taiheiyo (Japan), Votorantim (Brazil), Titan (Greece) (Howard Klee and "World Business Council for Sustainable Development in Switzerland", 2007). The aforementioned cement companies are producing approximately 33% of the cement in the world. The research project was focused on (Klee and WBCSD, 2007):

- Resource productivity – improved by more efficient practices in mining, use of energy, recycle and reuse of manufacturing wastes.
- Climate protection – management of CO_2 abatement, reduction of dust from quarry processes, SO_x and NO_x, as well as other pollutants.
- Ecological stewardship – is dealing with resource conservation, quarry management and closure.

- Employee well being – consideration to employee occupational health and safety issues.
- Community well-being – development of better exchange of ideas and engagement practices in neighboring areas (World Business Council for Sustainable Development (WBCSD), 2002, p. 4-5).

More than 2,000 companies worldwide, including over one-third of the 250 largest companies, as noted by the Global Reporting Initiative (GRI), have issued numerous environmental or social reports (Andrews and Slater, 2002, p. 89). Sustainability reporting, as mentioned previously by Andrews and Slater, is performed by companies as a response to stakeholder concerns, and it is a part of strategy that includes adopting sustainable business practices, or developing business practices that are integrated with environmental management (Andrews and Slater, 2002, p. 89).

Sustainable Industrial Ecology

Sustainable industrial ecology is another area being explored by members of the manufacturing, construction, and processing industries. Optimal resource consumption is being studied through a framework that integrates different processes, economic and environmental constraints, and health and safety considerations (Basu and Zyl, 2006, p. 299). Basu and van Zyl (2006) have conducted research that provides a comprehensive review of environmental management practices in the area of mining and minerals industry. This research focuses on two concepts: industrial ecology (IE) and cleaner production, which provides a review for environmental management practices in the area of mining and minerals industry. The impact of the construction sector on the environment occurs in all of the stages of construction, from the mining of raw materials (quarry, operation and cement production) to the construction of buildings (noise, dust, and the generation of hazardous materials), as well as to the operation of facilities (the disposal of wastewater, energy consumption, and toxic emissions) (Basu and van Zyl, 2006).

Cement Industry

The cement industry is affected by many environmental issues, particularly high levels of carbon dioxide emissions. In this type of industry emissions reducing policies are designed to decrease carbon dioxide emissions per ton of cement produced, assuming installation of fuel-efficient kiln technologies. This could be done by partial replacement of non-carbonate additives of calcium oxide in the kiln raw materials, and by partial replacement of supplementary cementitious materials (SCM) (Hendrik G. van Oss, 2006). Oss states that many foreign countries are ahead of the United States in the use of SCM. Since the clinker manufacturing (kiln) technological phase of cement production is energy-intensive and is not required by SCM, their utilization lowers the marginal economic as well as environmental costs of the cement in concrete production (Hendrik G. van Oss, 2006).

Oss also points out an important issue that plays a significant role in the cost structure of cement. The price of fossil fuel is one of the major components in the cost of cement. In some cement producing companies expensive fossil fuels are replaced by burning waste materials in kilns as low-cost substitutes. Moreover, the cement kilns can serve as an effective way of destroying wastes (Hendrik G. van Oss, 2006). The tendency of using waste materials as substitutes for expensive fuel positively affects the use of waste fuels (Hendrik G. van Oss, 2006).

Sustainable design and operation is a result of following factors mostly important in all industries and particularly for cement industry.

One of the important issues in sustainable design and operation is cost effectiveness. National research states that the sustainable design approach should not add more than 2% to the cost of any structure. If done thoughtfully the sustainable design may add no cost. The research also states that the sooner the sustainability is implemented into a project, the more likely it can be achieved cost-effectively.

Currently the design of structures has numerous options when it considers sustainable design and construction. Environmentally friendly materials and technologies are not an innovation, but the use of those materials in various places could be an innovation. These materials are in use in all stages of design and construction, operation or maintenance of structures. Big companies are supporting implementation of green structures, since mostly these companies are those that have an engineering and economic potential for innovations and implementation of projects. Government is rewarding sustainable approaches in design and operation. Individuals all around the world are making decisions for use of materials and technologies that will have impact on future generations.

Sustainable design of industrial sector such as cement manufacturing plant should not be limited only by selection of environmentally friendly materials but also technology, which is going to be used in operation stage of a plant.

A number of studies state that the wet process of cement manufacturing is moving out of use, since at the beginning it is not expensive to build a plant for wet technology, but later on it is very energy extensive in comparison to dry process. For sustainable future it is very important to make right selection of materials during the design stage, since some materials can be environmentally friendly, but at the same time have very short life.

Environmental Footprint of Cement Industry

The environmental footprint of industries is the impact of a company resulted from production and use of raw materials and nonrenewable resources/products as well as wastes.

Like other industries, in cement industry companies are reporting about current conditions and trends for minimization of Environmental footprint. The Canadian cement industry is continuously reporting about the reductions of its environmental footprint. According to their report, the grey cement industry decreased from 2003 to 2006, in contrast to 10% increase in total production (Cement Association of Canada, 2008):

- the amount of SO_2 emissions by 14% of total
- the amount of NO_X emissions by 23% of total.

Also, they stated that from 1990 to 2006 Canada's cement producers improved the energy efficiency of their manufacturing operations. The improvement was 11% per ton of cement. Correspondingly, the reduction of greenhouse gas emissions intensity of their production was 6.4% per ton of cement (Cement Association of Canada, 2008).

According to Geisinger, E. (2005), Corporate Environmental Reporting is a voluntary based activity. The purpose of voluntary environmental reporting is to provide interested parties with an adequately accurate condition of environmental footprint of the reporting company. This means that the reporting of cement companies should provide information about all relevant emission components, which include (Geisinger, E., 2005):

- Total direct CO_2 emissions of the reporting unit (conventional kiln fuels, calcination, non-kiln fuels, alternative kiln fuels);
- If applicable acquired emission rights, and resulting net emissions from those rights;
- Main indirect emissions (consumption of electricity, and bought clinker). Reporting should be in absolute units such Mt CO_2/year and in specific units like kg*CO_2/t for cementitious materials. It is mentioned that reporting of net emissions alone by omitting gross emissions is not acceptable. In particular, cement companies should include the following types of activities in their voluntary reporting:
    - Information about clinker production, including raw material quarrying.
    - Information about grinding of clinker, additives and cement substitutes such as slag.

Environmental Impact of Production Operations

The cement industry has experienced large improvements in technologies, and since 1975 has improved its energy efficiencies by about 33 percent. Currently, the cement industry is making its contribution to production of CO_2 by producing less than 1.5 percent of U.S. total emissions of CO_2 (Canadian Precast/Prestressed Concrete Institute, 2007). It is well below from other sources such as electricity generating plants with 33% and transportation with 27%. United States' Department of Energy stated that cement production now is responsible only for 0.33 percent of energy consumed in the United States. The concrete industry along with cement industry was one of the first groups that started taking care of climate change (Canadian Precast/Prestressed Concrete Institute, 2007). In 1990s, the cement industry significantly strengthened its dedication to improving its production processes by generating minimum emissions and reducing the use of raw materials and the energy consumption. Cement producers worked together with EPA and the agency's Climate Wise Program to find better solutions for emission minimization. As a result, they developed a method for measuring the amount of carbon dioxide emissions. Then, the U.S cement industry implemented a voluntary program to reduce carbon dioxide emissions from production. According to this process, the level of carbon dioxide emissions generated from cement production will be minimized by 2020, and the amount of abatement was 10% per ton lower than the 1990 baseline emissions level. For this purpose, the cement industry selected tree focus areas (Canadian Precast/Prestressed Concrete Institute, 2007):

- Implement new technologies and equipment in order to have better energy efficiency in the process of the cement production.
- Develop product formulation in order to reduce consumption of energy in manufacturing process and also minimize the amount of natural resources used in process. A good example of this could be the use of crushed limestone and industrial by-products such as fly ash in cement.
- Finding new places for cement applications that will increase energy efficiency as well as durability. The U.S. cement industry made similar efforts all over the world. Establishment of the global protocol is a good example of this. It was designed to measure the greenhouse gas emissions generated by cement industry.

In the cement industry the environmental impact of production operations has direct and indirect effects on the environment.

Filling the Gap between Production and Consumption

PCA states that in 2005, which was the peak, utilization rate of cement production in U.S. cement manufacturing plants reached to 91.5%. Domestic production was not able to produce enough cement to satisfy United States' cement consumption. The difference between consumption and production should be satisfied by cement import, and in 2005 it was 33.7 million metric tons. This number is for combined cement and clinker imports. The imported cement comes mostly from four major producers in the world. According to PCA, in 2005 approximately 52% of imported cement and clinker was shipped from China, Canada, Thailand, and Greece. Even though the local production is not satisfying the domestic consumption, the United States is a cement exporter. But those are really small if compared to the total amount. Cement exports from the United States hardly go above 1% of the total cement production. PCA mentioned that in 2005 exported cement was only 844,689 metric tons.

The way the plants are designed affects the cement price. According to PCA, the cement industry has increased its efficiency by making new investments in plants, which use dry process of production rather than more energy-intensive wet process. Japan employs similar approach by making gradual change from wet to dry process. Starting from 1974, in the United States the quantity of wet process kilns decreased from 234 to 52. 83% of the cement presently manufactured in the United States is processed by dry technology.

To reduce the cost of cement, cement producers use alternative fuels from waste materials. Many companies all over the world already have the practice of using waste material. The use of waste material not only reduces the cost of produced cement, but also deceases environmental pollution. In France, cement producing companies modified their kilns, so they started using animal waste as well as alternative fuel. For these companies the use of animal waste reduced the use of fossil fuels by about 12 to 13 percent.

Use of alternative fuels in cement production is cost efficient, but not free of charge. Production of waste fuels is less expensive, but again not free. Although the raw material for secondary fuels is available at no cost, production of such fuels still requires some investments. A good example could be the production of secondary fuels in Tunisia. The price is about U.S. $50–55 per ton resulted from painstaking, sorting/separating of the calorific rich content, additional comminution, which is not always necessary, non fuel mass release (metals, stones, hazardous materials, etc.), homogenizing, storage, transportation and eventually feeding in the cement plant. The investment for each cement plant was calculated based on theoretical substitution rate, which is 15% or about €1 million, designed for feed and conveying equipment in plants. Tunisian government subsidized natural gas used in cement industry, and that subsidy is covering 90% of energy need. Thus, the use of secondary fuel can not be considered as an economically efficient solution.

In order to be able to find the optimal combinations of various factors involved in cement production to have minimized LLC the economic-mathematical model is needed.

METHODOLOGY

The mathematical model was developed and used for various case study analyses. Data collected from existing sources are used to calculate LCC for different case studies, showing how much each kiln should produce to provide minimum possible LCC. The model could also be used to analyze the construction of cement plant, providing information for the number of kilns necessary to achieve minimum possible LCC over a given period of time.

For case studies data were collected and categorized as inputs necessary for cement production. Collected data include raw material and energy requirements for cement production along with amount of emissions associated with production process, material availability, emission and energy limits.

Data were analyzed and the collected information is organized into specific focus areas.

Life Cycle Cost Analysis

In life cycle cost models the goal is to minimize the life cycle cost (LCC) of the considered facility, while satisfying the forecasted demand and various constraints. The main decision variables represent the optimal production of cement by each producing unit within the plant. The objective function of the linear model for cement production can be presented as (Avetisyan, 2008):

$$LCC(Z) = K_0 + \sum_{t=1}^{T} \left[\sum_{i=1}^{n} E_{it}(Z_t) + S_t + IMP_t \right] * \beta_t \rightarrow \min \quad (1)$$

$$E_{it}(Z_t) = e_i * c_{it} \quad (2)$$

$$S_t = s * x_t \quad (3)$$

$$IMP_t = p * q_t \quad (4)$$

$$Z = (Z_1, Z_2, ..., Z_t, ..., Z_T),\ \beta_t = (1+\rho)^{-t},\ x_0 = 0,\ x_T = 0$$

where,

n represents the number of cement producing units within the plant;

Z_t is a vector, representing the parameters of cement producing units (productivity, reliability, etc.) at time t;

K_0 is the amount of total investments and costs necessary for establishing a cement producing plant at the beginning of the considered period. Since these expenses occur in the first year of the projection period they are not discounted;

$E_{it}(Z_t)$ represents the total operation and maintenance costs for each cement production unit at time t, which are in functional relation with Z_t;

S_t represents the inventory storage costs at time t;

IMP_t represents the penalty costs for importing cement from other producers at time t, which are assumed to be higher (by 20-30%) than that from own plant;

c_{it} represents annual cement production by producing unit i at the beginning of t interval of time;

x_t represents annual cement inventory that is stored at the end of t interval of time. It should be noted that both at the beginning and at the end of the considered period no cement is stored, i.e. $x_0 = 0$ and $x_T = 0$ respectively;

q_t represents the amount of cement imported from other producers at t interval of time;

T is the projection period, ρ is a coefficient considering the time factor, and β_t is a coefficient of discounting;

s represents the unit cost of cement inventory storage;

p represents the unit cost of imported cement;

e_i represents the unit costs of cement production, which vary across producing units. This can be explained by numerous factors related to the productivity, efficiency of resource use, etc.

The breakdown of unit costs considered in this model can be presented as:

1. Producer price of inputs.
2. Transportation costs of inputs, which are usually calculated based on the shipment distance from the source to the cement producing plant through existing as well as possible newly constructed roadways.
3. Salaries of the personnel.
4. Cement production costs, which include all the above mentioned costs plus taxes and fees.

The following constraints are included in the model of cement production:

1. Cement Demand Constraint
2. Input Constraint
3. Energy Constraint
4. Emissions Constraint
5. Capacity and Import Constraints

These constraints are represented by mathematical expressions that are included in the economic-mathematical model of the cement production.

Cement Demand Constraint

The total amount of cement produced and stored during the previous period in the plant should satisfy the predicted demand at each *k* interval of time (Avetisyan, 2008):

$$\sum_{i=1}^{n} c_{ik} + x_{k-1} + q_k \geq C_{\min k} + x_k \qquad (5)$$

where,

C_{mink} is the minimum required cement production at each *k* interval of time, which is based on the forecasts of cement demand for the considered plant.

Input Constraint

The input requirement is calculated for each time interval and is described by the input constraint. At each *k* interval of time the total demand for input *j* is defined as a sum of the input requirements by producing units, which can not exceed the maximum available input supply in each *k* interval of time (Avetisyan, 2008):

$$\sum_{i=1}^{n} c_{ik} * m_i^j \leq M_k^j \qquad (6)$$

where,

m_i^j represents consumption of input *j* for producing one unit of cement by production unit *i* at the beginning of *k* interval of time.

Energy Constraint

At each *k* interval of time the electric and thermal energy demand is defined as a sum of the energy requirements of all cement producing units. It follows that the energy requirement should not exceed the maximum available amount of energy supply in each *k* interval of time (Avetisyan, 2008):

$$\sum_{i=1}^{n} c_{ik} * l_{ik} \leq L_k \qquad (7)$$

where,

l_{ik} represents energy requirement for producing one unit of cement by production unit *i* at the beginning of *k* interval of time.

L_k is the total maximum available amount of energy supply at each *k* interval of time.

Emissions Constraint

The process of cement production is associated with intensive emissions. In this model, emissions constraints are used to limit air pollution. In particular, at each *k* interval of time the total amount of emissions of gas *g* is defined as a sum of the emissions from producing units. The latter can not exceed the maximum permitted level of emissions for the considered plant during each *k* interval of time (Avetisyan, 2008):

$$\sum_{i=1}^{n} c_{ik} * y_i^g \leq Y_k^g \qquad (8)$$

where,

y_i^g represents the amount of emissions of type *g* that are associated with producing one unit of cement by production unit *i* at the beginning of *k* interval of time.

Capacity and Import Constraints

Cement producing units located in the plant have limited annual production capacities. This is also considered in the model by including capacity constraints for each k interval of time (Avetisyan, 2008):

$$c_{ik} \leq Cap_{ik}^{max} \qquad (9)$$

$$q_t \leq \alpha * C_{min\,k} \qquad (10)$$

where,

Cap_{ik}^{max} represents maximum available capacity of the cement producing unit *i* at each *k* interval of time;

α is a coefficient defining the amount of maximum available import as a percentage of the required production.

Data for Case Studies

To perform the economic analysis, the data were collected from different sources. Then, the averages were calculated and used for case studies.

In "Assessment of NO_x emissions reduction strategies for cement kilns - Ellis county" prepared in 2006, the authors mention about the average capital investment for cement dry process plant to be approximately $133/ton. To calculate the cost of a plant with an average producing line capacity, it is necessary to multiply the production with the approximate average capital investment per ton. In the United States, the cement kiln average capacity is 532,000 tons annually, based on the data from "PCA Annual Yearbook 2007". Data presented in USGS report state that in 2002 the production of a clinker was 418,000 tons/year and the corresponding amount of cement produced was 468,000 tons/year. Since the kiln capacity is 418,000 metric tons in 2002, and the cement producing capacity is 468,000 metric tons, then the addition to clinker to make cement will be 1.12%, which should not exceed 5%. Therefore, to get the average quantity of cement for the corresponding kiln capacity, the amount of clinker is increased by 1.12%. The average corresponding amount of cement produced will be 537,958.4 tons/year, based on above mentioned assumptions. Since these numbers are approximate averages, those could be rounded before using in the economic analysis. The numbers used in the analysis are based on the average capacity of 540,000 tons/year (Avetisyan, 2008).

In the United States, the average cost of producing one ton of Portland cement is $71.5, according to the data provided by Lehigh Cement Company. The economic-mathematical model is developed for 5 producing lines. There may be some plants, which exceed the accepted number of kilns for the analysis, but the majority of plants have less than 5 kilns (Avetisyan, 2008).

The storage cost of one ton of cement in "Flat" storage terminal is U.S. $7.0, in "Dome" terminal is U.S. $5.50, and in "Silo" terminal is U.S. $5.0, according to Cement Distribution Consultants (2008). One ton of Portland cement, in average requires 152 kWh/ton electricity, which is equivalent to $517.8*10^3$ Btu/ton, as stated by "PCA Annual Yearbook 2007". Other energy sources are also necessary for cement production. According to "PCA Annual Yearbook 2007", the following fuels were used in the United States cement industry:

Gasoline	$2.2*10^3$ Btu/ton
Middle distillates	$33.6*10^3$ Btu/ton
Residual oil	$6.1*10^3$ Btu/ton
LPG	$1.0*10^3$ Btu/ton
Natural gas	$151.1*10^3$ Btu/ton
Coal	$2,646.1*10^3$ Btu/ton

Petroleum Coke	$874.9*10^3$ Btu/ton
Waste fuel	$416.5*10^3$ Btu/ton

The most widely used fuels are Coal and Coke. These two fuels together are 75.7% of the total fuels used in the U.S. cement industry (PCA, 2007).

The proportions of materials necessary for production of Portland cement vary due to required specifications of cement properties. The proportions of these materials also differ from one plant to another. Production of one ton of Portland cement requires from 1,500kg to 1,700kg of raw material. For the case study, the proportion of raw material is selected based on "Report to Congress on Cement Kiln Dust: Cement Industry Overview" prepared by the "U.S. EPA, Office of Solid Waste" in 2006.

The list of raw materials necessary for the production of one ton of Portland cement is presented below:

Limestone	1,348.48 kg
Shale	73.28 kg
Clay	59.36 kg
Sand	41.28 kg
Marl	30.4 kg
Ash	23.04 kg
Iron Ore	10.24 kg
Gypsum	6.4 kg
Bauxite	1.76 kg
Mill Scale	1.6 kg
Diatomaceous Earth	1.44 kg
Slag	1.12 kg
Mag Rock	0.16 kg
Other	1.6 kg

As already mentioned, production of 1,000 kg of cement requires from 1,500 kg to 1,700 kg input of raw material. The rest of the material is considered a by-product and goes to the atmosphere as emissions. Those emissions vary from plant to plant, and from country to country. For environmental protection and sustainable development, countries and local government agencies are setting emission limits. It is mandatory for all plants to comply with regulations, and get permits to pollute the environment. The regulation of emission limits is strict and requires all plants to operate within those limits or stop their operation. There are some types of emissions, which have no limitations in the United States, but are recognized as significant polluters by other countries. A good example is carbon dioxide, which was suggested to be included as emission in initiatives such as Clean Power Act and Clean Air Act. The bills suggest annual minimization of the amount of carbon dioxide, but unfortunately those suggestions are not playing significant roles in regulations and limitations. According to the report developed by International Energy Agency Greenhouse Gas R and D Programme (2004), the average CO_2 emission associated with the production of one ton of cement is 0.81ton. The world's largest emitter, China, is emitting 0.88 kg CO_2 per kg of cement, but the most carbon intensive cement producing region is India (0.93 kg CO_2/kg), then North America (0.89 kg CO_2/kg). As previously mentioned, there is no cap for carbon dioxide, but companies in cement industry are trying to minimize their emission levels voluntarily. There are companies, which are far below from the average amount of emissions. According to "Global Nation Organization", in 2007 cement producing company, Lafarge, has improved operation efficiency to reduce its carbon dioxide emissions from 763 pounds per ton in 1990, which is equivalent to 347 kilograms of CO_2 per ton of cement, to 655lb/ton in 2006. Lafarge also announced that its goal is to reach 610lb/ton of cement by 2010.

PCA mentioned that carbon emissions from cement production are 1.5% of the United States total carbon emissions. In the case study, the number, derived from the total amount of carbon dioxide in the Clean Air Act initiative, serves as a constraint of carbon dioxide emissions for the economic-mathematical model. The rate of minimization of carbon dioxide of this initiative can be seen for the power sector in **Table 1.1**. According to the Energy Information Administration, in 2007 the total U.S. emissions were 5,984 $MMTCO_2$ (Energy Information Administration, 2008).

Table 1.1
Carbon Dioxide Cap by Clean Air Act and Clear Skies Act

Emissions	**Clean Air Act**	**Clear Skies Act**
Carbon Dioxide (CO_2)	2,332 million metric tons CO_2(636 million metric tons carbon equivalent) in 2009 2,244 million metric tons CO_2(612 million metric tons carbon equivalent) in 2013	No cap

For the case study we calculate the tendency of U.S. carbon dioxide emissions, based on this data. This can be done by substituting the amount of carbon dioxide for the years given in the initiative with the total amount of carbon dioxide for the United States. The reduction rate of emissions is assumed to be linear for the considered period of time.

NO_x emissions have more accurate regulations and limitations. In "Pollution Prevention and Abatement for Cement Industry" (WBCSD, 2004), the World Business Council for Sustainable Development states the limit for NO_x to be equal to 2.4kg per ton, which is equal to 0.0024ton NO_x per ton of cement produced. Currently, there are plants with varying control of NO_x emissions, ranging from 2.8lb to 3.2lb per ton. If there is no control, NO_x emissions associated with the production of ton of cement are 4.2lb, according to PCA report (PCA, 2006) about "Assessment of NO_x Emissions Reduction Strategies for Cement Kilns – Ellis County".

As mentioned above, World Business Council for Sustainable Development (2004) declared the limit for NO_x - 600 mg/ Nm^3 equal to 2.4 kg/ton, which is equivalent to 5.286lb/ton. Another limit for NO_x was proposed by EPA in 2003, which is close to the limit adopted by the World Bank in 2003, and republished by WBCSD in 2004, equal to 5.1lb/ton (EPA, 2008).

There are also state regulations for some pollutants. The state regulations for Pennsylvania are presented below (The Environmental Quality Board, 2008):

a) "During the period from May 1 through September 30, 2009, and for each year thereafter, the owner or operator of a Portland cement kiln may not operate a Portland cement kiln in a manner that results in NO_x emissions in excess of the allowable limits established under subsection (b).
b) The owner or operator of a Portland cement kiln shall determine allowable emissions of NO_x by multiplying the tons of clinker produced by the Portland cement kiln for the period from May 1 through September 30, 2009, and for each year thereafter by: 3.44 pounds of NO_x per ton of clinker produced for long dry-process cement kilns."

Regulations vary from state to state. For example, NO_x regulations in the State of California (Amended June 6, 1986) require (South Coast Air Quality Management District, 1986):

"(b) Requirements

1. No person shall operate a gray cement kiln unless such kiln is equipped with a device, which continuously monitors and records NO_x emissions in a manner approved by the Executive Officer whenever the kiln is operating. Such records as well as heat input and clinker production records shall be maintained at the facility for at least two (2) years and shall be available to and in a manner and form acceptable by the Executive Officer upon request.
2. No person shall operate a gray cement kiln capable of discharging nitrogen oxides into the atmosphere unless such discharge of nitrogen oxides into the atmosphere is limited to no more than:
   (A) 11.6 lb/ton of clinker produced when averaged over any 24 consecutive hour period, and
   (B) 6.4 lb/ton of clinker produced when averaged over any 30 consecutive day period."

Particulates ($PM_{2.5}$ and PM_{10}) are another form of emissions associated with the production of cement, and, according to Environmental Protection Agency (1994 and 2005), they range from 0.38 lb/ton to 0.89lb/ton.

Limits for this pollution are stated by World Business Council for Sustainable Development (2004). According to WBCSD (2004), the limit for particulates is 50 mg/Nm^3 equivalent to 0.2 kg/ton, which is equal to 0.44lb/ton.

Another limit for this pollution in California (Adopted February 7, 1986) requires (South Coast Air Quality Management District, 1986):

"(b) Requirements:

No person shall operate a cement kiln and clinker cooler capable of discharging particulate matter into the atmosphere unless such discharge of particulate matter into the atmosphere from such cement kiln and clinker cooler when combined is limited to no more than:

- 0.40 pound per ton of kiln feed for kiln feed rates less than 75 tons per hour. (South Coast Air Quality Management District, 1986)"

There is also another limit by Environmental Protection Agency (2005) for particulate matter from the cement production:

"August 17, 1971 are regulated to limit PM emissions from Portland cement kilns to 0.15 kg/Mg (0.30 lb/ton) of feed (dry basis), and to limit PM emissions from clinker coolers to 0.050 kg/Mg (0.10 lb/ton) of feed (dry basis) (Environmental Protection Agency, 2005)".

The total of these limits is 0.4lb/ton, which is the same as California's limit.

SO_2 emission associated with the production of cement is 2.58kg per ton of cement, equivalent to 5.68lb/ton, according to Cement Association of Canada (2008).

Another number for SO_2 associated with the production of cement, provided by Environmental Protection Agency (1994), is 10lb/ton.

World Business Council for Sustainable Development (2004) has specific limit for this pollution as well, which is 400 mg/Nm^3 equal to 1.6 kg/ton, which, in its turn, is equivalent to 3.524lb/ton.

Although the amount of Mercury from the cement production is considered not significant, the latest regulations already take it into account, and define requirements for existing and new plants. Based on data from WBCSD (2004), the amount of Mercury generated from the production of one ton of cement ranges from 0.01mg/Nm^3 to 0.3mg/Nm^3, equivalent to 0.000088lb/ton and 0.00264lb/ton, correspondingly. The same report also states the limit for mercury to be 0.12mg/Nm^3 equivalent to 0.001lb/ton of cement produced.

All data used in the case study analysis are from above mentioned ranges. The amounts of emissions were collected for long dry-process cement kilns.

The case studies were conducted based on the market behavior of the U.S cement industry during the last several years. The cement production for the benchmark year 2009 was selected to be close to that of 2006 (94,693,000 tons of clinker), being equal to 95,753,562 tons (94,693,000+1.2% of 94,693,000). This is also based on the PCA forecast that for coming years the demand of cement will not continue to rise, and, even, most probably will decrease. The production capacity of a hypothetical cement plant was selected to be 2,140,000 tons per year. Based on this number and using annual percentage changes for corresponding years, the cement production was calculated. The results are presented in **Table 1.2**.

Table 1.2

Cement Production for 2009-2020

Year	Forcasted Demand ton/year
2009	2,140,000
2010	2,149,433
2011	2,121,797
2012	2,105,338
2013	2,079,988
2014	2,040,959
2015	2,015,477
2016	2,087,488
2017	2,126,403
2018	2,100,981
2019	2,132,927
2020	2,126,508

Analyses were conducted for all years between 2010 and 2020. Therefore, benchmarking values (numbers for 2009 in **Table 1.2** and **Table 1.3**) were not included in computations. CO_2 emission limits were calculated based on the Clean Air Act initiative and 2007 PCA report, which stated that CO_2 emissions from the cement industry were 1.5% of total U.S. CO_2 emissions. The results of these computations are presented in **Table 1.3**.

Table 1.3

Calculated CO_2 Emissions for Case Study

Year	CO_2 based on Clean Air Act (ton/year)	CO_2 1.5% ton	U.S. total cement production	Plant production (ton/year)	Calculated CO_2 limit for case study (ton/year)
2009	5,984,000,000	89,760,000	95,753,562	2,140,000	2,006,050
2010	5,927,547,170	88,913,208	95,333,342	2,149,433	2,004,681
2011	5,871,094,340	88,066,415	96,151,202	2,121,797	1,943,388
2012	5,814,641,509	87,219,623	97,734,237	2,105,338	1,878,838
2013	5,758,188,679	86,372,830	100,554,097	2,079,988	1,786,644
2014	5,701,735,849	85,526,038	105,433,659	2,040,959	1,655,592
2015	5,645,283,019	84,679,245	111,947,686	2,015,477	1,524,543
2016	5,588,830,189	83,832,453	114,763,783	2,087,488	1,524,865
2017	5,532,377,358	82,985,660	115,497,599	2,126,403	1,527,833
2018	5,475,924,528	82,138,868	117,642,599	2,100,981	1,466,919
2019	5,419,471,698	81,292,075	118,032,713	2,132,927	1,469,000
2020	5,363,018,868	80,445,283	118,781,581	2,126,508	1,440,186

For Case Study I, the capacities of the production lines were selected to be close to average kiln capacity in the United States, which is presented in **Table 1.4**.

Table 1.4
Production Line Capacities

Production Line Capacities	1	2	3	4	5
ton/year	400,000	450,000	530,000	550,000	600,000

The capital cost associated with the total capacity of the hypothetical plant is calculated based on the aforementioned data and the total capacity, which is presented in **Table 1.5**.

Table 1.5
Capital Cost and Total Capacity

Capital cost, $	336,490,000
Total capacity ton/year	2,530,000

Sensitivity analyses of the results were also conducted. For that purpose the demand was increased by 5% from 2010 to 2020, which is presented in **Table 1.6**.

Table 1.6
5% Increase of Cement Demand

Years	Cement ton	Cement1 ton
2010	2,149,433	2,256,905
2011	2,121,797	2,227,887
2012	2,105,338	2,210,605
2013	2,079,988	2,183,987
2014	2,040,959	2,143,007
2015	2,015,477	2,116,251
2016	2,087,488	2,191,863
2017	2,126,403	2,232,724
2018	2,100,981	2,206,030
2019	2,132,927	2,239,573
2020	2,126,508	2,232,834

For the case studies the material proportions were selected from the above mentioned numbers, and are presented in **Tables 1.7** and **1.8**. In the first column of these two tables number 4 represents the reference value of the line from which numbers are derived for other production lines. Percentage change describes the change of material usage for every producing unit, compared to reference value.

Table 1.7
Calculated Material Proportion for Production of One Ton of Portland Cement

% change	Lime	Shale	Clay	Sand	Marl	Ashc
	kg	kg	kg	kg	kg	kg
1 (4+3% of 4)	1,388.93	75.48	61.14	42.52	31.31	23.73
2 (4+2% of 4)	1,375.45	74.75	60.55	42.11	31.01	23.50
3 (4+1% of 4)	1,361.96	74.01	59.95	41.69	30.70	23.27
4	1,348.48	73.28	59.36	41.28	30.40	23.04
5 (4-1% of 4)	1,335.00	72.55	58.77	40.87	30.10	22.81

Table 1.8
Calculated Material Proportion for Production of One Ton of Portland Cement

% change	Iron	Gyps	Baux	Mill	Diatom	Slag	Mgrock
	kg	kg	kg	kg	kg	kg	kg
1 (4+3% of 4)	10.55	6.59	1.81	1.65	1.48	1.15	0.165
2 (4+2% of 4)	10.44	6.53	1.80	1.63	1.47	1.14	0.163
3 (4+1% of 4)	10.34	6.46	1.78	1.62	1.45	1.13	0.162
4	10.24	6.40	1.76	1.60	1.44	1.12	0.160
5 (4-1% of 4)	10.14	6.34	1.74	1.58	1.43	1.11	0.158

The same approach was used for calculation of the energy use for other producing units, again based on the reference number, which is number 4 in the first column. Values are presented in

Table 1.9. The selection of fuel types is based on 2007 PCA report, illustrating the most widely used fuel types in the cement production. Producing unit number 4 is the reference value, which is from the above mentioned data.

Table 1.9 (continued on following page)
Calculated Energy Use for Production of One Ton of Portland Cement

% change	Elec.	Coal	Coke	Wstfuel
	kWh	Btu	Btu	Btu
1 (4+3% of 4)	156.56	2,725,483.00	901,147.00	428,995.00
2 (4+2% of 4)	155.04	2,699,022.00	892,398.00	424,830.00
3 (4+1% of 4)	153.52	2,672,561.00	883,649.00	420,665.00
4	152.00	2,646,100.00	874,900.00	416,500.00
5 (4-1% of 4)	150.48	2,619,639.00	866,151.00	412,335.00

To be consistent in calculations, the same approach was used for calculating the emissions from other producing units, again based on the reference number, which is number 4 in the first column. Values are presented in

Table 1.10. Producing unit number 4 is the reference value, which is again from the above mentioned data.

Table 1.10
Calculated Emissions from Production of One Ton of Portland Cement

% change	CO_2	NO_x	SO_2	PM	Mercury
	ton	ton	ton	ton	ton
1 (4+3% of 4)	0.83	0.00140	0.00266	0.0001543	0.000000638
2 (4+2% of 4)	0.83	0.00139	0.00263	0.0001528	0.000000632
3 (4+1% of 4)	0.82	0.00138	0.00260	0.0001513	0.000000625
4	0.81	0.00136	0.00258	0.0001498	0.000000619
5 (4-1% of 4)	0.80	0.00135	0.00255	0.0001483	0.000000613

SO_2 emissions are calculated, but, unfortunately, the amounts of SO_2 emissions from cement production exceed the limit for this type of emission, and the optimal solution becomes infeasible. The model accounts for this type of pollution as well, but the constraint for SO_2 is turned off. After having improved technologies, this can also be considered as one of the constraints.

The computer code is written in a way that it considers all production inputs as constraints. In most countries the raw material is not considered as a scarce input for the cement production, but there are some regions in the world that have scarcity of one or more types of raw material. The model can also be used for those cases, helping to make more informed decisions. For the case studies, the total amount of material used is calculated by multiplying the average amounts of materials, necessary for the production of one ton of Portland cement, by the total production for particular year, and, then, are increased by 20% not to act as constraints. These numbers are presented in **Tables 1.11** and **1.12**. The 20% increase is not a fixed number and was selected only to increase the limit for raw materials used in the cement production.

Table 1.11
Raw Materials with 20% Increase

Year	Lime	Shale	Clay	Sand	Marl	Ashc
	kg	kg	kg	kg	kg	kg
2010	3,512,942,331	190,902,656	154,639,488	107,539,051	79,195,425	60,021,796
2011	3,467,775,741	188,448,183	152,651,258	106,156,400	78,177,194	59,250,084
2012	3,440,874,975	186,986,324	151,467,088	105,332,907	77,570,746	58,790,460
2013	3,399,443,753	184,734,841	149,643,288	104,064,605	76,636,724	58,082,570
2014	3,335,657,065	181,268,502	146,835,402	102,111,951	75,198,724	56,992,717
2015	3,294,011,118	179,005,350	145,002,151	100,837,075	74,259,861	56,281,158
2016	3,411,702,620	185,401,020	150,182,923	104,439,876	76,913,087	58,292,024
2017	3,475,304,021	188,857,290	152,982,652	106,386,858	78,346,911	59,378,711
2018	3,433,754,547	186,599,381	151,153,647	105,114,935	77,410,224	58,668,801
2019	3,485,965,811	189,436,680	153,451,983	106,713,239	78,587,269	59,560,878
2020	3,475,475,161	188,866,590	152,990,186	106,392,097	78,350,769	59,381,635

Table 1.12
Raw Materials with 20% Increase

Year	Iron	Gyps	Baux	Mill	Diatom	Slag	Mgrock
	kg	kg	kg	kg	kg	kg	kg
2010	26,676,354	16,672,721	4,584,998	4,168,180	3,751,362	2,917,726	416,818
2011	26,333,371	16,458,357	4,526,048	4,114,589	3,703,130	2,880,212	411,459
2012	26,129,093	16,330,683	4,490,938	4,082,671	3,674,404	2,857,870	408,267
2013	25,814,476	16,134,047	4,436,863	4,033,512	3,630,161	2,823,458	403,351
2014	25,330,096	15,831,310	4,353,610	3,957,828	3,562,045	2,770,479	395,783
2015	25,013,848	15,633,655	4,299,255	3,908,414	3,517,572	2,735,890	390,841
2016	25,907,566	16,192,229	4,452,863	4,048,057	3,643,251	2,833,640	404,806
2017	26,390,538	16,494,086	4,535,874	4,123,522	3,711,169	2,886,465	412,352
2018	26,075,023	16,296,889	4,481,645	4,074,222	3,666,800	2,851,956	407,422
2019	26,471,501	16,544,688	4,549,789	4,136,172	3,722,555	2,895,320	413,617
2020	26,391,838	16,494,899	4,536,097	4,123,725	3,711,352	2,886,607	412,372

The energy necessary for cement production is also calculated, and the results are increased by 20%. Calculated energy numbers are presented in **Table 1.13**.

Table 1.13
Calculated Energy with 20% Increase

Year	Elec.	Coal	Coke	Wstfuel
	kWh	Btu	Btu	Btu
2010	395,977,126	6,893,388,631,909	2,279,213,073,602	1,085,029,426,397
2011	390,885,970	6,804,758,978,866	2,249,908,782,967	1,071,078,989,720
2012	387,853,729	6,751,972,050,498	2,232,455,442,720	1,062,770,250,192
2013	383,183,622	6,670,672,248,600	2,205,574,676,052	1,049,973,542,777
2014	375,993,618	6,545,504,687,300	2,164,189,581,240	1,030,271,986,040
2015	371,299,307	6,463,783,534,514	2,137,169,500,150	1,017,408,957,381
2016	384,565,435	6,694,727,622,153	2,213,528,285,636	1,053,759,893,665
2017	391,734,554	6,819,531,598,431	2,254,793,165,590	1,073,404,221,589
2018	387,051,118	6,737,999,753,315	2,227,835,676,722	1,060,570,990,233
2019	392,936,346	6,840,453,053,612	2,261,710,584,107	1,076,697,289,154
2020	391,753,845	6,819,867,424,521	2,254,904,202,303	1,073,457,081,105

The limits for pollutants are calculated through multiplying the allowable amount of pollution per ton of Portland cement by the total cement production in a particular year.

To maintain consistency in data calculations, the total values for SO_2 are also calculated. These calculations are based on limitations provided by different agencies such as Environmental Protection Agency, state regulations or WBCSD. These numbers are calculated and used as constraints in the economic-mathematical model.

Table 1.14

Calculated Emission Limits for Hypothetical Plant

Year	CO_2	NO_x	SO_2	PM	Mercury
	ton	ton	ton	ton	ton
2010	2,004,681.35	5,158.64	3,439.09	429.89	0.98
2011	1,943,387.81	5,092.31	3,394.88	424.36	0.96
2012	1,878,837.58	5,052.81	3,368.54	421.07	0.96
2013	1,786,644.35	4,991.97	3,327.98	416.00	0.94
2014	1,655,592.08	4,898.30	3,265.53	408.19	0.93
2015	1,524,543.39	4,837.15	3,224.76	403.10	0.92
2016	1,524,864.87	5,009.97	3,339.98	417.50	0.95
2017	1,527,832.60	5,103.37	3,402.25	425.28	0.97
2018	1,466,919.30	5,042.35	3,361.57	420.20	0.95
2019	1,469,000.07	5,119.02	3,412.68	426.59	0.97
2020	1,440,185.85	5,103.62	3,402.41	425.30	0.97

The production costs are selected close to the number provided by Lehigh Cement Company, which provided $71.5 per ton of cement produced. Capacities with corresponding production costs for *Case Study I* are presented in **Table 1.15**.

Table 1.15

Capacities of Producing Units and Corresponding Production Costs

Capacities	1	2	3	4	5
ton/year	400,000	450,000	530,000	550,000	600,000
O&M costs per ton of cement, $	72.69	72.93	72.83	72.90	72.83

RESULTS

This section presents the results of case studies and their differences. It also discusses the benefits of choices, based on different numbers of production lines in cement plants.

In this research three case studies were investigated. *Case Study I* is for a cement plant with 5 production lines. In the model those lines are described as producing units. The output of the developed economic-mathematical model gives detailed data for each producing unit in the solution output, which also includes information about calculations in the model. Data are extracted from those outputs and are discussed below.

Case Study I

The results of *Case Study I* are summarized in tables and graphs under this subsection. Numerical values of these graphs are presented in **Tables 2.16** and **2.17.**

Since the initial information used in this model is partially stochastic, it is useful to see how sensitive the original optimal solution is to the various parameters of the model. This is usually implemented by changing the value of the parameter from its initial estimate to other possibilities in the range of likely values. The optimal solution can be reliable only when it is justified by the results of sensitivity analysis. Moreover, sometimes the constraints of a problem are resulting from management policy decisions, which need to be reviewed after estimating their potential impact. Thus, it is very important to check the optimal solution of the linear model by sensitivity analysis. For the cement plant with 5 production lines, the results are also presented in **Figure 2.2** and **Figure 2.3**.

In **Figure 2.2** the production of each producing unit is presented graphically. The change of production in each unit can be seen from the graph, and conclusions can be made. The production of the first producing unit, called “cem1.L”, is steady under *Case Study I*. “cem1.L” should operate at its maximum capacity, equal to 400,000 tons each year, from 2010 to 2014. Then, the output of the unit is decreasing to 315,462.4 tons a year, after which it experiences a small increase. Beginning from 2017, the production of “cem1.L” decreases. Then there is steady state for one year that turns to producing 216,218.8 tons in 2020, which is the last year in this analysis.

The second producing unit, called “cem2.L”, starts from a low level. To satisfy the minimum LCC condition, it should start from 69,433 tons in 2010. Then there will be need to decrease the production of this unit until 2012. During the next year it will produce approximately half of its capacity, and then will work by its full capacity until the end of the projected period by producing 450,000 tons each year. After conducting the sensitivity analysis, the operation schedule of the production unit changed, resulting to 176,905 tons production for the first year. Then, in 2011, it should produce slightly less compared to the previous year, but after 2011, it should work with its maximum capacity.

The analysis revealed an interesting behavior for the producing unit called “cem3.L”. This production line is satisfying all of the constraints within the projected period of 2010-2020. The behavior of this unit is changing when its parameters are being changed in the model. It should start and continue to produce cement with its maximum production capacity, equal to 530,000 tons per year.

The producing line, called “cem4.L”, has only one year decrease in its maximum production capacity. In 2013, it should produce 391,786.7 tons. But before and after 2013 it should continue to work with its maximum capacity. Sensitivity analysis illustrated a change in the schedule of this line as well. It will be necessary to decrease the production of this unit in 2012, if there is an increase in the demand. In that case the unit will be required to produce

279,443.4 tons in 2012. After conducting the sensitivity analysis, we see that the unit should continue to work by its maximum capacity before and after 2012.

According to the analysis, the producing unit, called “cem5.L”, will be required to work with its maximum production capacity from 2010 to 2013, equal to 600,000 tons per year. Then, in 2014, it should produce 70,049.7 tons of cement. The year of 2014 will be the last year for this unit to produce cement. A close look at the values of production and demand reveals that for each year there is a deficit. The gap should be filled by imported cement. This import can be both from overseas and from neighboring producers. In the case studies the import is assumed to be 20% more expensive than the own production of cement. Also, there is a limit on the amount of imported cement. It cannot exceed 30% of the total demand in any year of the considered period. The numbers in **Table 2.16** show that beginning from 2015 the gap between demand and production should be satisfied by the import. From **Figure 2.2** we see that the increase in imports is not linear but steady. After the sensitivity analysis, the cement import is also changed. Both the quantity and the start year are changed.

As previously mentioned, the model is a good decision making tool. It is not only providing the necessary production of each producing unit, but also tells how much cement should be stored in storages each year. Storage issue is another problem for cement plants, since determining the optimal size of the storage is very important, giving information to decision makers about the optimal time and the optimal amount of investments. In the case studies the storage capacity is assumed to be 60,000 tons. **Table 2.16** shows that the need for storage starts in 2013. But after 2014 there is no need for storage. Since the construction of storages is expensive, the owners will delay the investment for storage for two years. Then, in 2012, they can start building the storage to have it ready for the next period. **Table 2.16** shows that after 2014 there is no need for storage for the rest of the projected period. Therefore, the storage can be deconstructed and moved to another facility for similar purposes. But the results of the sensitivity analysis show that after increasing the demand, the optimal solution requires having storage also from 2012 to 2013. So the decision maker will have better understanding of the situation and will be prepared for possible increase in demand. In summary, the storage will be required from 2012 to 2014. The results are different before and after the sensitivity analysis not only for each production unit, but also for the total production. Data for the total production before and after the sensitivity analysis are also presented in **Table 2.18** and **Table 2.19**. The results of the sensitivity analysis show that in *Case Study I* the most sensitive production units are “cem2.L”, “cem4.L”, “cem5.L”, while “cem1.L” and “cem3.L” are the least sensitive units.

The model also gives the unit production cost in today’s dollar value. The norm considering the time factor is equal to 0.012, which represents a discount rate of 1.2%. The most important result of this model is the amount of LCC. For this analysis the LCC is $1,926,334,906, which represents the investment plus operation and maintenance costs for the projected period of time. This number represents the LCC of the hypothetical plant before the sensitivity analysis. After the sensitivity analysis the LCC is $2,014,992,896. The increase in LCC is normal, since the demand has been increased by 5% for the sensitivity analysis, so more expenses are necessary to satisfy the increased demand.

Table 2.16
Case Study I Results before Sensitivity Analysis

Case Study I	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
cem1.L	400,000	400,000	400,000	400,000	400,000	315,462.4	315,841.2	319,332.9	247,669.4	250,117.6	216,218.8
cem2.L	69,433	41,797	25,338	218,201.3	450,000	450,000	450,000	450,000	450,000	450,000	450,000
cem3.L	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000
cem4.L	550,000	550,000	550,000	391,786.7	550,000	550,000	550,000	550,000	550,000	550,000	550,000
cem5.L	600,000	600,000	600,000	600,000	70,049.7						
store.				60,000	19,090.7						
impcem.						150,923.9	241,646.8	277,070.1	323,311.6	352,809.4	380,289.2

Table 2.17
Case Study I Results after Sensitivity Analysis

Case Study I	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
sens-cem1.L	400,000	400,000	400,000	400,000	400,000	315,462.4	315,841.2	319,332.9	247,669.4	250,117.6	216,218.8
sens-cem2.L	176,905	147,887	450,000	450,000	450,000	450,000	450,000	450,000	450,000	450,000	450,000
sens-cem3.L	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000	530,000
sens-cem4.L	550,000	550,000	279,443.4	550,000	550,000	550,000	550,000	550,000	550,000	550,000	550,000
sens-cem5.L	600,000	600,000	600,000	225,140.8	70,049.7						
sens-store.			48,838.37	19,992.2							
sens-impcem.					122,965.1	270,788.6	346,021.8	383,391.1	428,360.6	459,455.4	486,615.2

Table 2.18
Case Study I Total Production before Sensitivity Analysis

Case Study I	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
Total prod.	2,149,433	2,121,797	2,105,338	2,139,988	2,000,050	1,845,462	1,845,841	1,849,333	1,777,669	1,780,118	1,746,219

Table 2.19
Case Study I Total Production after Sensitivity Analysis

Case Study I	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
sens-total prod.	2,256,905	2,227,887	2,259,443	2,155,141	2,000,050	1,845,462	1,845,841	1,849,333	1,777,669	1,780,118	1,746,219

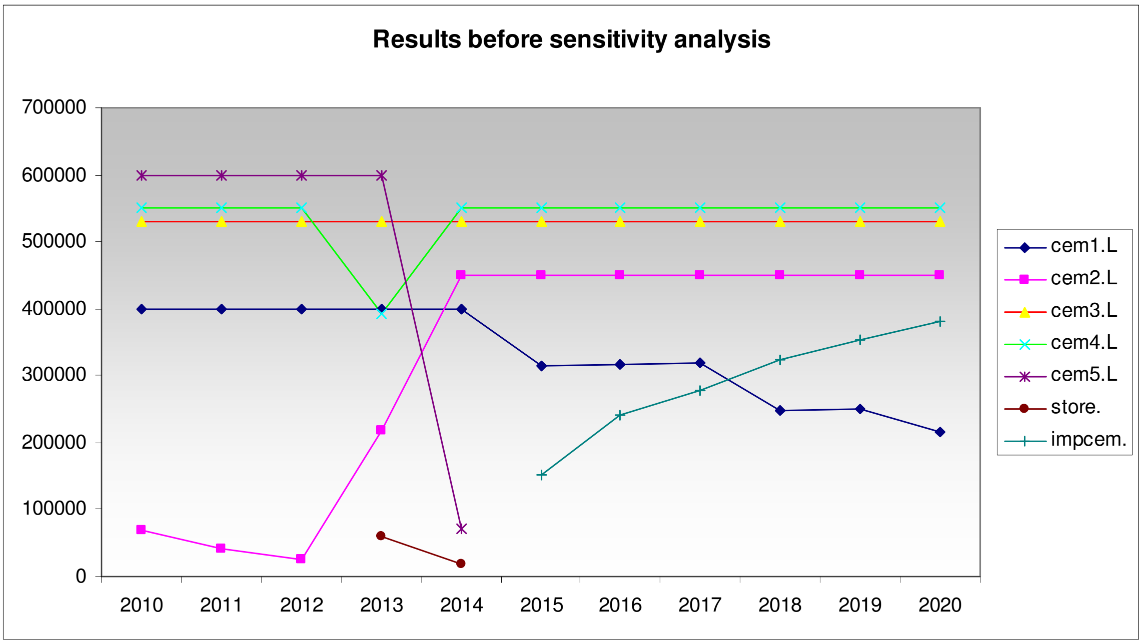


Figure 2.2 Production of Producing Units before Sensitivity Analysis (Case Study I)

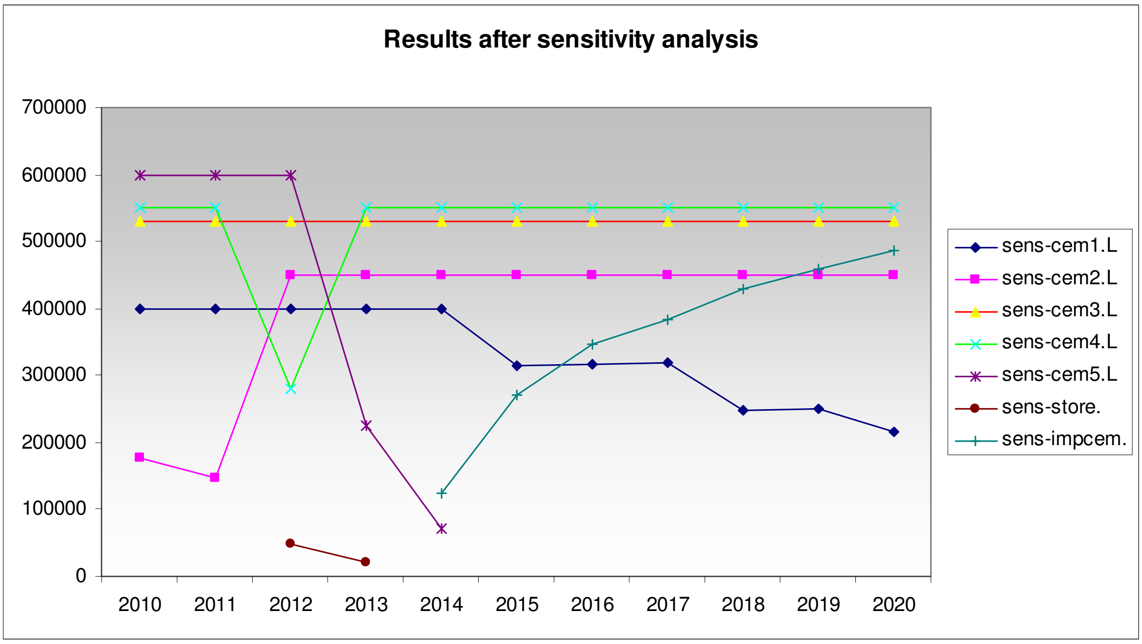


Figure 2.3 Production of Producing Units after Sensitivity Analysis (Case Study I)

Case Study II (Alternative I)

To further validate the effectiveness of the developed model *Case Study II* is conducted. In this case study we have four production units to satisfy the same forcasted demand. In the model a modification is done just by turning off one of the units. The capital investment, the number of production units, the production capacities and the production costs of producing units are the only data that changed.

The results for *Case Study II* are summarized in graphs and in tables. Numerical values of these graphs are presented in **Table 2.20** and **Table 2.21**. For the cement plant with 4 production lines the results are also presented in **Figure 2.3** and **Figure 2.**4.

Figure 2.3 presents the production of each producing unit. The first producing unit, called “cem1.L”, has steady production with the maximum capacity equal to 500,000 tons until 2013. Then it is decreasing to 5,402.353 tons in 2014. In this particular case the year of 2014 should be the last year for this unit to operate. After the sensitivity analysis, the numbers have been changed for this producing unit. Decrease in production should start one year earlier being equal to 159,581.2 tons in 2013, and, then, 5,402.353 tons in 2014. It should produce 500,000 tons annually from 2010 to 2012.

The second producing unit, called “cem2.L”, starts with its maximum capacity in the first year, and, then, decreases its production to 271,797 tons. In 2014, it should produce 334,868 tons. Before and after 2014 its production should be equal to its maximum capacity. The sensitivity analysis shows that there should be decrease of production in 2011, being equal to 377,887 tons. Before and after 2011 it should produce 650,000 tons annually.

The producing line, called “cem4.L”, has low start equal to 299,433 tons in 2010. In 2011, it should produce 650,000 tons. Then it decreases its production to 255,338 tons in 2012. In 2013, it should continue its operation with 605,120 tons, and the rest of the projected period it should operate with its maximum capacity. After the sensitivity analysis, the production of this unit changed. It will need to start with 406,905 tons in 2010, and, then, continue with its maximum capacity.

According to the analysis, the producing unit, called “cem5.L”, will be required to work with its maximum production capacity from 2010 to 2014, equal to 700,000 tons per year. Then, it will have decreasing production beginning from 2015 until the end of the period. After the sensitivity analysis, the operation schedule of this line has changed, requiring a decrease in 2012, equal to 466,672.2 tones.

The numbers in **Table 2.20** show that from 2015 the gap between the demand and production should be satisfied by importing cement. The import is increasing gradually, which can be seen from **Figure 2.3**. After the sensitivity analysis, the need for cement import is also changed.

The storage capacity is selected to be 60,000 tons. From **Table 2.20** it is clear that the need for storage starts in 2013. But after 2014 there is no need for storage.

Like in previous example, the results indicate the need for storage from 2012 to 2014. The results of the sensitivity analysis show that in 2012 the required storage capacity is not equal to its maximum number. So the decision makers can invest in the storage construction gradually. The results are different before and after the sensitivity analysis not only for each production unit, but also for the total production. The data for the total production before and after the sensitivity analysis are also presented in **Table 2.22** and **Table 2.23**. The results of the sensitivity analysis show that in this case study all production units are extremely sensitive.

Like *Case Study I*, in this case also the model gives the unit production cost in today's dollar value, which can be found in the Appendix F. The norm considering the time factor is again assumed to be equal to 0.012, which represents a discount rate of 1.2%. In *Case Study II* the LCC is $1,923,364,931, which represents the investment plus operation and maintenance costs for the projected period of time. This number is the LCC of the hypothetical plant before the sensitivity analysis. After the sensitivity analysis, the LCC is $2,011,931,949. As in *Case Study I,* in this case also there is some increase in LCC. As previously mentioned, this increase is normal, since the demand increased by 5% for the sensitivity analysis, and more expenses are necessary to satisfy the increased demand.

Table 2.20
Case Study II Results before Sensitivity Analysis

Case Study II	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
cem1.L	500,000	500,000	500,000	500,000	5,402.353						
cem2.L	650,000	271,797	650,000	334,868	650,000	650,000	650,000	650,000	650,000	650,000	650,000
cem4.L	299,433	650,000	255,338	605,120	650,000	650,000	650,000	650,000	650,000	650,000	650,000
cem5.L	700,000	700,000	700,000	700,000	700,000	550,346.7	550,727.8	554,240.2	482,152.7	484,615.4	450,516
store.				60,000	24,443.35						
impcem.						140,686.9	236,760.2	272,162.8	318,828.3	348,311.6	375,992

Table 2.21
Case Study II Results after Sensitivity Analysis

Case Study II	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
sens-cem1.L	500,000	500,000	500,000	159,581.2	5,402.353						
sens-cem2.L	650,000	377,887	650,000	650,000	650,000	650,000	650,000	650,000	650,000	650,000	650,000
sens-cem4.L	406,905	650,000	650,000	650,000	650,000	650,000	650,000	650,000	650,000	650,000	650,000
sens-cem5.L	700,000	700,000	466,672.2	700,000	700,000	550,346.7	550,727.8	554,240.2	482,152.7	484,615.4	450,516
sens-store.			56,067.19	31,661.37							
sens-impcem.					105,943.3	265,904.3	341,135.2	378,483.8	423,877.3	454,957.6	482,318

Table 2.22
Case Study II Total Production before Sensitivity Analysis

Case Study II	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
Total prod.	2,149,433	2,121,797	2,105,338	2,139,988	2,005,402	1,850,347	1,850,728	1,854,240	1,782,153	1,784,615	1,750,516

Table 2.23
Case Study II Total Production after Sensitivity Analysis

Case Study II	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
sens-total prod.	2,256,905	2,227,887	2,266,672	2,159,581	2,005,402	1,850,347	1,850,728	1,854,240	1,782,153	1,784,615	1,750,516

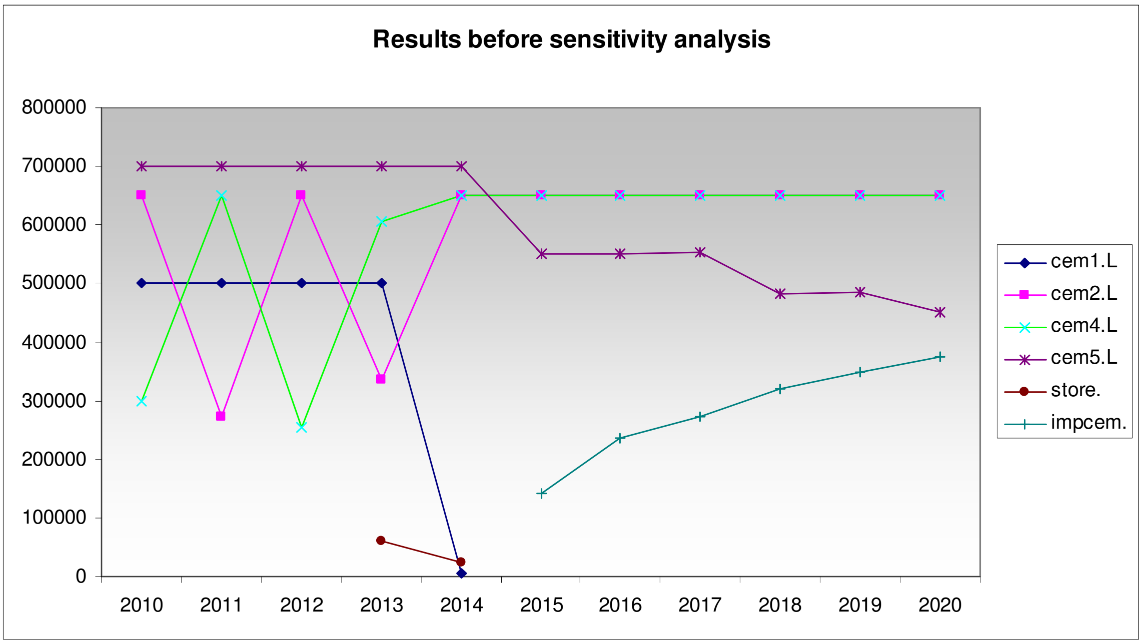


Figure 2.3 Production of Producing Units before Sensitivity Analysis (Case Study II)

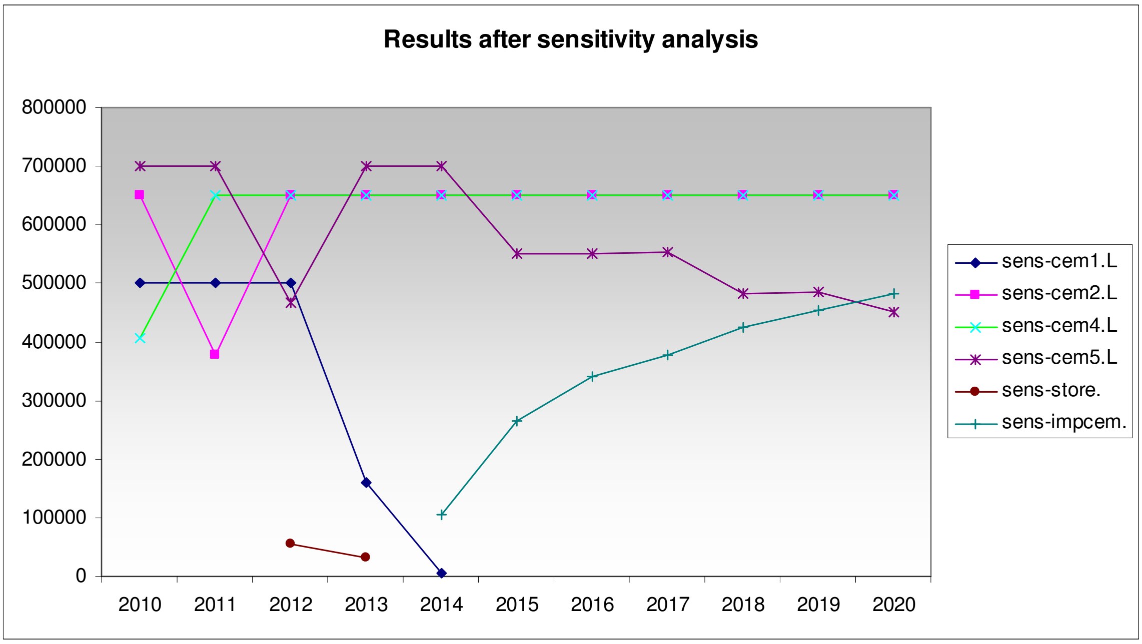


Figure 2.4 Production of Producing Units after Sensitivity Analysis (Case Study II)

Case Study III (Alternative II)

To compare the results and make some conclusions and recommendations *Case Study III* is conducted. In this case study simulations are done for three production units. Again, like in *Case Study II* the model is modified just by turning off two out of five units. The capital investment, the number of production units, and the production capacities are the only data that changed. The production costs of producing units are the same as in *Case Study II* .

The results for *Case Study III* are summarized in graphs and in tables, like in the preceding two case studies. Numerical values of these graphs are presented in **Table 2.24** and **Table 2.25**. For cement plant with 3 production lines the results are also presented in **Figure 2.5** and **Figure 2.6**.

Figure 2.5 shows the production of each producing unit. The first producing unit, called “cem1.L”, should work with its maximum capacity, equal to 825,000 tons each year during the first four years. Then. it is decreasing until the end of the projected period, and eventually decreases to 97,718.82 tons in 2020. After the sensitivity analysis, the demand is increased, and, therefore, this unit operates with its maximum capacity for the first three years, and, then, decreases its production until the end of the projected period.

The second producing unit, called “cem2.L”, starts with about half of its maximum capacity. Then its production should decrease in 2011 and in 2012. After this decrease it should increase in 2013 to 572,685.8 tons. In 2014, it should continue to work with its maximum capacity. After the sensitivity analysis, the production schedule for this unit is changed to 606,905 tons for the first year, and, then, there is a small decrease. Starting from 2012 it will operate with its maximum capacity.

According to the analysis, the producing unit, called “cem5.L”, will be required to work with its maximum production capacity during the projected period of time. It will experience a one time decrease in production in 2013 equal to 742,302.2 tons. The sensitivity analysis moved the decrease to 2012, making the unit to produce 612,530.2 tons for that particular year.

The numbers in **Table 2.24** show that from 2015 the gap between demand and production of cement should be satisfied by imported cement. **Figure 2.5** shows that the increase in import is not linear but steady. After the sensitivity analysis, the need for cement import has also changed. Both the investment and the time are changed, which are presented in **Table 2.25** and **Figure 2.6**.

The storage capacity for this case study is again selected to be 60,000 tons. **Table 2.24** shows that the need for storage starts in 2013. But after 2014 there is no need for storage. The results of the sensitivity analysis show that the optimal solution requires having storage also from 2012 to 2013.

The results are different before and after the sensitivity analysis not only for each production unit, but also for the total production. The data for the total production before and after the sensitivity analysis are also presented in **Table**

2.26 and **Table 2.27**. The results of the sensitivity analysis show that all production units in *Case Study III* are extremely sensitive.

Unit production costs in today's dollar value can be found in the Appendix F, and, again, the norm considering the time factor is assumed to be equal to 0.012, which represents a discount rate of 1.2%. In *Case Study III* the LCC is $1,920,062,000, which again represents the investment plus operation and maintenance costs for the projected period of time. This number is the LCC of the hypothetical plant before the sensitivity analysis. After the sensitivity analysis the LCC is $2,008,694,000.

Table 2.24
Case Study III Results before Sensitivity Analysis

Case Study III	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
cem1.L	825,000	825,000	825,000	825,000	351,137.6	196,962.4	197,341.2	200,832.9	129,169.4	131,617.6	97,718.82
cem2.L	499,433	471,797	455,338	572,685.8	825,000	825,000	825,000	825,000	825,000	825,000	825,000
cem5.L	825,000	825,000	825,000	742,302.2	825,000	825,000	825,000	825,000	825,000	825,000	825,000
store.				60,000	20,178.65						
impcem.						148,336	240,146.8	275,570.1	321,811.6	351,309.4	378,789.2

Table 2.25
Case Study III Results after Sensitivity Analysis

Case Study III	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
sens-cem1.L	825,000	825,000	825,000	505,316.5	351,137.6	196,962.4	197,341.2	200,832.9	129,169.4	131,617.6	97,718.82
sens-cem2.L	606,905	577,887	825,000	825,000	825,000	825,000	825,000	825,000	825,000	825,000	825,000
sens-cem5.L	825,000	825,000	612,530.2	825,000	825,000	825,000	825,000	825,000	825,000	825,000	825,000
sens-store.			519,25.18	232,54.65							
sens-impcem.					118,614.7	269,288.6	344,521.8	381,891.1	426,860.6	457,955.4	485,115.2

Table 2.26
Case Study III Total Production before Sensitivity Analysis

Case Study III	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
Total prod.	2,149,433	2,121,797	2,105,338	2,139,988	2,001,138	1,846,962	1,847,341	1,850,833	1,779,169	1,781,618	1,747,719

Table 2.27
Case Study III Total Production after Sensitivity Analysis

Case Study III	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
sens-total prod.	2,256,905	2,227,887	2,262,530	2,155,316	2,001,138	1,846,962	1,847,341	1,850,833	1,779,169	1,781,618	1,747,719

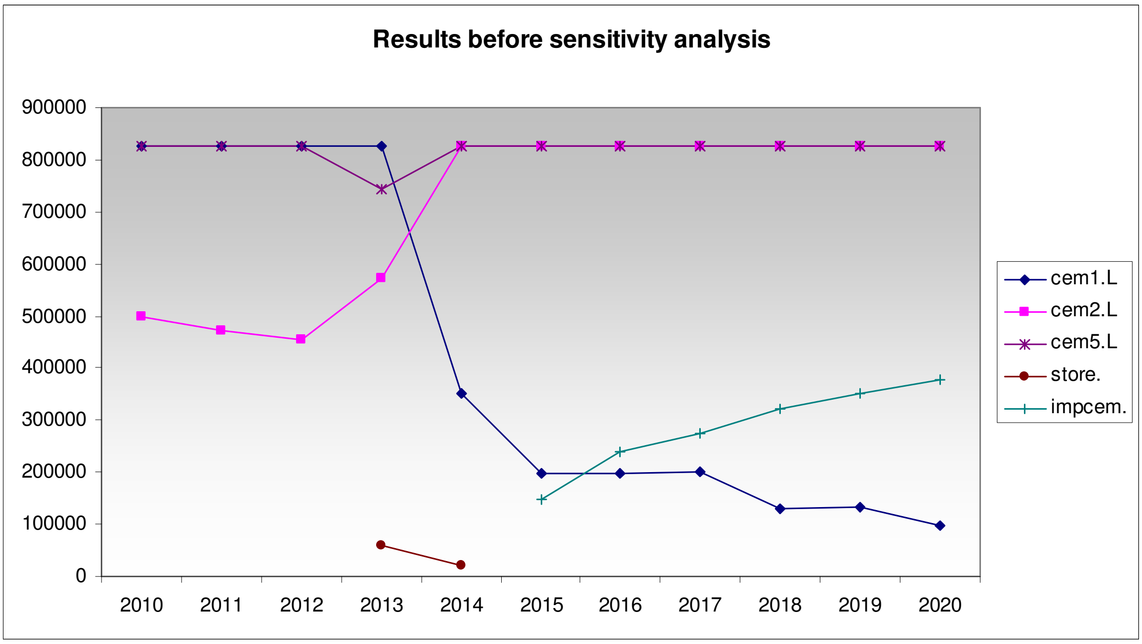


Figure 2.5 Production of Producing Units before Sensitivity Analysis (Case Study III)

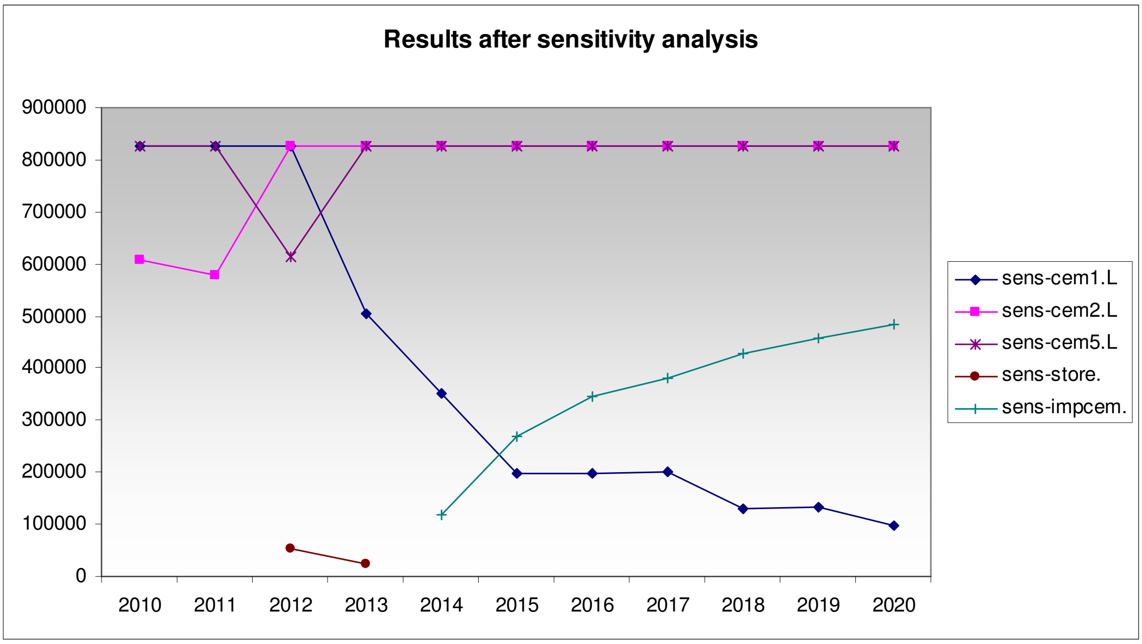


Figure 2.6 Production of Producing Units after Sensitivity Analysis (Case Study III)

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made based on the results of this research:

1. Formulation of the optimal strategy for the cement production industry helps to estimate specific industrial development policy programs and the projected investments in the cement industry. The uncertainty of forecasts, the infrastructure and geography of each country, make the selection of the optimal cement production plan more complex. The optimal development strategy of the cement industry will serve as a foundation for finding the optimal production plan in any cement producing plant.

   There are two risks associated with the optimal cement production strategy:

   - Underestimation of existing production capacities, which can lead to a long-term deficit. If the shortage continues for a long time, the cement producing plant will not be able to satisfy demand, being forced to import cement from other producers at relatively higher prices. This will reduce the firm profits and can negatively affect its reputation, making the firm less competitive in the market.
   - Overestimation of cement producing capacities, which can result in improper distribution or misuse of investment funds.

   The nature of this dual risk is asymmetric. The reputation of the firm damaged by underestimation can not be re-established in a short-term, leading to reduced competitiveness in the market. In contrast to the effects of underestimation, the impact of overestimation will be limited and easier to deal with using appropriate preventive regulations. To reduce the uncertainty and to maintain the risk at a reasonable level, the dynamics of factors, which negatively affect the forecasted demand for cement, should be carefully analyzed. The average and long-term development scenarios of the cement industry need to be checked annually either to confirm the initial production plan, or to make changes in investment projects.
2. It is suggested to use linear programming for such decision making problems, and verify the results through sensitivity analysis.
3. In this research three case studies were investigated. The output of developed economic-mathematical model is providing solution report, which includes detailed output for each producing unit.
4. In *Case Study I* the analysis shows that the LCC of the hypothetical plant before the sensitivity analysis is $1,926,334,906. After the sensitivity analysis the LCC is $2,014,992,896. The difference of these costs is 4.602% of $1,926,334,906, which resulted from 5% increase in demand.
5. In *Case Study II* the LCC is $1,923,364,931, which represents the investment plus operation and maintenance costs for the projected period of time. This number is the LCC of the hypothetical plant before the sensitivity analysis. The LCC after the sensitivity analysis is $2,011,931,949. As in *Case Study I,* in this case also the increase in LCC exists. This increase is close to 4.604% of $1,923,364,931.

6. In *Case Study III* the LCC of the hypothetical plant is $1,920,062,000 before the sensitivity analysis, which again represents the investment plus operation and maintenance costs for the projected period of time. After the sensitivity analysis the LCC is $2,008,694,000. The difference between LCC is 4.616% of $1,920,062,000.
7. The comparison of the results shows that savings from selecting *Case Study II* instead of *Case Study I,* to satisfy the same demand of the market, are equal to $2,969,975 for the projected period of time. After the sensitivity analysis simulation, demand increases in all case studies, and the savings become much higher being equal to $3,060,947. Difference between savings is equal to $90,972. This result shows that it is much better to have production units of *Case Study II,* rather than production units of *Case Study I*. From the results of the sensitivity analysis it is clear that the choice of the production units of *Case Study II* over the production units of *Case Study I* brings more savings, equal to $90,972. Therefore, it is preferable to have demand increase not only from the point of view of producing more and having more profits, but also having more savings from the correct choice of combination of production units.
8. After comparing the resuls of *Case Study II* and *Case Study III,* the savings are $3,302,931, and $3,237,949 after the sensitivity analysis. In this case the increase in demand is less preferable, since the amount of savings of $3,302,931 is larger than $3,237,949 by $64,982. Thus, it is recommended to choose the production units of *Case Study III* over the production units of *Case Study II,* if there is no increase in demand. This will save $64,982 compared to the increasing demand scenario.
9. If we compare the results of *Case Study I* and *Case Study III*, we can see that savings are $6,272,906, and after the sensitivity analysis those become $6,298,896. In this case, if demand increases the savings will also increase by $25,990. Therefore, the choice of the production units of *Case Study III* over the production units of *Case Study I* brings more savings.
10. The comparison of all the results reveals that the most saving occur if the production units of *Case Study III* are selected over the production units of *Case Study I,* being equal to $6,298,896.
11. The developed economic-mathematical model is a good decision making tool. The model can be used also by the members of the cement industry involved in policy making. By using the model, they will have a better understanding of how the proposed emission or resource limitations will affect their plants.
12. The model is also a good decision making tool for storage issues, since its output gives the time and duration of the required storage.

For future research it is recommended to develop a model that will be able to account also for energy and material balances in the LCC analysis of the cement production.

REFERENCES

Andrews, O. & Slater, A. (2002). Energy Utilities Tackle Sustainability Reporting. *Corporate Environmental Strategy*, *9*(1), 86-94.

Arikan, M. (2004). Feasibility analysis of manufacturing high performance—ecological—cement in Turkey. *Building and Environment*, *39*(9), 1125-1130.

Avetisyan, H. G. (2008). *Sustainable Design and Operation of the Cement Industry,* Master's Thesis. USA, Ohio: Ohio University.

Basu, A. J. & Dirk, J. (2006). Industrial ecology framework for achieving cleaner production in the mining and minerals industry. *Journal of Cleaner Production*, *14*(2), 299-304.

Canadian Precast/Prestressed Concrete Institute. (2007). *Facts about Cement Manufacturing.* Retrieved Apr. 20, 2008, from http://www.cpci.ca/?sc=sustainability&pn=cement

Cement Association of Canada. (2008). *Canadian Cement Industry Sustainability Report 2008.* Retrieved Feb. 25, 2008, from http://www.cement.ca/cement.nsf/eee 9ec7bbd630126852566c40052107b/cda31926e3e601228525740b006f526b/$FILE/Canadian%20Cement%20Industry%202008%20Sustainability%20Report.pdf

Cement Distribution Consultants. (2008). *Cement import operation: Operational costs versus investment payback period and R.O.I.* Retrieved May 3, 2008, from http://www.cementdistribution.com/table/build_your_own_import_terminal_table_1.html

Energy Information Administration. (2008). *U.S. Carbon Dioxide Emissions from Energy Sources 2007 Flash Estimate.* Retrieved May 27, 2009, from http://www.eia.doe.gov/oiaf/1605/flash/flash.html

Environmental Protection Agency. (1994). *Portland Cement Manufacturing Final Report, Emission Factor Documentation for AP-42 Section 11.6.* Retrieved June 3, 2008 , from http://www.epa.gov/ttn/chief/ap42/ch11/bgdocs/b11s06.pdf

Environmental Protection Agency. (2005). *Portland Cement Manufacturing Final Report, Emission Factor Documentation for AP-42 Section 11.6.* Retrieved June 3, 2008 , from http://www.epa.gov/ttn/chief/ap42/ch11/final/c11s06.pdf

Environmental Protection Agency. (2008). *Approval and Promulgation of Implementation Plans; Texas; Control of Emission of Oxides of Nitrogen From Cement Kilns.* Retrieved June 1, 2008, from http://www.epa.gov/EPA-AIR/2003/July/Day-30/a19279.htm

Environmental Protection Agency. (2008). *Environmental Protection Agency Environmental Performance of Building Guidelines.* Retrieved Feb. 25, 2008, from http://www.noaanews.noaa.gov/stories/s1119.htm

Geisinger, E. (2005). *Cement Sustainability Initiative.* Retrieved Feb. 25, 2008, from http://www.wbcsdcement.org/climate.asp

Global Reporting Initiative (GRI). (2008). *G3 Sustainability Reporting Guidelines.* Retrieved Apr. 4, 2008, from http://www.csrwire.com/News/11486.html

Klee, H. (2008). *The $4 Million Report From the Cement Industry That Says: Toxic Sludge is Good for You!* Retrieved Apr. 4, 2008, from http:// www.cementkiln.com/DARThe4MillionReportFromTheCementIndustry.htm

KPMG and UNEP. (2006). Carrots and Sticks for Starters: Current Trends and Approaches Involuntary and Mandatory Standards for Sustainability Reporting. Retrieved Apr. 4, 2008, from http://www.uneptie.org/outreach/reporting/ docs/Public-UNEP-KPMG-Report-FIN.pdf

Portland Cement Association. (2006). *Comments on the Final Report "Assessment of NOx Emissions Reduction Strategies for Cement Kilns – Ellis County".* Retrieved June 1, 2008, from http://www.tceq.state.tx.us/assets/public/implementation /air/sip/agreements/BSA/PCA_Comments-Final_Cement_Kiln_Report.PDF

Portland Cement Association. (2006). *Economics of the U.S. Cement Industry.* Retrieved Apr. 20, 2008, from http://www.cement.org/econ/industry.asp

Portland Cement Association. (2007). *PCA Annual Yearbook 2007.* Retrieved May 11, 2008, from http://www.cement.org/econ/pdf/2007YrBk.pdf

Portland Cement Association. (2008). *Cement Plants Take Steps to Go Green.* Retrieved Apr. 20, 2008, from http://www.cement.org/buildings/sustainable_cement.asp

Portland Cement Association. (2008). *Green in Practice 101 - LEED 2.2 Credits with Concrete.* Retrieved Apr. 22, 2008, from http://www.concretethinker.com/papers.aspx?docid=314

South Coast Air Quality Management District. (1986). *RULE 1112 - Emissions of Oxides of Nitrogen from Cement Kilns.* Retrieved June 1, 2008, from http://www.arb.ca.gov/DRDB/SC/CURHTML/R1112.HTM

South Coast Air Quality Management District. (1986). *RULE 1112.1 - Emissions of Particulate Matter from Cement Kilns.* Retrieved June 1, 2008, from http://www.arb.ca.gov/DRDB/SC/CURHTML/R1112-1.HTM

The Chartered Institute of Building (CIOB). (2004). *Sustainability and Construction.* Retrieved Feb. 20, 2008, from http://www.ciob.org.uk/filegrab/ sustainability%20.pdf?ref=74

The Environmental Quality Board. (2008). *Control of NOx Emissions from Cement Kilns.* Retrieved June 1, 2008, from http://www.pabulletin.com /secure/data/vol38/38-16/730.html

U.S. EPA, Office of Solid Waste, (2006). *Report to Congress on Cement Kiln Dust: Cement Industry Overview.* USA: Environmental Protection Agency.

van Oss, H. G. (2006). Cement. In. USGS (Ed.), *Mineral Commodity Summaries* (p. 44-45). Reston, VA: U.S. Geological Survey.

World Business Council for Sustainable Development. (2002). *Cement Industry.* Retrieved Feb. 27, 2008, from http://www.uneptie.org/Outreach /wssd/docs/further_resources/related_initiatives/WBCSD/WBCSD-cement.pdf

World Business Council for Sustainable Development. (2002). *The Cement Sustainability Initiative Executive Summary.* Retrieved Apr. 22, 2008, from http://www.wbcsdcement.org/pdf/agenda_summary.pdf%20

World Business Council for Sustainable Development. (2002). *Industrial Ecology in the Cement Industry.* Retrieved Apr. 20, 2008, from http://www.wbcsd.org/DocRoot/Q9STRLkJliURVchtjiuF/final_report9.pdf

World Business Council for Sustainable Development. (2004). *Pollution Prevention and Abatement for Cement Industry.* Retrieved June 1, 2008, from http://www.wbcsd.org/web/projects/cement/tf4/PPACI.pdf

Worrell, E., Martin, N., & Hendriks, C. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment*, *26*(8), 303-329.