Environmental improvement of operating supply chains:

a multi-objective approach for the cement industry

Dissertation submitted in partial fulfillment of the Ph.D. examination

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Ellos están interesados en lo mejor: aprender, enseñar, compartir y hacer crecer el conocimiento. Celebraría la existencia de uno, que sean seis resulta excepcional.

Para todos, mi enorme gratitud. Más linda que la satisfacción por los resultados, es la gratitud. Quedo con el gran gusto de lo aprendido, pero aún mayor es la alegría de reconocer cada vez, que el mundo produce gente capaz de cosas tan valiosas como el trabajo solidario para el crecimiento colectivo.
Abstract

Nowadays companies worldwide face a growing pressure to reduce the environmental impact of their manufacturing activities. However, the strategies used to achieve this goal are not clearly defined because of their conflicting relations with financial outcomes. In parallel, globalization trends imply that as companies grow, usually through mergers and acquisitions, their supply chains become more complex. The environmental improvement of these supply chains imply not only technical retrofit decisions aiming at adopting cleaner production technologies but also decisions regarding the structure of the supply chain itself. Making these decisions becomes a difficult task because of the large number of variables involved, and the diversity of the interactions among them. To tackle this problem, this research aims at providing a multi-objective solution approach for making technological retrofit decisions within an operating supply chain, so that both environmental and financial goals are best met. The proposed solution approach is applied to the case of an operating cement supply chain in Colombia. Several computational experiments were conducted, obtained results demonstrates that the proposed model is an effective tool for multi-objective improvement decisions making, towards a more sustainable production process.

Keywords: Sustainable supply chain management, technological updating decision making, enterprise wide optimization, multi-objective optimization, mixed integer linear programming.
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Chapter 1

Introduction

1.1 Background and motivation

In 1991, Michael E. Colby presented a discussion paper for the World Bank [1], in which he identified 5 paradigms of environmental management of a production process, summarized in Figure 1.1. Those paradigms create a continuum, from the conception of nature, as an infinite supplier of physical resources that does not need to be managed, to the anti-growth, with the wilderness preservationism as its major goal. Within the primordial dichotomy between “frontier economics” and “deep ecology”, middle paradigms offer a progression that represents “integration of economic, ecological, and social systems into the definition of development and the organization of human societies” [1]. Moving to the right side of the graphic consists of adopting a wide range of possibilities of variable complexity: tendencies between 1970-90 concentrated efforts in the so-called “end of pipe” strategies, which means, control technologies designed to capture the emitted pollutants, mainly to protect human health [1 2 3]. After the decade of 1990, production environmental management theories migrated to prevention instead of correction [2 3 4]; implying the assessment and management of environmental impacts, the reduction of pollution, the energy efficiency improvement, and the use of renewable resources. After more than two decades of growing environmental
concern, where are current production systems located in this continuum? CO₂ emissions may be considered as a suitable indicator of anthropogenic environmental impacts. A global comparison between CO₂ emissions and economic growth between 1972 and 2010 is presented in Figure 1.2 adapted from [5]; detailed reading of author work’s shows a clear parallel trend in Asian emerging countries [5], while European economies evidence a very soft “de-carbonation” process. Data from the International Energy Agency (IEA) [6] describes the tendency from 2012-2014; IEA remarks that “CO₂ emissions stayed flat in 2014 despite an increase of around 3% in the global economy, remarking that it is the first time in the last 40 years that a halt or reduction in emissions has not been tied to an economic crisis” [6]. How much is the global economy still developing at expense of the environmental degradation? Environmental improvement of production systems requires new management systems but begins with simple strategies, some of which constitute the scope of this research work: (i) energy efficiency through technological updating, (ii) green supply chain management and (iii) use of cleaner fuels.

![Figure 1.1: Evolution of paradigms in environmental management and development](image-url)
Statistics related to energy efficiency of production processes clearly show that there are very important improvements that should be undertaken. The first priority should be wider dissemination of current best practices [7]. Some detected necessities related to strategic production processes are published by the International Energy Agency. Based on [8, 7, 9, 10], Table 1.1 describes the potential reduction in global energy use for some important industrial sectors, and its equivalent percentage, considering the total energy consumption of each one.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Potential energy use reduction (EJ)</th>
<th>Percent reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals</td>
<td>5.2</td>
<td>15</td>
</tr>
<tr>
<td>Iron and Steel</td>
<td>4.7</td>
<td>20</td>
</tr>
<tr>
<td>Cement</td>
<td>2.5</td>
<td>30</td>
</tr>
<tr>
<td>Pulp and paper</td>
<td>1.4 – 2.4</td>
<td>not available</td>
</tr>
<tr>
<td>Glass</td>
<td>0.6</td>
<td>35-40</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.4</td>
<td>13</td>
</tr>
<tr>
<td>Petrochemical</td>
<td>not available</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1.1: Energy reduction potential in common materials production process
Having recognized the importance of technological updating, the concept of supply chain management (SCM) leads to introduce another improvement opportunity. SCM includes not only manufacturing processes, but also material sourcing, production allocation, delivery of the final product to the customers as well as end-of-life management of the product after its useful life [11]. It is not possible to have a global approximation on how much environmental damage could be saved through optimal SCM, but the improvement opportunities are clearly recognized, and proof of this is the wide academic production in the area of green supply chain management (GrSCM), as it is illustrated in Chapter 2. The idea of multiple connected decisions in production processes is also presented in [12]; under the concept of “enterprise wide optimization” (EWO), authors argue that optimization tools and computational advances have allowed to expand the boundaries of the production process analyses, making it possible to model decisions that simultaneously involve plant and network levels. Concurrent optimal production allocation and network design is also considered in [13, 14], these authors propose to benefit from regional environmental advantages for optimal production allocation. In [14], it is remarked the need to take into account the risk associated with increased transportation distances resulting from production allocation decision.

Cleaner fuel or energy sources selection constitutes the latter important aspect in short term environmental damage reduction from a supply chain perspective. \( CO_2, \ NO_X, \ SO_x, \) and particulate matter (PM) can be highly reduced by just switching from fossil energy sources to cleaner sources. However, selection of fuels or electrical energy sources is a difficult task highly dependent on local costs and availability.

At this point, it has been identified the improvement opportunities through technological updating, energy source selection and simultaneous supply chain optimization; a final idea considers the need of recognizing the financial implication of the decisions related to those subjects. The known question of “does it pay to be green?” [15] becomes highly relevant. The goal of achieving better environmental conditions has technical, legal, social and market pressures [16]; however, all of these drivers depend on the financial feasibility. Actually, some authors have coined the term “Best Available Technique Not Entailing Excessive Cost” -BATNEEC- [17, 18], in order to clarify the
need to ensure the economic viability of environmental solutions. After a complete review of 100 randomly selected refereed journal articles on SCM, authors in [19] concluded that against sustainability principles, theories related to transaction cost and competitive advantage dominate supply chain management tendencies. It means that, under the current economic principles, financial variables must be present in environmental management decisions of the firms; in other words, the use of “the most effective and advanced current stage in the development of technologies, activities and methods of operation, to reduce emissions and the impact on the environment”, namely best available technologies -BAT- [20] or best environmental practices -BEP- [21], has to ensure the firms profitability.

Considering arguments in [22], prevailing sustainable management efforts are equivalent to a planning process for achieving less unsustainable operations; “creating sustainable chains will likely require changes in both, practices and supply chain business models” [22]. Next steps to the right hand side of Figure 1.1 could be related to the development of new products or technologies that avoid natural resource depletion and undesirable outputs. Next ones should consider a rigorous consideration of the real limits to the consumption, recognizing the boundaries of the planetary system. Beneath this frame, the following management proposal seems to be a very short but necessary step in the sustainability route.

1.2 Problem description and methodological approach

Shifting the previously described situation to a particular case study, this research aims at offering a methodological approach to make environmental improvement decisions, in the context of (i) technological updating, (ii) raw materials and fuel selection, (iii) network design, and its (iv) environmental and financial implications. To illustrate the capabilities of this proposal, the methodological approach was applied to the cement industry, responsible for 5 to 7% of global \( \text{CO}_2 \) emissions. Decision making process requires information related to possible technology updating options for each production process at each facility, and for each option, its energy efficiency,
related emissions, costs and operating conditions. In relation to the supply chain network, it is necessary to know the magnitude and location of the demand, raw materials and fuel availability, and, for every case, transportation costs and emissions. The amount of possible scenarios resulting of such number of variables, means that the use of mathematical and computational tools becomes imperative.

As will be described in Section 2, mathematical programming has been widely used for supply chain management. These problems can be naturally modeled using mixed-integer formulations in which continuous variables denote mass flow rates, capacities and economic flows, while binary variables represent decisions on whether to operate an equipment, to select a given technology or/and expand it in capacity or not. Additionally, the need for simultaneous evaluation of environmental and financial subjects has been widely recognized from the point of view of the supply chain management. In response, multi-objective optimization has emerged as a useful and commonly used technique for modeling problems involving sustainability issues.

Previous considerations justify the use of multi-objective mathematical formulations as a decision making tool to improve environmental performance of a supply chain, ensuring firms financial sustainability. For the case study, the technical and financial information used, is based on several environmental road-maps for the cement industry that identify energy efficiency in the production process and the reduction of emissions during the combustion process at the kiln as the key strategies for environmental improvement in this sector [10, 23, 24, 25, 26, 27, 28].

Why do current supply chains operate under obsolete or inefficient conditions? This question is highly relevant and its answers are related to the lack of tools that allow the firms to make better informed decisions with respect to environmental benefits and related costs. In [27], the authors argue that, in spite of more efficient production technologies availability, obsolete facilities are still operating due to the lack of knowledge about technological options and uncertainty about its effects and plant-specific operating implications. Authors also suggest that although some energy-efficient technologies have short payback periods, the high initial capital cost of the project often deters its adoption and installation. Using mathematical programming tools, it is proposed a decision
model that allows to find optimal improvement strategies, providing the decision maker with the relevant information related to technological and supply chain operating conditions and describing its corresponding emissions levels and cost (or savings). Under this consideration, the main focus of this research work is summarized as follows:

- Identify environmental improvement opportunities related to technological updating.
- Simultaneously model a wide set of improvement strategies in relation to production process, fuel and raw materials supply and customer service network design.
- Recognize the global effect of plant level decisions.
- Obtain a set of efficient solutions that describes both, environmental and financial implications.
- Apply the proposed methodological approach to the case of a cement supply chain, a highly pollutant industry, that could reduce its global warming potential (GWP) emissions by 20% and obtain even higher reductions in other pollutant emissions.

1.3 Interdisciplinary approach and local significance

Environmental management is a typical interdisciplinary area; the nature of environmental problems involve a wide variety of knowledge areas from natural to social sciences, economy, statistics, engineering, etc. As will be illustrated in Section 2, operations research (OR) tools have been widely used for environmental management decision making. In spite of the development of OR in Colombia, its application to environmental management is narrow, while its potential application is wide. In the particular case of production process management, and more detailed, as a tool for technological upgrading decisions, this proposal has a very high local pertinence. Cleaner production is a global imperative but it is even more urgent in developing countries, where very obsolete production processes are still operating, while market demands are growing rapidly.
The Research Group in Production and Logistics Management, has been working since 2001 in the solution of problems related to inventory management, scheduling, routing problems, etc. This doctoral work is the first which involves environmental variables in the improvement strategy for a production process. Through its advance, the group has recognized the relevance of adopting an integral view in the solution of production problems, incorporating environmental variables. This research work have reaffirmed the importance of the interdisciplinary work; the qualification of environmental management decisions obtained through the use of mathematical decisions tools is an evident result of this work.

1.4 Dissertation outline

The remainder of this document is organized as follows. The literature around how multi-objective optimization methods have been used to address problems in the area of green supply chain is summarized in Chapter 2. In Chapter 3 the most relevant technical and environmental aspects of the cement production process are described. Chapter 4 presents a multi-objective mixed integer linear formulation proposed to address the problem of selecting the best set of technical projects to improve the environmental performance of a cement supply chain, considering as well production location and distribution strategies (i.e. supply chain design). Results are presented in Chapter 5 for a test instance. Finally, Chapter 6 summarizes the results of the case study and its extended implications in firm’s environmental management and public policy design. The information used to build the test instances and detailed results for each computational experiment are included as annexes.
Chapter 2

Literature review

In 1992, Talcot - cited by [2] [4], described the opportunity that environmental management could find in the operations research area. The author recognized that similar to its financial counterpart, natural resources are also limited and their use demands a rigorous planning process. The tools used to make economic efficient decisions should also be used for environmental management. The complexity of many environmental problems, in relation to supply chains, implies that it is almost impossible to make decisions based on intuition and requires the use of such formal tools [4].

Operations research makes use of mathematical models to represent problems that involve environmental and economic subjects [29]. The generic trade-off between environment and economy finds in the classic Pareto set of multi-objective optimization problems a suitable representation that facilitates its analysis. Increasing environmental quality may imply a higher financial cost, and vice versa. Operations research tools offer a quantitative approach to measure and understand such trade-off [30] [31]. The impact of decision making, whether at the strategic, tactical or operational levels, needs due consideration with respect to balanced, or multi-objective, performance metrics that take environmental issues into account, in addition to classical questions regarding supply chain management [32].

These reasons explain why, after the decade starting in 1970, and even frequently after 1990,
operations research has been a widely used tool for environmental management. “Whenever the problem to be solved consists of choosing the best from among a well-defined set of alternatives, optimization should be considered. If the meaning of best is also well-defined and if the system to be optimized is relatively static and free of feedback, optimization may well be the best technique to use” (Sterman, 1991 cited in [4]).

The academic literature offers a wide application set of operations research tools to solve environmental management problems, such as reverse logistics [33], green logistics [18, 34], budget allocation [35], facility and infrastructure location [36] and air quality improvement [37], among others. In [38] it is presented a literature review of 160 peer-reviewed papers in decision theory for sustainable supply chain management -SSCM-, finding that around 60% of the papers come from the operational research area. Other reviews found in [39, 40, 41, 42, 43] also evidence the very common and successful use of mathematical programming tools for SSCM. Among these previous works, special attention was devoted to those that present multi-objective structures to fulfill environmental and financial goals in supply chain design or operation.

It is possible to create a taxonomy of works based on multi-objective formulations, specifically in reference to the planet vs profit context, considering the level of detail in the modeling exercise and the scope of the analysis. According to the former, mathematical models can optimize decisions at the (i) process, (ii) network, and (iii) system level. At the process level, the goal is to improve the environmental performance of a manufacturing process by optimizing technology upgrading projects, production capacities and fuels. At the network level, the aim is to establish the optimal supply chain network configuration; whereas at the system level, both types of decisions (i.e. process and network) are tackled simultaneously. Enterprise Wide Optimization (EWO) [12], for instance, deals with type (iii) problems. According to the scope of the analysis, works dealing with either a (i) grassroots design or (ii) a retrofit, are presented. Type (i) works design new supply chains yet to established, whereas type (ii) consider the costs and emissions related to any possible change with respect to the current state of the system. Tables 2.1, 2.2 and 2.3 present the most relevant works identified at each level, from 1995 to the present. The revision allows to remark key elements

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to address the mathematical formulation of multi-objective models for SSCM: the mathematical treatment of environmental objective functions, the correlation between financial and environmental objectives, the dynamic or static nature of the model and the uncertainty and the methodological approach to face multi-objective formulation. All those subjects will be described in the following subsections.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Scope</th>
<th>Financial Goal</th>
<th>Environmental Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing process design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ashraf et al., 2008 [44]</td>
<td>Energy source selection</td>
<td>Cost</td>
<td>Total weight of NOx, HC, CO, and PM</td>
</tr>
<tr>
<td>Azapagic et al., 1999 [17]</td>
<td>Production design</td>
<td>Cost</td>
<td>LCA global indicator</td>
</tr>
<tr>
<td>Brunet et al., 2012 [45]</td>
<td>Production design</td>
<td>Economic performance</td>
<td>Three damage categories of LCA, selected by PCA methods</td>
</tr>
<tr>
<td>Gebreslassie et al., 2009 [3]</td>
<td>Operational parameters for a cooling system</td>
<td>Cost</td>
<td>LCA global indicator</td>
</tr>
<tr>
<td>Javidan et al., 2012 [46]</td>
<td>Power dispatch design</td>
<td>Cost</td>
<td>Fuel cost, power lost and pollutant emissions</td>
</tr>
<tr>
<td>Jia et al., 2006 [47]</td>
<td>Operating parameters of a chemical reactor</td>
<td>Cost</td>
<td>Environmental performance</td>
</tr>
<tr>
<td>Wu and Chang, 2004 [48]</td>
<td>Production planning</td>
<td>Cost</td>
<td>Environmental costs</td>
</tr>
<tr>
<td>Hu et al., 2006 [49]</td>
<td>Ethanol–gasoline blend design</td>
<td>Cost</td>
<td>Cost of net energy</td>
</tr>
<tr>
<td>Wang et al., 2007 [50]</td>
<td>Technology selection, operation conditions, equipment size</td>
<td>Net present value</td>
<td>GWP emissions or LCA global indicator</td>
</tr>
<tr>
<td>Manufacturing process improvement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Madaloni, 2015 [51]</td>
<td>Technology selection, operation conditions, equipment size</td>
<td>Profit</td>
<td>Carbon emissions</td>
</tr>
<tr>
<td>Ogbeide, 2010 [52]</td>
<td>Technology and fuel selection</td>
<td>Costs</td>
<td>Carbon emissions</td>
</tr>
</tbody>
</table>

Table 2.1: Process level optimization
<table>
<thead>
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<th>Authors</th>
<th>Scope</th>
<th>Financial Goal</th>
<th>Environmental Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absi et al., 2013 [53]</td>
<td>Lot sizing problem</td>
<td>Cost</td>
<td>Carbon emissions</td>
</tr>
<tr>
<td>Fahimnia et al., 2015 [54]</td>
<td>Tactical planning</td>
<td>Cost</td>
<td>Carbon emissions, energy consumption, and waste generation</td>
</tr>
<tr>
<td>Network improvement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramudhin et al, 2010 [55]</td>
<td>Logistic network, distribution strategies</td>
<td>Cost</td>
<td>Carbon emissions</td>
</tr>
<tr>
<td>Wang et al., 2011 [59]</td>
<td>Production allocation</td>
<td>Cost</td>
<td>Costs of environmental improvement investments</td>
</tr>
<tr>
<td>Zhang et al., 2014 [61]</td>
<td>Suppliers selection, production allocation, materials flows</td>
<td>Cost</td>
<td>Carbon emissions and a third goal namely lead time</td>
</tr>
<tr>
<td>Ubeda et al., 2011 [64]</td>
<td>Routing problem</td>
<td>Cost</td>
<td>Carbon emissions</td>
</tr>
</tbody>
</table>

Table 2.2: Network level optimization

<table>
<thead>
<tr>
<th>Authors</th>
<th>Scope</th>
<th>Financial Goal</th>
<th>Environmental Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bojarski et al., 2009 [58]</td>
<td>Production allocation, supplier selection, technology selection, materials flows</td>
<td>Net present value</td>
<td>Carbon emissions</td>
</tr>
<tr>
<td>Khorsand and Heydari, 2010 [60]</td>
<td>Production allocation, power sources selection, production design</td>
<td>Cost</td>
<td>Carbon emissions, energy consumption, and waste generation</td>
</tr>
<tr>
<td>Pinto-Varela et al., 2012 [60]</td>
<td>Production allocation, supplier selection, technology selection, materials flows</td>
<td>Profit</td>
<td>LCA global indicator</td>
</tr>
<tr>
<td>Miret et al., 2015 [61]</td>
<td>Logistic network, distribution strategies</td>
<td>Cost</td>
<td>Carbon emissions</td>
</tr>
</tbody>
</table>

Table 2.3: Enterprise wide optimization
2.1 Environmental objective function

Financial variables describing the economic performance of the supply chain can be easily handled (i.e. cost or net present value), as they can be directly expressed in algebraic terms as a single objective function in the mathematical model. In contrast, the environmental performance requires modeling a wide variety of physico-chemical phenomena with different units, magnitudes, improvement strategies and occasionally opposite behaviors.

Authors in [39, 41, 42] identify many possible ways to address environmental subjects in decision making tools: life cycle assessment (LCA), reasoning maps, analytic hierarchy process (AHP), analytic network process (ANP), data envelopment analysis (DEA), equilibrium models, simulation, etc. LCA is the most commonly used technique [42]. LCA indicators and their impact categories are very frequently used in the formulation of mathematical optimization models, as it provides a method for assessing different environmental impacts such as air pollution, water eutrophication, global warming potential, human toxicity, resource depletion, etc., and to transform direct measures related to each category into a single aggregate environmental damage indicator. This aggregated environmental impact can be directly used as a single objective function in an optimization problem.

Based on [65], Figure 2.1 describes LCA assessment methodology, starting from a detailed inventory of inputs (used resources and energy) and outputs (emissions, effluents and waste generation) continuing with the evaluation of the magnitude and significance of the potential environmental impacts and finally, ending with normalization, weigh and sum of damages, to obtain a single impact indicator [65].

LCA methodology considers very wide boundaries over the supply chain. The complete assessment implies that environmental impacts are not only related to the production process but also to raw materials production, transportation process, energy generation, etc. Azapagic and Clift [17] particularly focuses on the application of LCA in process optimization and introduce a framework referred to as Optimum LCA Performance (OLCAP). Among the reviewed papers, authors in [53, 17, 45, 3, 62, 58, 60, 64], use LCA methodology to represent environmental goals as a single
objective function in the mathematical model.

Several authors recognize the limitations of employing such an aggregated metric and prefer to address each environmental impact separately, even if this leads to more complex models containing three, four or more objectives. Another strategy to simplify the calculations is to group environmental objectives so as to eliminate redundant metrics. In Oliva et al., Kosting et al., and Brunet et al., a comprehensive review of those objective reduction methodologies is presented, including principal component analysis, evolutionary algorithms, clustering techniques, and decomposition or reduction algorithms. These authors’ own approach relies on solving an optimization problem for finding the best clusters of objectives. In Jia et al., the environmental objective function is defined using the analytical hierarchy process, which allows grouping nine environmental impact categories into a single indicator.

Based on environmental economic principles, other authors translate the environmental damage
into financial costs taking into account the externalities [61]. In [61] Eco-cost represents the necessary costs that should be incurred in order to counteract the negative impact of the activity made on the capacity of Earth [61]. “It quantifies the impact in terms of pollution and material depletion by allocating a cost penalizing the use of an alternative that would reduce its impact on the environment, and would be called a sustainable solution” [61]. The total Eco-costs are computed as the sum of the following contributions: (i) depletion of natural resources, (ii) effect on ecosystems, (iii) effect on human health, and (iv) global warming (CO\textsubscript{2} and other greenhouse gases). Authors present a monetary value for CO\textsubscript{2}, SO\textsubscript{x}, PO\textsubscript{x}, caringenic substances, etc. A similar strategy is used in [48]. In spite of the common use of those assessment damage methods, it is widely recognized that every monetary valuation of environmental damage implies a large amount of assumptions that may lead to lose modeling rigour or assertiveness.

Finally, it is important to refer the case where CO\textsubscript{2} emissions are the unique environmental objective. Here, the carbon payment system allows to build only one financial objective as CO\textsubscript{2} emissions are directly transformed into cost. In opposition to the eco-cost methodology [61], those CO\textsubscript{2} emissions costs do not represent its externalities; carbon pricing is used as a public instrument to induce the firms to reduce their CO\textsubscript{2} emissions. The authors in [55] evaluate the impact of carbon taxes on supply chain configuration, while in [73, 74] it is described its effect in electricity production systems. In [56] different operating conditions in a steel production plant are selected considering its cost, emissions and carbon trading influence.

### 2.2 Environmental performance Vs. costs

There are classic discussions regarding the relationships between environmental and financial results from an operational point of view. The conflict known as “planet Vs. profit”, or “private Vs. common interests” [75] has been widely debated since the text “Green and Competitive: Ending the Stalemate”, [76, 77]; in this work, the authors formally argued that there is no trade-off between the environment and the economy: “Properly designed environmental standards can trigger innovations
That lower the total cost of a product or improve its value”. In that way, public benefits are not in conflict with private ones; instead, there is a common positive effect. That statement is well known as the Porter’s hypothesis and has been the subject of several research works. Even though an extensive body of literature stresses that environmental protection bears a cost, a parallel position has emerged showing that green measures can provide economic and social benefits [78]. In relation to this subject, King and Lenox [15] conclude that there is evidence of an association between lower pollution and higher financial valuation, but the firm’s fixed characteristics and strategic position might cause this association. These authors suggest that “when does it pay to be green?” may be the right question to ask. Hence, the resulting problem is not only to evaluate relationships between environmental and financial variables of a productive system, but else, to discover the strategies for better financial and environmental results. Additionally, it is important to be aware that while negative externalities have not been incorporated to firms balances, those trade-off will always be incomplete or imprecise. In other words, environmental investments always have unaccounted benefits related to negative avoided externalities.

Among the reviewed papers, only [34] reports a win-win situation in terms of economic vs environmental results, while most of the authors clearly obtain “planet Vs. profit” trade-offs [3, 17, 49, 50, 55, 60, 52, 79, 80, 46, 45, 66, 67, 61]. Opposite situation was found in the review published in [39], where 191 papers were analyzed, founding 124 win-win-situations and 72 trade-off’s (authors indicate that these categories are not mutually exclusive, so a paper can address both). The revision about this subject ratifies the importance of the modeling process so as to have a better understanding of each particular behaviour regarding each production system.

2.3 Multiple planning periods

In order to achieve a better representation of reality, it is important to take into account the dynamic nature of the decisions, but multi-period planning models are more complex in its mathematical formulation and its computational cost grows exponentially. Among previously enunciated
academic publications, multi-period mathematical formulations are found in [54, 53, 48, 64, 62, 79]. These dynamic formulations have various common implications: (i) the financial treatment of cost and cash flows requires to consider the change in the value of money over time. Some authors include depreciation costs [64] or salvage values [64, 62, 79, 63]. In the cases of [64, 62, 79], investment costs are considered and, in those models, are equally distributed among every planning period; (iii) new constraints are involved in the mathematical problem; in [62, 79] authors limit the number of changes in production conditions in each plant, along the planning period; (iv) with respect to emissions constraints, periodic, cumulative, global or rolling constraints could be proposed, as described in [53]; (v) models which consider the long or mid term decisions, have to find the strategy to address uncertainty, because “available data at the moment of strategic decisions making, are generally aggregated and lose accuracy as the time horizon recedes” [42].

2.4 Uncertainty

In [12], it is found a very complete synthesis of uncertainty treatment in SCM mathematical models. The author remarks that uncertainty is a critical issue in supply chain operations; “furthermore, it is complicated by the fact that the nature of the uncertainties can be quite different in the various levels of the decision making process (e.g., strategic planning vs. short term scheduling)”. Operational uncertainty is a common subject related to quality, inventory management and handling processing time; much less work has focused on uncertainty at the tactical level, for instance, production planning with uncertain demand [12].

Other kinds of uncertainty belong to the area of environmental management, and come from the environmental impact assessment. In [62], it is indicated that the Eco-indicator methodology is affected by three main sources of uncertainty: (i) the operational or data uncertainty, (ii) the fundamental or model uncertainties, and (iii) the uncertainty on the completeness on the model. “Whereas the second and third sources of uncertainty cannot be covered by standard statistical analysis, the first can be easily documented”. These authors assume that the emissions released
and resources consumed per-unit of reference follow normal distributions. The assumption makes it possible to perform an analytical integration of the probability function that characterizes the Eco-indicator [62]. The normal probability distribution is one of the most widely used statistical distributions in LCA and has been repeatedly applied in the LCA literature [62]. A similar statistical treatment is used by [81, 64].

Other approximations to the uncertainty problem in multi-objective supply chain optimization are proposed by [59], to achieve the scheduling horizon on 30 power generating system including wind turbines; the uncertainty related to demand variation, equipment failure and wind unpredictability is considered. In [48], authors use a mixed-integer linear problem for production planning process in the scenario of uncertainty in legal boundaries for pollutant production, in this case, uncertainty is modeled using grey programming techniques.

### 2.5 Methodological approach

Multi-objective mathematical programming -MMP- is a suitable tool to address sustainability problems. The latter achieved global significance in 1987 with the Brundtalnd report [82]. By this time, the concept contributed to create an idea of environmental degradation, population, production and consumption growth, and their consequences to the future. But in terms of enterprise management, a higher impact was due to “the triple bottom line”, a term coined in 1994, by John Elkington [83]. The author argued that companies should consider three different bottom lines (TBL): “people, planet and profit”. This idea aims to measure, manage and target not only the financial, but also the social and the environmental performance of a company. As an integral part of optimization activities, MMP has a tremendous practical importance since almost all real-world optimization problems are ideally suited to be modelled using multiple conflicting objectives [84]. Hence, multi-objective optimization has emerged as a useful and commonly used technique for modeling problems involving sustainability issues.

As stated by [85], “when optimization problems have a multi-objective structure, there is not a
unique optimal solution, in contrast, a solution that proves best by one criterion (i.e. one objective function) may rate among the poorest to another”. This particularity leads to the concept of non-dominated solutions: a non-dominated solution cannot be improved with respect to one objective without lowering its quality with respect to some other objective. Non-dominated solutions are also known as a Pareto-optimal solutions and form the so-called Pareto frontier. Thus, solving a multi-objective optimization problem means not to find a single solution; instead, depending upon the solution approach, a set of non-dominated solutions is to be found, and the larger this set, the better information for decision makers. Treating environmental aspects as additional objectives to be optimized rather than constraints permits identification of solutions where significant environmental savings can be attained at a marginal increase in the cost imposed on the system [45, 67].

The most common approach used to solve multi-objective optimization problems is the $\epsilon$ constraint method, proposed by Haimes et al. (1971) [86]. This solution method suggests reformulating the MMP by just keeping one of the objectives and restricting the others within user-specified values, named $\epsilon$ constraints. The solution to the resulting problem largely depends on the chosen $\epsilon$ values. Moreover, as the number of objectives increases, there exist more $\epsilon$ values. The weighted sum method allows to scale a set of objectives into a single objective by pre-multiplying each objective with a user-supplied weight. The values assigned as weights depend on the importance of each objective in the context of the problem and a scaling factor. The scaling effect can be avoided somewhat by normalizing the objective functions. After the objectives are normalized, a composite objective function can be formed [84]. The third generic multi-objective exact solution method is named goal programming. In this case, it is formulated a target for each objective function and a new single objective consists of minimizing the distances from the solution to the goal or target value of each objective [85].

Among multi-objective exact solution approaches found the reviewed literature, the $\epsilon$ constraint is -by far- the most used method, as it is found in [17, 64, 49, 52, 57, 45, 67, 3, 50, 79]; goal programming is used by [55, 61] while weighted sum is used in [56, 58, 87]. Heurisic and metheuristic solutions are proposed by [53, 88, 30, 34, 81, 46, 47, 59, 60, 54].
2.6 Technological updating decisions

Reviewed mathematical models for sustainable supply chain design address a wide variety of problems, from facility location, production planning, technology selection, transportation decisions, material recovery for recycling, capacity expansion, supplier selection to the definition of technical operation conditions, etc. (For further details, see Tables 2.1, 2.2, and 2.3.) Notwithstanding the very important environmental impact reduction potential, through technological updating of operating systems and despite the big amount of SCM multi-objective published models, very few works address the retrofit decision of operating processes. Among the reviewed papers, only [89, 62, 79, 63] consider technological updating as an option to environmental performance improvement, and are the closest to the problem under study in this research.

In [89] the authors present a review of research works addressing retrofit decisions, and propose a methodology for modeling process flowsheets and retrofit modifications using a multiperiod generalized disjunctive programming (GDP) model. The problem is later reformulated as a mixed-integer linear program (MILP) which allows to describe a network of processes within a single chemical plant. This case refers to a single production plant, the objective function includes profit from sales and capital costs and energy costs over the planning horizon. The authors begin by highlighting the necessity to recognize the current state of the system, the possible changes and the technical constraints with respect to the current conditions. From a practical point of view, the authors remark that “the formulation of detailed models for each part of the processes in a plant network is a cumbersome task involving the collection of many types of data. In fact, the data collection step alone may be too time-consuming to make process modeling worthwhile”.

In [62], an optimization strategy is presented for the environmentally conscious design of a chemical supply chain, that applies the concept of EWO and considers environmental and financial objective functions. Financial results are related to the purchases of raw materials, the operating and inventory costs associated with plants and warehouses and the cost of transporting materials between the supply chain entities. Cost investment is associated to the decisions regarding capacity
expansions in the plants. Environmental damage is accounted from the purchases of raw materials, the production rates at the manufacturing plants and the transportation flows. Those damages are described in terms of LCA categories. The decisions to be made include number, location, capacities and technologies of plants (i.e. strategic decisions) and production rates at the plants at each time period; material flows between plants, warehouses and markets, and sales of products (i.e. planning decisions). In [79] the authors present an extension of the proposed problem in [62], focusing on the treatment of uncertainty to describe environmental damage factors.

Ogbeide [52] presents an optimization model with the objective of minimizing the total cost to achieve a defined \( CO_2 \) emission level in a single operating cement plant. Strategies are related to fuel selection, adopting technologies to gain in operational efficiency and apply carbon sequestration techniques. Retrofit costs for switching from one fuel to another are also considered. The model selects the best strategy or mix of strategies in order to meet a certain \( CO_2 \) reduction target at the least cost, provided that the demand and other requirements are met.

2.7 Concluding remarks and contribution

Within the framework of sustainable supply chain management, this research belongs to the area of multi-objective optimization and simultaneously address plant and network level decisions, it means that also can be classified within the area of Enterprise Wide Optimization proposed by [12]. The most relevant characteristics of this work with respect to other works within this group, are the following:

- The proposed mathematical model focuses on technology-updating decisions for a manufacturing process. It considers the current technological state at each stage of the process. A set of technology-updating alternatives are defined. The cost related to every possible change is also considered. The selected updates define the new operating conditions along with its environmental and financial implications.
• Unlike other formulations found in the literature, the manufacturing process is not modeled as a single stage within the supply chain. Instead, it is decomposed into sub-processes. This approach allows assessing the environmental impacts associated with each stage of the process. This modeling approach also accounts for the flow of sub-products between the individual components of the process. Hence, technology-updating decisions are implemented in specific plants, and those improvements may imply the redesign of the entire supply chain.

• The set of possible technological updates are considered as projects. These projects allow the user to relate pollutant emissions or resource consumption to a variety of variables, according to the particularities of the case study at hand. Closing decisions (i.e., shutting down a facility) are also allowed.

• A novelty in the mathematical formulation consists of identifying the period in which every updating project is implemented and hence, defines investments cash flows and production planning according to stoppages for construction or retrofit times.

• The environmental impact is considered as an inventory of $CO_2$, $NO_x$, and $SO_x$ emissions related to each possible technical option at each stage of the process and thus, of the supply chain. This strategy ensures modeling environmental variables directly as the physical phenomena, avoiding the uncertainty related to the process of describing those impacts as LCA classic damage categories. Of course, this dis-aggregation of the environmental impacts provides technical advantages in the decision making process, but requires the definition of one objective function for every pollutant.

• The model accounts for cost and pollution caused by transportation. Therefore, the trade-off between large-scale production in few production plants and increased transportation costs, is considered.

• Cement sector is the perfect target to explore the capabilities of the proposed model for the following reasons: (i) its important contribution to GWP emissions, (ii) the wide gap between current operation systems and the best available technologies or practices, and (iii) the important growth in global cement production, specially in emerging economies.
Computational experiments describe a realistic scenario of a current operating cement supply chain in Colombia. The use of parameters from environmental improvement technical road-maps published by the Cement Sustainable Initiative (CSI), The European Cement Research Academy (ECRA), the Industrial Efficiency Technology Database and The Energy Star Program, among others, allowed to have a near real approximation to the $CO_2$ abatement costs for the cement case. These road-maps are based on commercially available efficiency technologies used anywhere in the world applicable to the cement industry.
Chapter 3

Case study

Concrete is considered to be the second most consumed substance in the world -the first is water [90]. The amount used in construction nearly doubles that of all other building materials, including wood, steel, plastic, and aluminium [90]. With respect to other commonly used materials, cement, which is the main component of concrete, has not the highest energy-intensity or carbon footprint (see Figure 3.1); however, due to the very common use of this material, the cement industry consumes approximately 2-3% of the worldwide primary energy [90, 91], and its absolute CO\textsubscript{2} emissions represents around 5%-7% of the total [90, 10]. During 2009-2011, the annual worldwide cement production was estimated to be 3 Gt [90, 10]. In 2013 [92], it was reported to be 3.7 Gt. Cement consumption is so significant that it is frequently used as a country development indicator.

The very high carbon emissions of global cement production has motivated this industrial sector to develop road-maps to reduce its impacts on climate change. As it is illustrated in figure 3.2 from global current emissions or baseline (BL) emission of 2.34 GT (it corresponds to the sector emissions in 2009), reduction strategies could allow to achieve global emissions of 1.55 GT in 2050. Those strategies include improving the energy efficiency and the use of cleaner fuels but also suggest the use of alternative cementing materials and carbon sequestration. For each strategy, its percentage participation in relation to the total potential reduction, is indicated in the figure.
Global and country-specific studies provide guidelines for emissions reduction [10, 23, 24, 25, 26, 27, 28]. For the Chinese and Indian cases, first and second world cement producers, authors in [26, 27] estimate energy savings potential and $CO_2$ emissions reduction for the period from 2010 to 2030. In India, although the very high current improvements that allowed to reduce $CO_2$ emissions form 1.12 ton per cement ton in 1996, to 0.76 in 2013 [93], the study found that cumulative fuels saving potential exceeds the current annual total fuel consumption of this sector, and the electricity savings potential is five and a half times the size of the industry’s current annual electricity consumption. In the Chinese case, authors report energy cumulative savings potential higher than 500 millions of GJ within the same period; this data is equivalent to 30% of primary energy supply of Latinoamerica [27]. Other published statistics refer to the German cement industry case [28]. In this case study, the $CO_2$ cost-effective abatement curve was constructed and makes evident the possibility to avoid 3.4% of annual emissions, with savings of 14.5 millions of euros (2012). These cases illustrates both, environmental and financial advantages.
In conclusion, potential environmental improvements are recognized for the cement sector. Those important efforts to create technological updating road-maps \[10\, 23\, 24\, 25\, 26\, 27\, 28\] lead to practical management questions for the firms: How should improvement strategies be selected? How do those technical changes in the production plants modify the entire supply chain? What are the related costs and the consequent emission reduction? Systematic tools based on mathematical programming offer a framework to tackle these questions. This research was motivated by a particular case study of a cement production company in Latin America, that has recently grown by means of the acquisition of several small firms, consolidating a set of 10 operating production plants with ages ranging from 15 to 50 years, with diverse technical conditions and production capacities. The aim of the firm is to improve its overall environmental performance, measured as the amount of emissions of $CO_2$, $NO_x$, and $SO_x$. This situation requires to select the particular set of updating options according to the initial conditions of every production plant. Technological updating projects also imply changes in production capacities and hence, determine changes in the supply chain. Different fuels and raw materials supplier are also available. A synthesis of the case is presented in Figure 3.3 where production plants, customers (circles), different available fuels (triangles) and raw materials suppliers (rectangles) are represented with hypothetical materials flows.
For a better understanding of this case study, a short description of the cement production process is provided next. The data related to each possible production technology, costs and emissions data have been retrieved from a wide revision of the technical literature of the cement sector [10, 23, 24, 25, 26, 27, 28]. The data related to plant locations, current operating technologies, production capacities, demand and costs do not correspond to any particular industry, but yet represents a realistic scenario.

### 3.1 Cement production

The raw materials for cement production are limestone and other carbonated rocks. These rocks are quarried, crushed and entered into a calcination kiln. In the kiln, the temperature rises up
to $1450^\circ$C, inducing a chemical reaction that converts the rocks into carbon dioxide and clinker ($CaCO_3 \rightarrow CaO + CO_2$) [94]. Finally, the clinker is mixed with other additives in a mill to obtain cement [94].

In older cement plants, crushed limestone and water are mixed to obtain a homogeneous slurry before entering the wet kiln tube. These old kilns need to be long. Here thermal energy is used for both the calcination process and for evaporating the water contained in the slurry. The first technological improvement towards kilns with higher thermal efficiency led to the so-called long dry kilns, which were designed to avoid mixtures with water. The next improvement was the introduction of a tower-mounted cyclone preheater where the calcination process begins. Later on, the calcination process was partly transferred to a precalciner attached to the preheater in a preheater-precalciner kiln line [95]. Preheater-precalciner kiln lines constitute the state of the art for the clinker production technology and can be as short as one-fourth the length of a wet kiln tube of similar capacity [95]. Published technical statistics for cement production show energy efficiency improvements of $30 - 40\%$ between a line with a wet kiln tube and another one with preheater-precalciner [10, 96, 95]. Concerning the burner inside the kiln, the state of the art technology is based on multi-channel burners [10]. This allows the simultaneous use of different types of fuels and facilitates the re-circulation of hot air and ultimately improve thermal efficiency [10].

Despite technology advances in clinker production, many long dry kilns (without preheaters and precalciners) and long wet kilns still operate worldwide [10]. Wet kilns can be improved with a preheater, leading to a so-called “semi-dry” system. Long dry kilns can also be equipped with a preheater or both a preheater and precalciner. In that case, the kiln length may be reduced, thus improving the thermal efficiency and reducing the mechanical stress of the kiln shell due to torsion. The retrofit of an old kiln may become attractive when a new kiln line is too expensive [10]. The capacity of modern kilns with a preheater and precalciner can be improved by adding cyclone preheaters in a number that may go from two to six. These multicyclone systems have higher production capacity and lower marginal energy consumption [10]. This sequential set of technical improvements in kiln technologies can lead to significant environmental and financial benefits.
Environmental performance improvements of the kiln process might be attained by changing the type of kiln, but also through other strategies. These include a better thermal isolation of the combustion camera, the reuse of heat with air recirculation, the installation of co-generation or control systems, the use of mineral additives (to reduce the calcination temperature) and the installation of emission filters (which enhance energy efficiency). These strategies are referred to as complements in the remainder of this document.

To produce cement, the nodules of clinker are mixed with gypsum and ground to powder. Grinding is the activity with the highest electric power demand in cement production. Modern grinding technologies are claimed to use from 20% to 50% less energy than their older counterparts. Advances in milling technologies are related to the replacement of traditional ball mills (BM) with high-pressure grinding rolls (HPGR) and vertical roller mills (VRM) [10, 96]. Between 20% and 50% of the power demand in cement production is related to grinding activities, including the grinding of raw materials before clinker production [24].

The described differences among different cement production plants may lead to very wide variations in its environmental impacts. In particular, the carbon footprint of one ton of cement shows variations between 650 to 950 Kg of $CO_2$ [96, 10]. A detailed description of those differences and improvement opportunities are provided next.
3.1.1 Energy consumption and environmental impacts

Probably, the most recognized environmental impact of cement production is the emission of $CO_2$. Data reported in [23, 97] shows that about 40% of the industry’s emissions are due to thermal energy consumption at the kiln; 10% is associated to transportation activities and electricity consumption. The remaining 50% of $CO_2$ emissions are originated from the process that converts limestone ($CaCO_3$) into calcium oxide ($CaO$), the primary precursor of cement. It is chemically impossible to convert $CaCO_3$ to $CaO$ in order to produce cement clinker, without generating $CO_2$. Hence, there is a wide percentage of emissions that could only be avoided by replacing the clinker with other kind of cementing materials.

Other atmospheric pollutants associated to the combustion process in the kilns are $SO_x$, $NO_x$ and particulate matter. The improvement of the energy efficiency in the whole process leads to a general reduction of all these pollutants, because less energy is used, but the use of some particular fuels may reduce the emission of one pollutant at the expense of increasing the emissions of some others. For instance, the use of cleaner fuels may reduce the emissions of $SO_x$, but due to its lower heat capacity, it could also lead to an increase in the emissions of $CO_2$. Another example is the case of natural gas, that reduces emissions of $CO_2$, but increases the emissions of $NO_x$ due to the higher combustion temperature. Those physicochemical phenomena force the particular analyses of every possible technical improvement in terms of its costs, environmental impacts and operating conditions. Control technologies can also reduce emissions of $SO_x$ and $NO_x$ in an independent way, but always demand additional power, with the corresponding increase in the emissions of $CO_2$.

Thermal energy is 100% used in the kiln process, while the average share of electricity consumption is as follows: 5% for raw material extraction and blending, 24% for raw material grinding, 6% for raw material homogenization, 22% for clinker production including solid fuels grinding, 38% for cement grinding and 5% for conveying, packing and loading [10]. The exact distribution of those relative percentages of energy consumption depends on the kind of thechnology for every process as will be illustrated in next subsection.
Mining and quarrying activities related to raw materials extraction, typically involves rock drilling, blasting, excavation, hauling and crushing. Environmental impacts related to those activities have a small participation in global $CO_2$, $SO_x$, and $NO_x$ global emissions of cement production; mainly involves intensive ecosystem and forest covert damage not included in this academic exercise.

3.1.2 Technical improvement options

The improvement of the environmental performance of the manufacturing process can be achieved by improving or replacing the production technologies, by using cleaner fuels and/or by taking economies of scale. In the proposed solution approach, all these alternatives were considered and applied to three main process in cement production: (i) raw materials milling (ii) kiln process and (iii) cement milling. Table 3.1 represents the echelons of the SC included in this work and their relation to the goals of emissions reduction; in this table, (-) represents the not addressed items of the model approach and (X) represents the addressed items. Following sections describe the generic improvement options for each process, that constitute the base to construct the test instance for the case study.
Cement supply chain

<table>
<thead>
<tr>
<th>Emissions Reduction Target</th>
<th>Fuel production</th>
<th>Gypsum and limestone mining</th>
<th>Raw materials milling</th>
<th>Clinker production</th>
<th>cement milling</th>
<th>Fuel and raw material supply, transport and distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect CO₂ emissions due to fuel production</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Indirect CO₂ emissions due to electricity consumption</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Direct NOₓ and/or SOₓ emissions in combustion process</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Direct CO₂ emissions in combustion process</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Direct CO₂ emissions in calcination process</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.1: Reduction targets and related echelons of the supply chain

Raw materials preparation

Crushing and milling raw materials approximately consumes 5% of the total electricity demand of the manufacturing process. Reduction in this energy use mainly refers to updating the milling equipment. Approximately, 1.7 ton of calcareous materials are required to produce one ton of clinker. Raw materials have to meet certain physico-chemical characteristics that are necessary for the clinker burning process, as these may affect the production process and clinker quality [24]. Table 3.2 includes average electricity consumption of main milling equipment and represents the main updating options for raw materials milling. Three main mill technologies were considered: (i) ball mills, (ii) vertical roller mills, and (iii) high pressure roller mills. Five production capacities were considered for each technology.
### Table 3.2: Electrical energy use, in main milling systems. Source: [96]

<table>
<thead>
<tr>
<th>Mill Technology</th>
<th>Energy consumption (kWh/raw material ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball mill</td>
<td>22</td>
</tr>
<tr>
<td>Vertical roller mill</td>
<td>16</td>
</tr>
<tr>
<td>Hybrid systems</td>
<td>18-20</td>
</tr>
<tr>
<td>Roller press integral</td>
<td>12</td>
</tr>
<tr>
<td>Roller press - pregrinding</td>
<td>18</td>
</tr>
</tbody>
</table>

### Kiln process

Under conditions of 25°C and 0.101 MPa, the theoretical thermal energy consumption for limestone transformation to generate 1 ton of clinker, is approximately 1.76 GJ (Taylor, 1992. cited by [98]). This value is known as formation enthalpy, but in the real production process, the required amount of energy is significantly higher because of the heat lost by radiation or convection [98]. Hence, real energy consumption is between 2.5 to 6 GJ per clinker ton. Higher values are due to obsolete kiln technologies while lowest are obtained through the use of BAT. Based on [10, 23, 24, 25, 26, 27], Table 3.3 illustrates the energy used to produce 1 ton of clinker, for six different kinds of kilns: (i) wet kiln, (ii) semi-wet kiln, (iii) long dry kiln, (iv) dry kiln with preheater, (v) dry kiln with preheater and precalciner, and (vi) multichannel dry kiln with preheater and precalciner; (those are the most common kinds of clinker kilns operating around the world).

<table>
<thead>
<tr>
<th>Kind of kiln</th>
<th>Thermal energy (GJ/clinker ton)</th>
<th>Electrical energy (kWh/ clinker ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet kiln</td>
<td>5.5-7</td>
<td>100</td>
</tr>
<tr>
<td>Semi-Wet kiln</td>
<td>5-5.5</td>
<td>110</td>
</tr>
<tr>
<td>Dry long kiln</td>
<td>4-5</td>
<td>90-110</td>
</tr>
<tr>
<td>Dry kiln with preheater</td>
<td>3.5-4</td>
<td>75-90</td>
</tr>
<tr>
<td>Dry kiln with preheater and precalciner</td>
<td>3-3.5</td>
<td>75</td>
</tr>
<tr>
<td>Multichannel burner in dry kiln with preheater and precalciner</td>
<td>2.5-3</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3.3: Average energy requirements for one ton of clinker
Each kiln technology also implies different electrical energy consumption levels. The length of the rotary kiln, the pumping system for raw materials circulation and the preheater and precalciner systems define the amount of electricity required. In comparison to the wet process, a dry kiln demands 5-7 additional kWh per clinker ton [96]. The power use of multi-channel technologies, remains more or less unchanged as the higher consumption for control fittings and air delivery channels is offset by the reduction of the primary air [10]. In the case of preheater and precalciner systems, there is a higher electricity use transporting raw materials into the cyclone systems, but less energy use for rotating the kiln, because it is significantly shorter. Power use in a typical cement plant is 111 kWh per ton of cement but it can have a significant variation in industrial practice, in a range from 3 to 9 kWh per ton of cement [10].

Other efficiency improvement or emission reductions depend on less intensive improvement projects such thermal isolation, control systems, changes in the mixture of combustion gases, kiln fans optimization, heat recover, and co-generation, technical improvement of cyclone systems, additives in the raw materials mixture, etc. The main technologies described in Table 3.3 correspond to mutually exclusive options, complementary projects are non-exclusive. The use of these technical complements have a percentage impact over different thermal energy, electricity consumption or both, as it is illustrated in Table 3.4 based on [10, 23, 24, 25, 26, 27].
<table>
<thead>
<tr>
<th>Technical complement</th>
<th>Thermal energy reduction (%)</th>
<th>Electrical energy reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy management, automatization and Control Systems</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Speed drivers for rotatory motors</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Shell heat loss reduction</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Oxigen enrichment in combustion camera</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Improve raw mix burnability e.g. by mineralizers</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Sistem cooler improvement and heat recycling for preheater process</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Heat Recovery for Cogeneration</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>Low pressure drop and high efficiency cyclones</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Flame control. Gyro-therm technology. Air reduction</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Retrofit uni-flow burner with advanced multi-channel burner</td>
<td>5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.4: Aproximated energy reduction by instaling complementary technologies to operating kilns

**Fuel and electricity**

The selection of the fuel for the kiln is one of the most important actions to achieve cleaner cement production. Opportunities not only come from the use of natural gas, as a low carbon footprint fuel, but also form alternative ones such as urban waste, used tires or biomass -See Table 3.5 based on Ecoinvent 3.0. Due to their ability to consume most industrial and municipal waste, cement plants could be called “scavengers” [99]. Using alternative fuels, cement industry reinforce its competitiveness and at the same time contributes to climate change mitigation and waste problems solutions [100]. Alternative fuels not only reduce the use of non-renewable fossil fuels as coal but also contributes to reduce $CO_2$ emissions and eliminates the need for disposal of those materials used as fuels.
<table>
<thead>
<tr>
<th>fuel</th>
<th>emission factor (ton CO₂ /GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal</td>
<td>0.14593</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>0.098035</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>0.093401</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.069509</td>
</tr>
<tr>
<td>Hardwood chips from forest</td>
<td>0.0095094</td>
</tr>
</tbody>
</table>

Table 3.5: CO₂ emission factors for heat production with different kinds of fuels

During the combustion process, the organic constituents of the fuels are destroyed due to the high temperatures, long residence time and oxidizing conditions. Inorganic constituents directly combine with the raw materials and are incorporated into the clinker [99]. Fossil fuels can be substituted up to 100% by alternative fuels but there are certain technical limitations. While the use of alternative fuels contributes to reduce CO₂ emissions, they do not reduce the actual energy demand, on the contrary, both the thermal and electrical energy demand may increase by 0-0.3 GJ per clinker ton and 0-3 kWh per clinker ton, respectively, due to its lower calorific power, moisture content or preprocessing requirements [100, 9]. Finally, it is important to consider the content of side products like trace elements or chlorine, that could result in new toxic emissions [100, 9].

Thermal and electrical energy use in the kiln process, variate according to the kiln technology. CO₂, NOₓ, and SOₓ, emissions of the combustion process results on the energy efficiency of each kind of kiln, but also depend on the kind of fuel or, indirectly, on the electrical energy source. Direct pollutant emissions are those produced during the energy use, while indirect emissions occur during upstream process. In the case of fuels, the indirect emissions are related to the extraction, refining or manufacturing process, and the second to the combustion process. In the case of electricity, the former are due to the generation process and the latter, related to the use. While emissions in thermal energy are mainly related to the combustion (use phase), emissions of electricity are related to the generation process (the use phase does not generate any).

For the case study, coal, natural gas, and two mixtures of coal with alternative fuels as tires or biomass were considered, all of them compatible with the chemical requirements of the clinker. Fuel
selection depends on direct emissions during the combustion process but also on fuel transportation. Due to the location of certain cement plants, not all of the alternative fuels are available (e.g., tires are available if the production plant is close to urban areas; biomass may be available in agro-industrial regions). It is therefore relevant to use a mathematical modeling tool, to assist the strategic decision-making process of selecting the fuels in relation to pollutant emission but also to transportation intensity. Hence, final $CO_2$ emissions of each technological option depends on its thermal and electrical efficiency but also on the emission factor of the used fuel. Not so detailed information was available for the case of $NO_x$ and $SO_x$ emissions. For those gases, emission values of each improvement project were only referenced on the higher and lower reported values for the cement production process \cite{101, 102, 24}.

According to LCA principles, the selection of clean electricity sources is a very important element in global process pollutant reduction. Differences in $CO_2$ emissions among different generation systems also represent important differences in the global emissions of electricity demanding industrial process, specially in those with high electricity intensity. Mining and Energy Planning Unit of Colombian government (UPME) defines the $CO_2$ footprint of the national electrical energy generation system, which includes hydroelectrical, thermal and biofuel generation plants. Combined emissions (emissions in construction and operating stage) is estimated in 0.2129 kg de $CO_2$/kWh \cite{103}.

**Scale benefits**

In \cite{104}, the authors remark the thermal energy efficiency benefits derived from increasing the capacity of the kiln. Based on a simulation study, they demonstrate efficiency returns to scale. E.g, it is possible to reduce the thermal energy consumption by more than 400 MJ/t clinker by replacing two less efficient 3,000 t/d plants by one 6,000 t/d BAT-plant \cite{104}. The same authors also indicate that due to decreased volume flows as a consequence of lower specific heat losses, it is also possible to reduce the per-unit electricity demand (e.g. for fans) with large scale production. The relation between per-unit energy consumption and scale production is not expected to be linear.
Mill process

Cement milling equipment are similar to raw mills but have higher technical requirements as the final product has to be finest and much more homogeneous. Cement milling is the process with the largest electrical energy demand in cement production. Electricity consumption for some cement milling technologies is presented by [96], and also represents main updating projects for milling process, as it is exposed in Table 3.6. The energy efficiency of ball mills is relatively low, consuming up to 30-42 kWh/ton clinker. Several new mill technologies can significantly reduce power consumption in the finish mill to 20-30 kWh/ton clinker, including roller presses, roller mills, and roller presses used for pre-grinding in combination with ball mills. The grinding efficiency also becomes higher with pressurized interior operation conditions [96]. Additional improvement strategies commonly consist of using integral classifiers for finish grinding. Classifiers separate the finely ground particles from the coarse particles; the large particles are then recycled back to the mill. Control systems allow to improve the flow conditions in the mill and classifiers, attaining a stable and high quality product [96].

<table>
<thead>
<tr>
<th>cement mill technology</th>
<th>Energy consumption (kWh/raw material ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball mill</td>
<td>55</td>
</tr>
<tr>
<td>Ball mill/separator</td>
<td>47</td>
</tr>
<tr>
<td>Roller press/ball mill/separator</td>
<td>41</td>
</tr>
<tr>
<td>Vertical roller press/separator</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 3.6: Electrical energy in main cement milling systems

Transportation

Production allocation has important implications over transportation pollutant emissions and costs, even more in the case of a very voluminous, highly demanded and heavy material as cement. A first consideration in energy efficiency is to locate cement plants closer to the source of raw materials [10]. Traditionally, main location criteria for cement plants was limestone availability. Demand
location is also a crucial subject; the cost of cement transportation by land is significant and it is said that cement could not be economically hauled beyond 200 or at most 300 Km \[105\]. The price of long road transportation may even be higher than the cement price \[105\]. The introduction of environmental issues in supply chain management decisions, introduce a new subject in cement supply chain network design: the availability of cleaner fuels as a strategic resource \[106\] \[107\]. Natural gas is not available for every plant, used tires constitute a strategic fuel for cement industry, specially near urban areas; biomass could be a viable fuel near to agro-industrial areas, coal mines are not a common resource and generates important regional advantages in financial terms but its high \(CO_2\) emissions are an evident disadvantage.
Chapter 4

Model description

A mixed-integer mathematical model to optimize technology updating decisions so as to minimize the cost and environmental impacts of an operating supply chain is proposed. It allows to describe the current state of an operating supply chain and select, among defined sets of technology-updating alternatives, those ones that efficiently reach the defined objectives. The manufacturing process is decomposed into sub-processes. Each sub-process has its own improvement alternatives. The modeling approach also describes the flow of sub-products between the individual components of the process. Hence, technology-updating decisions are implemented in specific plants, and those improvements may imply the redesign of the entire supply chain. The main assumptions used for model formulation are described:

- The current state of each production process at each plant is described through its fixed and operational costs, energy use and pollutant emissions. Similar parameters describe each improvement option; in this case, updating costs are also included. The investment cost associated with each technological improvement strategy depends on the project to be executed and the current technology of each equipment.

- Energy efficiency is mainly defined by the operating technology. The production capacity is managed as a discrete variable that modifies this efficiency, through economies of scale. Each
available fuel defines the emissions per-unit of energy produced (through the so-called emission factor); hence, energy consumption, with its costs and emissions, vary with the technology, the production scale, the use of complements to improve the energy efficiency and the kind of fuel. In the case of milling processes, operating technology and production volume defines energy efficiency; whereas emissions depend on the kind of energy used.

- The relationship between per-unit energy consumption and scale production is not expected to be linear, hence, a parameter in the model defines the production range in which each possible per-unite energy requirement is valid. These ranges follow as a piecewise linear function.

- The environmental impact is quantified through the emissions of three target pollutants (CO$_2$, NO$_x$, and SO$_x$) at each stage of the process.

- The operating cost are defined as a per-unit cost, that is, the total operating cost of an operational strategy is computed by multiplying the per-unit cost by the total production assigned to the equipment. The emissions to the environment are defined in a similar way, so within a range of production, the total emissions attributed to a given process are defined by a linear function of the total production.

- The closing costs depend on the current technology of the equipment being removed from operation.

- The transportation emissions and costs are defined as unitary parameters: USD/Km/ton and CO$_2$/Km/ton. Same parameter is used for every route in the network, however, model structure allows to replace this constant by a particular parameter for every route, attending differences due to the topography or the kind of route.

- Two parameters defines the fuel supplier; they describe CO$_2$ emissions and cost of transportation process of available fuel for each case.

- The transportation affects the emissions of CO$_2$ and the associated cost. In this case study, the emissions of NO$_x$ and SO$_x$ corresponding to transportation are not included, as they are
The capabilities of the model proposed are illustrated through its application to a cement industry. For the current case study, three main sub-process of the cement production were considered: (i) the raw materials milling (ii) the calcination process into the kiln, and (iii) the cement milling process. The first and the third have a very high electrical energy demand while the second has the higher thermal energy consumption. Hence, the case study refers to a four echelon supply chain, including raw materials suppliers, clinker production, cement production and distribution to customers.

4.1 Mathematical formulation

The direct formulation of the problem leads to a non linear formulation described in Section 4.1.1; a linearization strategy is described in Section 4.1.2 this formulation corresponds to a static problem; multi-period formulation is presented in Section 4.1.3. Environmental objective function is presented here as $\text{CO}_2$ emissions minimization; using the same objective function structure, others emissions minimization as $\text{NO}_x$ and $\text{SO}_x$, can be included, as illustrated in sub-section 4.1.2.

4.1.1 Non linear formulation

Sets

R, Raw material mills
K, Kilns
M, cement mills
A, Available tech. for raw material mill $r \in R$
B, Available tech. for kiln $k \in K$
$\text{Co}_{bk}$, Available complements compatible with tech. $b \in B$ in kiln $k \in K$
G, Available technologies for cement mill $m \in M$

$H_{ar}$, Available capacities for tech. $a \in A$ in raw mill $r \in R$

$I_{bk}$, Available capacities for tech. $b \in B$ in kiln $k \in K$

$J_{gm}$, Available capacities for tech. $g \in G$ in mill $m \in M$

F, Available fuels

Y, Gypsum suppliers

C, Customers

**Parameters**

In the case of parameters that belong to the sets of available technologies, the first element always describes the “do-nothing” option; in other words, operating conditions if no change is implemented over a particular process.
\( \alpha_{ar} \quad \text{Per-unit electricity use if tech } a \in A \text{ is used in rawmill } r \in R \)

\( c_{\alpha_{har}} \quad \text{Percentual electricity reduction with capacity } h \in H \text{ of tech } a \in A \text{ in raw mill } r \in R \)

\( \beta_{bk} \quad \text{Per-unit thermal energy use if tech } b \in B \text{ is used in kiln } k \in K \)

\( \gamma_{bk} \quad \text{Per-unit electricity use if tech } b \in B \text{ is used in kiln } k \in K \)

\( c_{\beta_{cbk}} \quad \text{Percentual thermal energy reduction if complement } c \in C \text{ is used with tech. } b \in B \text{ in kiln } k \in K \)

\( e_{\beta_{ibk}} \quad \text{Percentual thermal energy reduction with capacity } i \in I \text{ of tech } b \in B \text{ in kiln } k \in K \)

\( c_{\gamma_{cbk}} \quad \text{Percentual electricity reduction if complement } c \in C \text{ is used with tech. } b \in B \text{ in kiln } k \in K \)

\( e_{\gamma_{ibk}} \quad \text{Percentual electricity reduction with capacity } i \in I \text{ of tech } b \in B \text{ in kiln } k \in K \)

\( \varepsilon_{gm} \quad \text{Per-unit electricity use if tech } g \in G \text{ is used in mill } m \in M \)

\( q_{har} \quad \text{capacity value of the } h \text{-th capacity of tech } a \in A \text{ in raw mill } r \in R \)

\( q_{ibk} \quad \text{capacity value of the } i \text{-th capacity of tech } b \in B \text{ in kiln } k \in K \)

\( q_{jgm} \quad \text{capacity value of the } j \text{-th capacity of tech } g \in G \text{ in mill } m \in M \)

\( e_{\varepsilon_{jgm}} \quad \text{Percentual electricity reduction with capacity } j \in J \text{ of tech } g \in G \text{ in mill } m \in M \)

\( \zeta_{f} \quad \text{CO}_2 \text{ foot print of 1GJ of energy form fuel } f \in F \)

\( \eta_{f} \quad \text{Cost of 1GJ of energy form fuel } f \in F \)

\( \nu_{f} \quad \text{Specific heat of fuel } f \in F \)

\( \phi \quad \text{CO}_2 \text{ foot print of 1kWh of available electricity} \)

\( \rho \quad \text{CO}_2 \text{ cost of 1kWh of available electricity} \)

\( \varphi \quad \text{Per-unit, per distance } \text{CO}_2 \text{ transportation emisions} \)

\( \chi \quad \text{Per-unit, per distance transportation cost} \)

\( D_{c} \quad \text{Demand of customer } c \in C \)
Fixed costs if tech $a \in A$ is used in rawmill $r \in R$

Percentual fixed costs variation if capacity $h \in H$ of tech $a \in A$ is used in rawmill $r \in R$

Fixed costs if tech $b \in B$ is used in kiln $k \in K$

Percentual fixed costs variation if capacity of tech $i \in I$ of tech $b \in B$ is used in kiln $k \in K$

Fixed costs variation if complement $c \in Co$ is used with tech. $b \in B$ in kiln $k \in K$

Fixed costs if tech $g \in G$ is used in mill $m \in M$

Percentual fixed costs variation with capacity of tech $j \in J$ of tech $g \in G$ is used in mill $m \in M$

Per-unit operating costs if tech $a \in A$ is used in rawmill $r \in R$

Per-unit operating costs if tech $b \in B$ is used in kiln $k \in K$

Per-unit operating costs if tech $g \in G$ is used in mill $m \in M$

Total cost of installing tech. $a \in A$, in raw mill $r \in R$

Total cost of installing tech. $b \in B$, in kiln $k \in K$

Total cost of installing complement $c \in Co$ with tech. $b \in B$ in kiln $k \in K$

Total cost of installing tech. $g \in G$, in raw mill $m \in M$

Annualized cost of installing tech. $a \in A$, in raw mill $r \in R$

Annualized cost of installing tech. $b \in B$, in kiln $k \in K$

Annualized cost of installing complement $c \in Co$ with tech. $b \in B$ in kiln $k \in K$

Annualized cost of installing tech. $g \in G$, in raw mill $m \in M$

Percentual variation in executing cost if $h$-th capacity of tech. $a \in A$ is instaled in raw mill $r \in R$

Percentual variation in executing cost if $i$-th capacity of tech. $b \in B$ is used in kiln $k \in K$

Percentual variation in executing cost if $j$-th capacity of tech. $c \in C$ is used in mill $m \in M$

Closing cost of rawmill $r \in R$

Closing cost of kiln $k \in K$

Closing cost of mill $m \in M$
Distance between quarry $r \in R$ and kiln $k \in K$ 

Distance between kiln $k \in K$ and mill $m \in M$

Distance between gypsum supplier $y \in Y$ and mill $m \in M$

Distance between mill $m \in M$ and customer $c \in C$

Distance between fuel supplier $f \in F$ and kiln $k \in K$

Cost transportation of 1 GJ of fuel $f \in F$ and kiln $k \in K$

Emission factor of transportation 1 GJ of fuel $f \in F$ and kiln $k \in K$

**Binary decision variables:**

- $X_{Rar}^R = 1$ if tech. $a \in A$, is operating in raw mill $r \in R$
- $X_{bk}^K = 1$ if tech. $b \in B$, is operating in kiln $k \in K$
- $X_{gm}^M = 1$ if tech. $g \in G$, is operating in cement mill $m \in M$
- $X_{cbk}^C = 1$ if complementary tech $c \in C$ is used with tech. $b \in B$ in kiln $k \in K$
- $X_{fk}^F = 1$ if fuel $f \in F$ is used in kiln $k \in K$
- $X_{har}^H = 1$ if h-th capacity of tech. $a \in A$ is used in Raw mill $r \in R$
- $X_{ibk}^I = 1$ if i-th capacity of tech. $b \in B$ is used in kiln $k \in K$
- $X_{jgm}^J = 1$ if j-th capacity of tech. $g \in G$ is used in Mill $m \in M$
- $a_r^R = 1$ if raw material mill $r \in R$ remains in operation
- $a_k^K = 1$ if kiln $k \in K$ remains in operation
- $a_m^M = 1$ if mill $m \in M$ remains in operation
Continuous decision variables:

\[ A^R_r \] Production volume of raw material mill \( r \in R \)

\[ A^K_k \] Production volume of kiln \( k \in K \)

\[ A^M_m \] Production volume of mill \( m \in M \)

\[ T^{RK}_{km} \] amount of limestone transported from raw material mill \( r \in R \) to kiln \( k \in K \)

\[ T^{KM}_{mp} \] amount of clinker transported from kiln \( m \in M \) to mill \( m \in M \)

\[ T^{YM}_{mc} \] amount of gypsum transported from gypsum supplier \( y \in Y \) to mill \( m \in M \)

\[ T^{MC}_{mc} \] amount of cement transported from mill \( m \in M \) to customer \( c \in C \)

Objective functions

Minimize \{Total cost, CO₂ emissions\}

\[
E^O(\text{CO}_2) = \sum_{a \in A} \sum_{r \in R} \sum_{h \in H} \phi \cdot \alpha_{ar} \cdot e_{\alpha_{har}} \cdot X^R_{ar} \cdot X^H_{har} \cdot A^R_r + \\
\sum_{b \in B} \sum_{k \in K} \sum_{f \in F} \sum_{c \in C} \sum_{i \in I} \zeta_f \cdot \beta_{bk} \cdot e_{\beta_{ibk}} \cdot c_{\beta_{cbk}} \cdot X^F_{fk} \cdot X^K_{bk} \cdot X^I_{ibk} \cdot X^C_{cbk} \cdot A^K_k + \\
\sum_{b \in B} \sum_{k \in K} \sum_{m \in M} \sum_{i \in I} \phi \cdot \gamma_{bk} \cdot e_{\gamma_{ibk}} \cdot c_{\gamma_{ck}} \cdot X^K_{bk} \cdot X^I_{ibk} \cdot X^C_{ck} \cdot A^K_k + \\
\sum_{y \in Y} \sum_{m \in M} \sum_{j \in J} \phi \cdot \epsilon_{gm} \cdot e_{\epsilon_{jgm}} \cdot X^M_{gm} \cdot X^J_{jgm} \cdot A^M_m
\]  \hspace{1cm} (4.1)

\[
E^T(\text{CO}_2) = \sum_{r \in R} \sum_{k \in K} \varphi \cdot H^{RK}_{rk} \cdot T^{RK}_{rk} + \sum_{k \in K} \sum_{m \in M} \varphi \cdot H^{KM}_{km} \cdot T^{KM}_{km} + \\
\sum_{m \in M} \sum_{c \in C} \varphi \cdot H^{MC}_{mc} \cdot T^{MC}_{mc} + \sum_{y \in Y} \sum_{m \in M} \varphi \cdot H^{YM}_{ym} \cdot T^{YM}_{ym} + \\
\sum_{b \in B} \sum_{k \in K} \sum_{f \in F} \sum_{c \in C} \sum_{i \in I} \tau^F_{fk} \cdot (\beta_{bk} \cdot e_{\beta_{ibk}} \cdot c_{\beta_{cbk}} \cdot X^K_{bk} \cdot X^I_{ibk} \cdot X^C_{cbk} \cdot A^K_k \cdot X^F_{fk} / \nu) \hspace{1cm} (4.2)
\]
The objective of minimizing the emissions of CO₂ is defined by five terms: fuel and energy costs (Eq. 4.3), other operational costs (Eq. 4.4), fixed operation of the facilities (Eq. 4.1) and the transportation of materials (Eq. 4.2). The total cost \( C = \sum C_{FE} + C^{O} + C^{F} + C^{E} + C^{S} \) is comprised of the emissions associated with the operation of the facilities (Eq. 4.1) and the transportation of materials (Eq. 4.2). The total cost is defined by five terms: fuel and energy costs (Eq. 4.3), other operational costs (Eq. 4.4), fixed operation of the facilities (Eq. 4.1) and the transportation of materials (Eq. 4.2).
cost (Eq. 4.5), cost of executing the technological improvement projects (Eq. 4.6), shut-down costs (Eq. 4.7) and transportation cost of materials and fuels (Eq. 4.8). Financial objective function groups operational and investment costs. Although they correspond to different concepts in accounting terms (the former are expenses while the latter are assets), they can be grouped in the same objective function because of its similar unit of measurement. This mathematical treatment is also used by authors in [62, 64, 63, 79]. In this static formulation, investment cost are annualized, as expressed in (Eq. 4.9), where $E$ represents the annualized executing cost of every improvement option and $TE$, the total correspondent costs; $d$ is equal to the discount rate and $n$, the number of planning periods. (Detailed notation for each case, namely raw material mill, kiln of cement mill, is described in model parameters).

$$E = \frac{TE \cdot d}{(1 + d)^{-n}}$$

(4.9)

**Constraints**

$$q_R \cdot X_R^{r} \leq A_R^{r} \leq q_{a(h+1)r} \cdot X_R^{r} \quad \forall \ r \in R, \ \forall \ k \in K$$

(4.10)

$$q_K^{b} \cdot X_{ibk}^{b} \leq A_K^{k} \leq q_{b(i+1)k} \cdot X_{ibk}^{k} \quad \forall \ b \in B, \ \forall \ k \in K$$

(4.11)

$$q_M^{g} \cdot X_{gjm}^{g} \leq A_m^{m} \leq q_{g(j+1)m} \cdot X_{gjm}^{m} \quad \forall \ g \in G, \ \forall \ m \in M$$

(4.12)

$$\sum_{m \in M} T^{MC}_{mc} = D_c \quad \forall \ c \in C$$

(4.13)

$$A_R^{r} = \sum_{k \in K} T_{rk}^{RK} \quad \forall \ r \in R$$

(4.14)

$$A_K^{k} = \rho \cdot \sum_{r \in R} T_{km}^{RK} \quad \forall \ k \in K$$

(4.15)

$$A_m^{M} = \sum_{k \in K} T_{km}^{KM} + \sum_{y \in Y} T_{ym}^{YM} \quad \forall \ m \in M$$

(4.16)
\[ A^M_m = \sum_{c \in C} T^{MC}_{mc} \quad \forall \ m \in M \] (4.17)

\[ \sum_{a \in A} X^R_{ar} = a^R_r \quad \forall \ k \in K \] (4.18)

\[ \sum_{b \in B} X^K_{bk} = a^K_{k} \quad \forall \ m \in M \] (4.19)

\[ \sum_{g \in G} X^M_{gm} = a^M_{m} \quad \forall \ p \in P \] (4.20)

\[ X^R_{rk}, X^M_{sm}, X^P_{tp}, a^K_{k}, a^M_{m}, a^R_r \in (0, 1) \] (4.21)

\[ A^K_{k}, A^M_{m}, A^R_r, T^{MK}_{km}, T^{RK}_{rk}, T^{MC}_{mc} \geq 0 \] (4.22)

Constraints 4.10–4.12 ensure that the production capacity of each equipment lies in its correspondent range. Constraints 4.13 enforce demand satisfaction, while constraints 4.14–4.17 defines the correct mass balance. Constraints 4.18–4.20 guarantee that if a technical option is selected for a given equipment, then that particular equipment needs to be in operation. Those constraints also ensure the selection of one main technology per equipment. Constraints 4.21–4.22 defines the domain of decision variables.

### 4.1.2 Linearization strategy

Equations 4.1–4.6, and 4.8 corresponds to non linear expressions. The proposed linearization strategy consists in the creation of improvement projects that simultaneously represents various decisions: (i) main production technology and (ii) operation capacity range. In the case of the kiln process, other decision variables into the operating projects formulation are: (iii) operating fuel and (iv) technical complements. Hence, new sets of possible updating projects for each production equipment are created in replacement of set of possible operating technologies, fuels, capacities and complements. Emissions and cost of the created projects are pre-computed to create new parameters of the model.
$U^R$ production projects for raw materials mill $r \in R$

$U^K$ production projects for kiln $k \in K$

$U^M$ production projects for cement mill $m \in M$

After creating those sets of projects, binary variables represents the selected operational project and continue variables represent the quantity of limestone, clinker or cement, that will be processed in each equipment, with a defined production project:

$x^R_{ar} = 1$ If project $a \in U^R$ is executed in raw mill $r \in R$, and zero otherwise

$x^K_{bk} = 1$ If project $b \in U^K$ is executed in kiln $k \in K$, and zero otherwise

$x^M_{gm} = 1$ If project $g \in U^M$ is executed in mill $m \in M$, and zero otherwise

$A^R_{ar}$ production volume of raw mill $r \in R$ associated with project $a \in U^R$

$A^K_{bk}$ production volume of kiln $k \in K$ associated with project $b \in U^K$

$A^M_{gm}$ production volume of mill $m \in M$ associated with project $g \in U^M$

linear formulation

Let $U^R$, $U^K$ and $U^M$ be the sets of technology upgrading projects that are available for the raw material mills, kilns and cement mills respectively. Within each main production technology, a project is a combination of fuel, production capacity and technical complements that can be installed on the main technology so as to improve its environmental performance. For every set, the current technological situation in each main production technology is defined as a project (i.e. the “do-nothing” project). Finally, let $C$ be the set of customers in the supply chain.

Parameters

New parameters linear formulation
\( \Pi_{ar} \) CO\(_2\) emissions if project \( a \in \mathcal{U}^R \) is executed in raw mill \( r \in R \)

\( \Upsilon_{bk} \) CO\(_2\) emissions if project \( b \in \mathcal{U}^K \) is executed in kiln \( k \in K \)

\( \Lambda_{gm} \) CO\(_2\) emissions if project \( g \in \mathcal{U}^M \) is executed in cement mill \( m \in M \)

\( E^R_{ar} \) cost of executing project \( a \in \mathcal{U}^R \) in raw materials mill \( r \in R \)

\( E^K_{bk} \) cost of executing project \( b \in \mathcal{U}^K \) in kiln \( k \in K \)

\( E^M_{gm} \) cost of executing project \( g \in \mathcal{U}^M \) in cement mill \( m \in M \)

\( O^R_{ar} \) per-unit operating cost if project \( a \in \mathcal{U}^R \) is executed in raw materials mill \( r \in R \)

\( O^K_{bk} \) per-unit operating cost if project \( b \in \mathcal{U}^K \) is executed in kiln \( k \in K \)

\( O^M_{gm} \) per-unit operating cost if project \( g \in \mathcal{U}^M \) is executed in cement mill \( m \in M \)

\( F^R_{ar} \) fixed cost if project \( a \in \mathcal{U}^K \) is executed in raw materials mill \( r \in R \)

\( F^K_{bk} \) fixed cost if project \( b \in \mathcal{U}^M \) is executed in kiln \( k \in K \)

\( F^M_{gm} \) fixed cost if project \( g \in \mathcal{U}^M \) is executed in cement mill \( m \in M \)

\( q^R_{ar} \) minimum production capacity if project \( a \in \mathcal{U}^K \) is executed in raw materials mill \( r \in R \)

\( q^K_{bk} \) minimum production capacity if project \( b \in \mathcal{U}^M \) is executed in kiln \( k \in K \)

\( q^M_{gm} \) minimum production capacity if project \( g \in \mathcal{U}^M \) is executed in cement mill \( m \in M \)

\( Q^R_{ar} \) maximum production capacity if project \( a \in \mathcal{U}^R \) is executed in raw materials mill \( r \in R \)

\( Q^K_{bk} \) maximum production capacity if project \( b \in \mathcal{U}^K \) is executed in kiln \( k \in K \)

\( Q^M_{gm} \) maximum production capacity if project \( g \in \mathcal{U}^M \) is executed in cement mill \( m \in M \)

**Objective functions**

\[
\text{Minimize } E(CO_2) = E^O(CO_2) + E^T(CO_2)
\] (4.23)
\[ \text{Minimize } C = C^O + C^F + C^E + C^S + C^T \] (4.24)

\[ E^O(\text{CO}_2) = \sum_{a \in UR} \sum_{r \in R} \pi_{ar}^R \cdot A_{ar}^R + \sum_{b \in UK} \sum_{k \in K} T_{bk} \cdot A_{bk}^K + \sum_{g \in UM} \sum_{m \in M} \Lambda_{gm} \cdot A_{gm}^M \] (4.25)

\[ E^T(\text{CO}_2) = \sum_{r \in R} \sum_{k \in K} \varphi \cdot H_{rk}^{RK} \cdot T_{rk}^{RK} + \sum_{k \in K} \sum_{m \in M} \varphi \cdot H_{km}^{KM} \cdot T_{km}^{KM} + \]
\[ \sum_{m \in M} \sum_{c \in C} \varphi \cdot H_{mc}^{MC} \cdot T_{mc}^{MC} + \sum_{y \in Y} \sum_{m \in M} \varphi \cdot H_{ym}^{YM} \cdot T_{ym}^{YM} + \sum_{b \in UK} \sum_{k \in K} \tau_{fk}^E \cdot \langle \Upsilon_{bk} \cdot A_{bk}^K / \nu_f \rangle \] (4.26)

\[ C^O = \sum_{a \in UR} \sum_{r \in R} O_{ar}^R \cdot A_{ar}^R + \sum_{b \in UK} \sum_{k \in K} O_{bk} \cdot A_{bk}^K + \sum_{g \in UM} \sum_{m \in M} O_{gm}^M \cdot A_{gm}^M \] (4.27)

\[ C^F = \sum_{a \in UR} \sum_{r \in R} F_{ar}^R \cdot A_{ar}^R + \sum_{b \in UK} \sum_{k \in K} F_{bk} \cdot A_{bk}^K + \sum_{g \in UM} \sum_{m \in M} F_{gm}^M \cdot A_{gm}^M \] (4.28)

\[ C^E = \sum_{a \in UR} \sum_{r \in R} E_{ar}^R \cdot A_{ar}^R + \sum_{b \in UK} \sum_{k \in K} E_{bk} \cdot A_{bk}^K + \sum_{g \in UM} \sum_{m \in M} E_{gm}^M \cdot A_{gm}^M \] (4.29)

\[ C^S = \sum_{r \in R} S_{r}^R \cdot (1 - a_{r}^R) + \sum_{k \in K} S_{k}^K \cdot (1 - a_{k}^K) + \sum_{m \in M} S_{m}^M \cdot (1 - a_{m}^M) \] (4.30)

\[ C^T = \sum_{r \in R} \sum_{k \in K} \chi \cdot H_{rk}^{RK} \cdot T_{rk}^{RK} + \sum_{k \in K} \sum_{m \in M} \chi \cdot H_{km}^{KM} \cdot T_{km}^{KM} + \]
\[ \sum_{m \in M} \chi \cdot H_{my}^{MY} \cdot T_{my}^{MY} \sum_{m \in M} \sum_{c \in C} \chi \cdot H_{mc}^{MC} \cdot T_{mc}^{MC} + \sum_{b \in UK} \sum_{k \in K} \tau_{fk}^C \cdot \langle \Upsilon_{bk} \cdot A_{bk}^K / \nu_f \rangle \] (4.31)

Equation 4.23 defines the objective of minimizing the emissions of \( \text{CO}_2 \), which is comprised of the emissions associated with the operation of the facilities (Eq. 4.25) and the transportation of materials (Eq. 4.26). The total cost is defined in equation 4.24 and is comprised of four terms: operating cost (Eq. 4.27), fixed cost (Eq. 4.28), the cost of executing the technological improvement

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projects (i.e. 4.29), the shut-down costs (Eq. 4.30) and transport cost (i.e. 4.31).

Constraints

\[
\sum_{a \in U^R} x_{ar} = 1 \quad \forall \ r \in R \tag{4.32}
\]

\[
\sum_{b \in U^K} x_{bk} = 1 \quad \forall \ k \in K \tag{4.33}
\]

\[
\sum_{g \in U^M} x_{gm} = 1 \quad \forall \ m \in M \tag{4.34}
\]

\[
q_{ar}^R \cdot x_{ar}^R \leq A_{ar}^R \leq Q_{ar}^R \cdot x_{ar}^R \quad \forall \ a \in U^R, \ \forall \ r \in R \tag{4.35}
\]

\[
q_{bk}^K \cdot x_{bk}^K \leq A_{bk}^K \leq Q_{bk}^K \cdot x_{bk}^K \quad \forall \ b \in U^K, \ \forall \ k \in K \tag{4.36}
\]

\[
q_{gm}^M \cdot x_{gm}^M \leq A_{gm}^M \leq Q_{gm}^M \cdot x_{gm}^M \quad \forall \ g \in U^M, \ \forall \ m \in M \tag{4.37}
\]

\[
\sum_{m \in M} T_{mc}^{MC} = D_c \quad \forall \ c \in C \tag{4.38}
\]

\[
\sum_{a \in U^R} A_{ar}^R = \sum_{k \in K} T_{rk}^{RK} \quad \forall \ r \in R \tag{4.39}
\]

\[
\sum_{b \in B} A_{bk}^K = \varrho \cdot \sum_{k \in K} T_{rk}^{RK} \quad \forall \ r \in R \tag{4.40}
\]

\[
\sum_{g \in G} A_{gm}^M = \sum_{k \in K} T_{km}^{KM} + \sum_{y \in Y} T_{my}^{MY} \quad \forall \ m \in M \tag{4.41}
\]

\[
\sum_{g \in G} A_{m}^M = \sum_{c \in C} T_{mc}^{MC} \quad \forall \ m \in M \tag{4.42}
\]

\[
\sum_{r \in U^K} x_{ar}^R = a_r^R \quad \forall \ r \in R \tag{4.43}
\]

\[
\sum_{s \in U^K} x_{sk}^K = a_k^K \quad \forall \ k \in K \tag{4.44}
\]
\[ \sum_{t \in U^M} x_{gm}^M = a_m^M \quad \forall \ m \in M \quad (4.45) \]

\[ x_{ar}^R, x_{bk}^K, x_{gm}^M, a_r^K, a_k^K, a_m^M \in (0,1) \quad (4.46) \]

\[ A_{ar}^R, A_{bk}^K, A_{gm}^M, T_{rk}^{RK}, T_{km}^{KM}, T_{mc}^{MC} \geq 0 \quad (4.47) \]

Constraints \(4.32\,4.34\) ensure the selection of one technical project per equipment. Constraints \(4.35\,4.37\) ensure that the production capacity of each equipment lies in between the minimum and maximum capacity of the selected project. Constraint \(4.38\) enforce demand satisfaction, while constraints \(4.39\,4.42\) ensures mass balances. Constraints \(4.43\,4.45\) guarantee that a if technical project is executed on a given equipment, then that particular equipment needs to be in operation. Finally constraints \(4.46\) and \(4.47\) define the domain of the decision variables.

**4.1.2.1 NOx and SOx emission minimization as additional objectives**

Reduction of \(NO_x\) and \(SO_x\) emissions as the third and fourth objectives of the model, implies to consider new parameters that defines their respective emissions related to each improvement project. As stated in table \(3.1\) of previous chapter, those gases are mainly associated with fuel combustion, hence, the resultant emission function only applies for the kilns, as it is described in equations \(4.48\,4.49\). Implications of two more objective functions to the implementation process are described in Section \(5.2\).

\(NO_x\) and \(SO_x\) emission parameters:

\[ \Gamma_{bk} \text{ NOx emissions if project } b \in U^K \text{ is executed in kiln } k \in K \]

\[ \Xi_{bk} \text{ SOx emissions if project } b \in U^K \text{ is executed in kiln } k \in K \]

\(NO_x\) and \(SO_x\) objective functions:
\[ E(NO_x) = \sum_{b \in U^K} \sum_{k \in K} \Gamma_{bk} \cdot A^K_{bk} \] (4.48)

\[ E(SO_x) = \sum_{b \in U^K} \sum_{k \in K} \Xi_{bk} \cdot A^K_{bk} \] (4.49)

### 4.1.3 Dynamic model

Multi-period formulation requires some variation of the original static formulation, as enunciated:

(i) a new set to represent every planning period \( T \) (ii) an auxiliary decision variable to recognize the period in which changes in operating projects for every equipment are implemented, and generates a set-up cost; (iii) new constraints to obligate only one technological change or closing decision for each equipment along the planning time and, (iv) an artificial “zero” planning period, that represents the initial state of the systems -for this initial period, demand is equal to zero-; this strategy allows to recognize changes executed in period one; (v) cost for every planning period are represented as the present value of future cash flows, (vi) all financial parameters need an additional index \( t \in T \). Hypothetical annual increments are used to define future costs of fuel, energy, labour, raw materials and project execution. After obtained future cash flows, its present value is computed with the inverse expression; expected inflation rate allows to obtain the present value of known future cash flows.

In [64], it is supposed that the total capital investment required to install and expand the capacities of the plants is distributed into equal amounts along the planning horizon. This assumption is also used in [62, 63]. Here instead, it is proposed to include investments in its total values, in the period in which the investments are projected; hence, model results describe the cash flow of every period, including the updating investments. A subsequent detailed financial analysis should include assets depreciation and salvage values. Such a detailed analysis would allow to make a complete financial
analysis and determine the payback period of the proposed investment; both subjects are out of
the scope of this research.

Binary decision variables:

\[ x^R_{art} = 1 \] If project \( a \in U^R \) is executed in raw material mill \( r \in R \), in the period \( t \in T \)

\[ x^K_{bkt} = 1 \] If project \( b \in U^K \) is executed in kiln \( k \in K \), in the period \( t \in T \)

\[ x^M_{gmt} = 1 \] If project \( g \in U^M \) is executed in mill \( m \in M \), in the period \( t \in T \)

\[ a^R_r = 1 \] If raw material mill \( r \in R \) is operating, in the period \( t \in T \)

\[ a^K_k = 1 \] If kiln \( k \in K \) is operating, in the period \( t \in T \)

\[ a^M_m = 1 \] If mill \( m \in M \) is operating, in the period \( t \in T \)

\[ z^R_{art} = 1 \] If project \( a \in U^R \) is executed by first time in raw material mill \( r \in R \), in the period \( t \in T \)

\[ z^K_{bkt} = 1 \] If project \( b \in U^K \) is executed by first time in kiln \( k \in K \), in the period \( t \in T \)

\[ z^M_{gmt} = 1 \] If project \( g \in U^M \) is executed by first time in mill \( m \in M \), in the period \( t \in T \)

Continuous decision variables:

\[ A^R_{art} \] production volume of raw material mill \( r \in R \) associated with project \( a \in U^R \), in the period \( t \in T \)

\[ A^K_{bkt} \] production volume of kiln \( k \in K \) associated with project \( b \in U^K \), in the period \( t \in T \)

\[ A^M_{gmt} \] production volume of mill \( m \in M \) associated with project \( c \in U^M \), in the period \( t \in T \)

\[ T^{RK}_{rkt} \] amount of mill limestone transp. from raw material mill \( r \in R \) to kiln \( k \in K \), in the period \( t \in T \)

\[ T^{KM}_{kmt} \] amount of clinker transp. from kiln \( k \in K \) to mill \( m \in M \), in the period \( t \in T \)

\[ T^{YM}_{ymt} \] amount of gypsum transp. from gypsum supplier \( y \in Y \) to mill \( m \in M \), in the period \( t \in T \)

\[ T^{MC}_{mct} \] amount of bulk cement transp. from mill \( m \in M \) to customer \( c \in C \), in the period \( t \in T \)

Objective functions

\[
\text{Minimize } E(CO_2) = E^O(CO_2) + E^T(CO_2) \quad (4.50)
\]
Minimize \( C = C^O + C^F + C^E + C^S \) \hspace{1cm} (4.51)

\[
E^O = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} \Pi^{R}_{ar} \cdot A^{R}_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} \chi^{K}_{bk} \cdot A^{K}_{bkt} + \sum_{c \in U^M} \sum_{m \in M} \sum_{t \in T} A^{M}_{cm} \cdot A^{M}_{cnt} \hspace{1cm} (4.52)
\]

\[
E^T = \sum_{r \in R} \sum_{k \in K} \sum_{t \in T} \varphi \cdot H^{RK}_{rk} \cdot T^{RK}_{rkt} + \sum_{k \in K} \sum_{m \in M} \sum_{t \in T} \varphi \cdot H^{KM}_{km} \cdot T^{KM}_{kmt} + \sum_{m \in M} \sum_{c \in C} \sum_{t \in T} \tau^{E}_{f} \cdot \langle \chi^{K}_{bk} \cdot A^{K}_{bkt} / \nu_{f} \rangle \hspace{1cm} (4.53)
\]

\[
C^O = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} O^{R}_{art} \cdot A^{R}_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} O^{K}_{bkt} \cdot A^{K}_{bkt} + \sum_{g \in U^M} \sum_{m \in M} \sum_{t \in T} O^{M}_{gmt} \cdot A^{M}_{gmt} \hspace{1cm} (4.54)
\]

\[
C^F = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} F^{R}_{art} \cdot A^{R}_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} F^{K}_{bkt} \cdot A^{K}_{bkt} + \sum_{g \in U^M} \sum_{m \in M} \sum_{t \in T} F^{M}_{gmt} \cdot A^{M}_{gmt} \hspace{1cm} (4.55)
\]

\[
C^E = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} E^{R}_{art} \cdot z^{R}_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} E^{K}_{bkt} \cdot z^{K}_{bkt} + \sum_{g \in U^M} \sum_{m \in M} \sum_{t \in T} E^{M}_{gmt} \cdot z^{M}_{gmt} \hspace{1cm} (4.56)
\]

\[
C^S = \sum_{r \in R} \sum_{t \in T} S^{R}_{rt} \cdot (1 - a^{R}_{rt}) + \sum_{k \in K} \sum_{t \in T} S^{K}_{kt} \cdot (1 - a^{K}_{kt}) + \sum_{m \in M} \sum_{t \in T} S^{M}_{mt} \cdot (1 - a^{M}_{mt}) \hspace{1cm} (4.57)
\]

\[
C^T = \sum_{r \in R} \sum_{k \in K} \sum_{t \in T} \chi_{t} \cdot H^{RK}_{rk} \cdot T^{RK}_{rkt} + \sum_{k \in K} \sum_{m \in M} \sum_{t \in T} \chi_{t} \cdot H^{KM}_{km} \cdot T^{KM}_{kmt} + \sum_{m \in M} \sum_{y \in C} \sum_{t \in T} \chi_{t} \cdot H^{MC}_{my} \cdot T^{MC}_{myt} + \sum_{m \in M} \sum_{c \in C} \sum_{t \in T} \tau^{C}_{f} \cdot \langle \chi^{K}_{bk} \cdot A^{K}_{bkt} / \nu_{f} \rangle \hspace{1cm} (4.58)
\]

Equation (4.50) defines the objective of minimizing the emissions of CO\(_2\), which is comprised of the emissions associated with the operation of the facilities (Eq. (4.52)) and the transportation of fuels, limestone, clinker, gypsum and cement (Eq. (4.53)). The total cost is defined in equation (4.51) and is comprised of the sum of future cash flows associated with: operating cost (Eq. (4.54), fixed cost
(Eq. 4.55), the cost of executing the technological improvement projects (i.e. 4.56), the shut-down costs (Eq. 4.57) and the transport costs (Eq. 4.58). Present Value of every period cash flows are obtained using the following expression, which is applied to every costs; in each case, $CF_t$ is substituted by the operating, fixed, improvement or shut down costs of each period.

$$PV = \sum_{t \in T} \frac{CF_t}{(1 + r)^{t-1}}$$

Constraints

$$q^R_{ar} \cdot x^R_{art} \leq A^R_{art} \leq Q^R_{ar} \cdot x^R_{art} \quad \forall a \in U^R, \forall r \in R, \quad \forall t \in T$$

$$q^K_{bk} \cdot x^K_{bkt} \leq A^K_{bkt} \leq Q^K_{bk} \cdot x^K_{bkt} \quad \forall b \in U^K, \forall k \in K, \quad \forall t \in T$$

$$q^M_{gm} \cdot x^M_{gnt} \leq A^M_{gnt} \leq Q^M_{gm} \cdot x^M_{gnt} \quad \forall c \in U^M, \forall m \in M, \quad \forall t \in T$$

$$\sum_{m \in M} T^{MC}_{cmt} = D_{ct} \quad \forall c \in C, \forall t \in T$$

$$\sum_{a \in U^R} A^R_{art} = \sum_{k \in K} T^{RK}_{rkt} \quad \forall r \in R, \forall t \in T$$

$$\sum_{b \in U^K} A^K_{bkt} = \mu \cdot \sum_{r \in R} T^{RK}_{rkt} \quad \forall k \in K, \forall t \in T$$

$$\sum_{g \in U^M} A^M_{gnt} = \sum_{y \in Y} T^{YM}_{gmt} + \sum_{k \in K} T^{KM}_{kmt} \quad \forall m \in M, \forall t \in T$$

$$\sum_{g \in U^M} A^M_{gnt} = \sum_{c \in C} T^{MC}_{mct} \quad \forall m \in M, \forall t \in T$$
\[
\sum_{a \in U^R} x_{art}^R = a_r^R \quad \forall r \in R, \forall t \in T \quad (4.68)
\]
\[
\sum_{b \in U^K} x_{bkt}^K = a_k^K \quad \forall k \in K, \forall t \in T \quad (4.69)
\]
\[
\sum_{g \in U^M} x_{gmt}^M = a_m^M \quad \forall m \in M, \forall t \in T \quad (4.70)
\]
\[
x_{art}^R - x_{art}^{R(t-1)} \geq z_{art}^R \quad \forall a \in U^R, r \in R, \forall t \in 2T..NT \quad (4.71)
\]
\[
x_{bkt}^K - x_{bkt}^{K(t-1)} \geq z_{bkt}^K \quad \forall b \in U^K, k \in K, \forall t \in 2T..NT \quad (4.72)
\]
\[
x_{gmt}^M - x_{gmt}^{M(t-1)} \geq z_{gmt}^M \quad \forall g \in U^M, m \in M, \forall t \in 2T..NT \quad (4.73)
\]
\[
z_{art}^R + x_{art}^{R(t-1)} \leq 1 \quad \forall a \in U^R, r \in R, \forall t \in 2T..NT \quad (4.74)
\]
\[
z_{bkt}^K + x_{bkt}^{K(t-1)} \leq 1 \quad \forall b \in U^K, k \in K, \forall t \in 2T..NT \quad (4.75)
\]
\[
z_{gmt}^M + x_{gmt}^{M(t-1)} \leq 1 \quad \forall g \in U^M, m \in M, \forall t \in 2T..NT \quad (4.76)
\]
\[
x_{art}^R \geq z_{art}^R \geq z_{art}^R \quad \forall a \in U^R, r \in R, \forall t \in 2..T \quad (4.77)
\]
\[
x_{bkt}^K \geq z_{bkt}^K \geq z_{art}^R \quad \forall b \in U^K, k \in K, \forall t \in 2..T \quad (4.78)
\]
\[
x_{gmt}^M \geq z_{gmt}^M \geq z_{art}^R \quad \forall g \in U^M, m \in M, \forall t \in 2..T \quad (4.79)
\]
\[
a_{art}^R \leq a_{art}^{R(t-1)} \quad \forall a \in U^R, r \in R, \forall t \in 2..T \quad (4.80)
\]
\[
a_{bkt}^K \leq a_{bkt}^{K(t-1)} \quad \forall b \in U^K, k \in K, \forall t \in 2..T \quad (4.81)
\]
\[
a_{gmt}^M \leq a_{gmt}^{M(t-1)} \quad \forall g \in U^M, m \in M, \forall t \in 2..T \quad (4.82)
\]
\[
out^R = a_{art}^{R(t-1)} - a_{art}^R \quad \forall a \in U^R, r \in R, \forall t \in 2..T \quad (4.83)
\]
\[
out^K = a_{bkt}^{K(t-1)} - a_{bkt}^K \quad \forall b \in U^K, k \in K, \forall t \in 2..T \quad (4.84)
\]
\[ \text{out}^M = a^R_{gm(t-1)} - a^M_{gmt} \quad \forall g \in U^M, m \in M, \forall t \in 2..T \] (4.85)

Constraints 4.60–4.62 ensure that the production capacity of each equipment lies in between the minimum and maximum capacity of the selected project. Constraint 4.63 enforce demand satisfaction, while constraints 4.64–4.67 ensures mass balances. Constraints 4.68–4.70 guarantee that if a technical project is executed on a given equipment, then that particular equipment needs to be in operation. Constraints 4.71–4.76 allow to recognize the period in which a new technical project begins its operation. Constraints 4.77–4.79 imply that technological changes can only occur in operating equipment. They also ensure the selection of exactly one technical improvement project per equipment. Constraints 4.80–4.82 ensure that a closed plant cannot operate again. Constraints 4.83–4.85 activate closing costs.
Chapter 5

Computational experiments

In this chapter, computational experiments conducted to test the performance of the proposed models are described. Section 5.1 illustrates data used to build the test instance. Section 5.2 describes the results of the first experiment, in which four objectives were addressed: total cost and the emissions of CO$_2$, NO$_x$, and SO$_x$. The aim of this experiment was to test the performance of the proposed four-objective model on a test instance that included a two-echelon supply chain and a single planning period. A second experiment was conducted that included five planning periods and a wider supply chain with three manufacturing process and also fuel and gypsum suppliers. Two objectives were considered for this experiment (i.e. total cost and CO$_2$ emissions); the summary of the results is presented in Section 5.3. Finally, Section 5.4 presents the results of a third experiment that included an hypothetical tax on the emissions of CO$_2$. In this last experiment, the problem was solved using a single objective function as emissions are represented by the aforementioned tax. A detailed description of obtained solutions of these computational experiments is included in annexed materials.
5.1 Test instance

A test instance was built using publicly available data including technologies, capacities, fuels and environmental improvement opportunities for the cement industry. A hypothetical yet realistic three-echelon supply chain was built. At the suppliers level, four fuel and three gypsum suppliers were included. At the manufacturing level, the instance is comprised of 10 facilities, with up to 3 manufacturing processes at each facility: raw materials milling, the kiln, and the cement milling process. Static four objective model was tested with two manufacturing process, namely kiln and mill; bi-objective dynamic model was tested with the complete manufacturing process, raw materials mill, kiln, and cement mill. As per the customers, 30 points of aggregate demand were considered.

Six main technologies were considered for the kiln process. For each main technology, up to three production capacities and up to five complementary technologies were included. For both, the main technologies and the complementary technologies, the do-nothing option is always used as the first operational project. Additionally, four hypothetical fuels were included under the assumption that only one fuel can be selected for any given kiln, except for the multichannel dry kiln technology, which can use several fuels simultaneously. It is important to note that the complementary technologies associated with one main technology are not mutually exclusive (i.e., several complementary technologies can be installed simultaneously in a kiln), making the number of feasible combinations of complementary technologies very large. It is hence left to the decision maker to specify the number of combinations to be analyzed so as to keep the model in a manageable size. The total number of combinations considering six main production technologies, one to three capacity ranges for each technology, four fuels and from two to five non exclusive technical complements for each kind of kiln is close to 1800, depending on the initial state of each kiln. To simplify the calculations, a representative combinations of those options was selected, creating a set of updating projects for each kiln that varies from 78 to 114, depending on its initial state. Note that not all complements and production capacity ranges are compatible with all kiln technologies. Similarly, a total of three main technologies were considered for both milling processes. Each one considers
five possible production capacity ranges, thereby leading to 15 updating projects available for any given mill.

The parameters that describe the improvement projects are based on published route maps for the environmental improvement of cement production [90, 91, 10, 23, 24, 25, 26, 27, 28] as described in Section 3. The hypothetical current state of each kiln in terms of technology and capacity, is described in Table 5.2 along with the number of available updating projects in each case. In the table, the technologies are labeled as w (wet), sw (semi wet), ld (long dry), ph (pre-heater), and pc (precalciner). It is assumed that all the kilns are currently operated with coal. For the test instance, all the raw material and cement mills operate with a ball mill system as the initial technology. Emissions and costs for the initial state of the system were obtained running the model avoiding all improvement projects, and using the demand for the first planning period. Table 5.1 describes the costs included in the test instance and the sources used to estimate each parameter value. Fuel, electricity and transportation costs were obtained from generic public sources. Some data were directly transcribed, whereas other were approximated considering the relative complexity among different technological options. In the case of limestone and gypsum, mining extraction was not considered as the same proportion of those materials is used in every possible scenario.

<table>
<thead>
<tr>
<th>Type of cost</th>
<th>Information source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology updating</td>
<td>Cement sector road-maps [10, 23, 24, 25, 26, 27]</td>
</tr>
<tr>
<td>Fixed</td>
<td>A fraction of the average commercial cost of cement in Colombia [108, 109]</td>
</tr>
<tr>
<td>Fuel</td>
<td>Cement sector publications [10, 23, 24, 25, 26, 27]</td>
</tr>
<tr>
<td>Electricity</td>
<td>Average cost of electricity in Colombia [110]</td>
</tr>
<tr>
<td>Variable</td>
<td>Fraction of the average commercial cement costs in Colombia</td>
</tr>
<tr>
<td>Raw materials</td>
<td>A fraction of the average commercial cost of cement in Colombia</td>
</tr>
<tr>
<td>Transportation</td>
<td>Average commercial cost of land freight in Colombia</td>
</tr>
<tr>
<td>Closing</td>
<td>A fraction of the cost of the equipment</td>
</tr>
</tbody>
</table>

Table 5.1: Information sources for costs used in the test instance
Due to the very low indirect emissions of $NO_x$ and $SO_x$ associated with electricity generation in the case study, only $CO_2$ emissions were used to describe the milling processes. A similar assumption was made for the transportation process, as these emissions are negligible when compared to the emissions of $CO_2$. In synthesis, the emissions of $NO_x$ and $SO_x$ in the case study only depend on the calcination process, while the emissions of $CO_2$ depend on the calcination, milling and transportation processes.

### 5.2 A four-objective static model

The MILP described in section 4.1.2 was implemented in Xpress Mosel 3.8® and solved using Xpress Optimizer 27.01.02®. The experiments were run on a machine with 16 GB of memory and eight AMD A10-5800B processors running at 3.8 GHz under Windows 7 at 64 bits. To solve the multi-objective MILP, the $\epsilon$-constraint method was used. Furthermore, to narrow down the number of solutions, the approach presented in was used. A detailed description of the proposed solution approach follows.

First, the four objectives were minimized to obtain a lower bound in each case. The worst (i.e., highest) value obtained for each objective after minimizing the other three was kept as an upper bound (see Table 5.3). Figure 5.1 shows the results of these four single objective solutions and the

<table>
<thead>
<tr>
<th>Facility</th>
<th>Technology</th>
<th>Capacity (t/year)</th>
<th>Updating projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>w</td>
<td>$0.66 \cdot 10^6$</td>
<td>114</td>
</tr>
<tr>
<td>2</td>
<td>ph,pc</td>
<td>$1.2 \cdot 10^6$</td>
<td>78</td>
</tr>
<tr>
<td>3</td>
<td>ph,pc</td>
<td>$1.2 \cdot 10^6$</td>
<td>78</td>
</tr>
<tr>
<td>4</td>
<td>w</td>
<td>$0.66 \cdot 10^6$</td>
<td>114</td>
</tr>
<tr>
<td>5</td>
<td>w</td>
<td>$0.66 \cdot 10^6$</td>
<td>114</td>
</tr>
<tr>
<td>6</td>
<td>ph,pc</td>
<td>$1.2 \cdot 10^6$</td>
<td>78</td>
</tr>
<tr>
<td>7</td>
<td>w</td>
<td>$0.66 \cdot 10^6$</td>
<td>114</td>
</tr>
<tr>
<td>8</td>
<td>ph</td>
<td>$1 \cdot 10^6$</td>
<td>90</td>
</tr>
<tr>
<td>9</td>
<td>ld</td>
<td>$0.75 \cdot 10^6$</td>
<td>98</td>
</tr>
<tr>
<td>10</td>
<td>ld</td>
<td>$0.75 \cdot 10^6$</td>
<td>98</td>
</tr>
</tbody>
</table>

Table 5.2: Current kiln technologies
trade-offs among them -in the figure, vertical scale is normalized-. Remarkably, the minimum $CO_2$ solution weakly dominates the minimum $NO_x$, as it shows the same performance in terms of $NO_x$ and $SO_x$, but lower $CO_2$ and Cost values.

![Figure 5.1: Solutions for single objective optimization](image)

<table>
<thead>
<tr>
<th>Objective</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CO_2$ (tons)</td>
<td>$4.16 \cdot 10^9$</td>
<td>$5.28 \cdot 10^9$</td>
</tr>
<tr>
<td>$NO_x$ (tons)</td>
<td>$3.43 \cdot 10^6$</td>
<td>$5.06 \cdot 10^6$</td>
</tr>
<tr>
<td>$SO_x$ (tons)</td>
<td>$6.84 \cdot 10^5$</td>
<td>$2.27 \cdot 10^6$</td>
</tr>
<tr>
<td>Cost (USD)</td>
<td>$5.14 \cdot 10^9$</td>
<td>$9.85 \cdot 10^9$</td>
</tr>
</tbody>
</table>

Table 5.3: Intervals found for each objective

After defining the intervals for each objective, a set of bi-objective models were solved by optimizing the cost against each single environmental objective separately. Each of these bi-objective models was solved via the $\epsilon$-constraint method. Figures 5.2, 5.3, and 5.4 present the Pareto sets for the total cost against the three contaminants optimized (i.e., $CO_2$, $NO_x$, and $SO_x$). In these figures, the current situation is depicted in the triangle, while the solutions in bigger squares are those that dominate the current state of the system.
Figure 5.2: Pareto solutions for Total Cost vs. Emmisions of CO$_2$

Figure 5.3: Pareto solutions for Total Cost vs. Emmisions of NO$_x$
Finally, the model was solved considering all the objectives simultaneously. Four sets of solutions were calculated, each corresponding to a different case in which one of the four objectives was defined as the objective function, while the remaining objectives were transferred to auxiliary constraints. The auxiliary single objective problem was solved $4 \times 7^3 = 1372$ times, considering seven values for each objective transferred to an $\epsilon$-constraint. Non-dominated solutions are easy to identify within bi-objective problems, but a higher number of objective functions generates a large number of solutions, hence decision-making poses difficulties when it comes to the selection of the one to be implemented in practice [111]. In this case, a total of 1126 feasible solutions were obtained.

Using a Pareto filter developed in [111], 26 non-dominated solutions were identified among the total set of solutions. This narrowing procedure is briefly described as follows: (i) the values for each objective function are normalized in order to obtain a common basis to facilitate the comparisons, (ii) redundant solutions are removed considering a given tolerance value (i.e., a tolerance of 0.01% was used in this case), (iii) a reduced pool of solutions is generated using the concept of dominance (i.e., a feasible solution is also a non-dominated solution, if no other feasible solution scores at least
as well in all objective functions, and strictly better in one \cite{55}).

The run time for each experiment is described in Table 5.4. The first column provides the objective function of the corresponding experiment; the second column lists the objectives that were used as constraints within the \( \epsilon \)-constraint approach, whereas the third and fourth columns respectively display the total running time for the complete cycle (i.e. the exploration of all the \( \epsilon \) values), and the average time of each run.

<table>
<thead>
<tr>
<th>Objective</th>
<th>( \epsilon )-constraints</th>
<th>Total run time (s)</th>
<th>Average run time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>-</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>( CO_2 )</td>
<td>-</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>( NO_x )</td>
<td>-</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>( SO_x )</td>
<td>-</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>( CO_2 )</td>
<td>7.88</td>
<td>1.20</td>
</tr>
<tr>
<td>Cost</td>
<td>( NO_x )</td>
<td>5.24</td>
<td>0.74</td>
</tr>
<tr>
<td>Cost</td>
<td>( SO_x )</td>
<td>9.50</td>
<td>1.35</td>
</tr>
<tr>
<td>( CO_2 )</td>
<td>( NO_x )</td>
<td>2.50</td>
<td>0.35</td>
</tr>
<tr>
<td>( CO_2 )</td>
<td>( SO_x )</td>
<td>27.92</td>
<td>3.99</td>
</tr>
<tr>
<td>( SO_x )</td>
<td>( NO_x )</td>
<td>1.33</td>
<td>0.19</td>
</tr>
<tr>
<td>Cost</td>
<td>( NO_x ), ( SO_x ), ( CO_2 )</td>
<td>667.92</td>
<td>0.64</td>
</tr>
<tr>
<td>( CO_2 )</td>
<td>( NO_x ), ( SO_x ), Cost</td>
<td>218.74</td>
<td>1.95</td>
</tr>
<tr>
<td>( NO_x )</td>
<td>( CO_2 ), ( SO_x ), Cost</td>
<td>408.07</td>
<td>1.19</td>
</tr>
<tr>
<td>( SO_x )</td>
<td>( CO_2 ), ( NO_x ), Cost</td>
<td>757.72</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Table 5.4: Computational times

The analysis of the results of this computational experiment was focused on detecting the main differences between the extreme solutions. Figure 5.5 provides the spatial structure of the two extreme solutions. The solution that minimizes the emissions of \( CO_2 \), to the left of the figure, concentrates clinker production in fewer and larger kilns, while maintaining most of the mills active in the system. On the other hand, the solution that minimizes the cost, to the right of the figure, although maintains all operating kilns and mills, implements some updating projects that reduce operational costs without incurring in high financial investments.
A sample of 13 representative non-dominated solutions is presented in Figure 5.6. Each solution is identified with an ID number in the horizontal axis. The height of the bars in the figure represents the variation of the annual cost and emissions with respect to the current state of the system, computed as a percentage. This analysis shows that reducing the emissions of \( CO_2 \) entails a higher cost than reducing emissions of \( NO_x \) and \( SO_x \). This is because the former are decreased by implementing changes in the production capacity, complements for higher energy efficiency and fuel selection. On the contrary, the latter are reduced by installing control technologies with lower investment and operational costs. It is worth noting that important improvements in the overall environmental performance can be achieved at a low marginal cost, as in solutions 7 to 13. As an example, solution 8 decreases \( CO_2 \) emissions by 21%, \( NO_x \) emissions by 42% and \( SO_x \) emissions by 77% at the expense of increasing the annual cost by 4%. These solutions are described in detail
For the above mentioned set of solutions (7 to 13), Table 5.5 describes further details of the kiln process. The first column corresponds to the ID of the solution (i.e., the same ID is used in Figure 5.6). The second column identifies the facility where kilns remain in operation (kiln facility indexes go from 1 to 10). Columns 3 and 4 describe the initial state of the system in terms of technology (Tech.) and production capacity (Q) of the kilns, while columns 5 and 6 describe the technology (Sol. Tech.) and production capacity (Sol. Q) of the corresponding solution. All kilns currently operate using fuel 1. The new selected fuel is presented in column 7, where mc represents a multi-channel operation. As an example, in solution 7 only kilns in facilities 5 and 7 remain in operation, while the rest are shut down. The main technology in facility 5 remains the same, but the production capacity was increased from 1.20 to 3.30 metric tons per year. On the other hand, a wet kiln in facility 7 was replaced by a dry kiln with preheater and precalciner, with a production capacity that moved from 0.66 to 2.4 metric tons per year. Solutions at the bottom of
the table (i.e the solutions on the right of Figure 5.6), tend to leave more kilns in operation, which implies relatively lower reductions of pollutant emissions, but also lower investments. A detailed description of all non-dominated solutions is included as supplementary material.

These results reveal that the environmental performance of the supply chain can be improved by shutting down most of the current operating equipment, an action that is offset by increasing the capacity in those that remain in operation. Energy efficiency of the new installed equipment contributes to reduce emissions and to achieve lower operational costs. Another strategy to reduce combustion emissions consists of using cleaner fuels or more efficient burners. Optimal potential capacity allocation is a simultaneous strategy to reduce logistics costs and transportation emissions.

<table>
<thead>
<tr>
<th>Sol.</th>
<th>Kiln</th>
<th>Initial state</th>
<th>Selected operational project</th>
<th>Operating kilns</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>5</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>w</td>
<td>1</td>
<td>ph, pc</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>w</td>
<td>1</td>
<td>ph, pc</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph,pc</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>w</td>
<td>1</td>
<td>ph,pc</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>ph,pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>w</td>
<td>0.6</td>
<td>ph, pc</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>ld</td>
<td>0.6</td>
<td>ld</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>ph,pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>w</td>
<td>0.6</td>
<td>ph, pc</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>ld</td>
<td>0.6</td>
<td>ld</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>ph,pc</td>
<td>4</td>
<td>ph, pc</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>w</td>
<td>0.6</td>
<td>ph, pc</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>ph</td>
<td>0.75</td>
<td>ph</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>w</td>
<td>0.6</td>
<td>sw</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>ph, pc</td>
<td>1.2</td>
<td>ph, pc</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>w</td>
<td>0.6</td>
<td>w</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>ld</td>
<td>0.75</td>
<td>ld</td>
</tr>
</tbody>
</table>

Table 5.5: Operating projects in a sample of non dominated solutions.
For the same set of solutions (i.e. 7 to 13), the total investment and closing costs, and the annual operational savings with respect to the initial state of the system are presented in Figure 5.7. Emissions reduction and short-term financial savings related to technology updating decisions are evident. In this figure, the investment cost is expressed as a total value (not annualized). A detailed financial analysis should include the cost of the capital, assets depreciation and the annual cash flows during the depreciation period. Such a detailed analysis would allow to determine the payback period of the proposed investment. Due to the static character of this model, the analysis was restricted to the information presented in Figure 5.7 where the total investment (not annualized) can be contrasted against the annual operational savings. As an example, the total investment in solution 12 is 398 USD billions, while annual savings with respect to the initial state of the system are equivalent to 129.8 USD billions. This implies that -in addition to the environmental advantages- within a very short period of time, the annual savings compensate the investment in technology improvement.
5.3 A bi-objective dynamic model

The multi-objective MILP proposed in Section 4.1.3 was solved using Gurobi 5.6.9. The experiments were run on APOLO, the scientific computing center of EAFIT University. In particular, the used machines have 16 GB of memory and eight Dell Power Edge 1950 GIII processors running at 2.33 GHz under Linux Rocks 6.1 at 64 bits. A test instance was built using parameters described in Annex 4. In this case, the instance included a three-echelon supply chain: suppliers, manufacturing and customers. At the suppliers level, two raw materials were included: gypsum and fuel, whereas the manufacturing level, the three main production processes were considered: raw materials mills, kilns and cement mills. The two objectives in the model were cost and emissions of CO$_2$.

All parameters were initially available as present values. Rates to convert them to future values, are based on a hypothetical growth in the cost of fuels, energy or capital: annual growth rates for investment costs were estimated in 0.01%; operating cost including fuel and energy, 0.03% per year; transporting cost, 0.02% per year and fixed cost, 0.02% per year. Then, future cash flows were expressed as present values using the same rate, equivalent to an hypothetical annual inflation forecast. In this experiment, investment costs are presented as their total value. A planning horizon of five years was considered. Two expected demand forecast scenarios were used, namely D(a) and D(b); as described in Table 5.6.

<table>
<thead>
<tr>
<th>Period</th>
<th>Demand (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D(a)</td>
</tr>
<tr>
<td>1</td>
<td>8.58</td>
</tr>
<tr>
<td>2</td>
<td>9.43</td>
</tr>
<tr>
<td>3</td>
<td>11.10</td>
</tr>
<tr>
<td>4</td>
<td>13.90</td>
</tr>
<tr>
<td>5</td>
<td>15.71</td>
</tr>
<tr>
<td>total</td>
<td>58.74</td>
</tr>
</tbody>
</table>

Table 5.6: Demand forecast scenarios $1 \cdot 10^6$ tons

This problem was also solved using the $\epsilon$-constraint approach. Table 5.7 and 5.8 show the computational times for every solution found, each of which includes, for every planning period, information
such as the selected operational project, assigned production volume and materials flows between facilities, suppliers and customers. A minimal gap of 2% was used. For each facility, updating or closing decisions are also described. A detailed description of every efficient solution found is included in Annex 4.

<table>
<thead>
<tr>
<th>Solution</th>
<th>time (s)</th>
<th>gap %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3174</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>2364</td>
<td>1.83</td>
</tr>
<tr>
<td>3</td>
<td>9513.00</td>
<td>1.93</td>
</tr>
<tr>
<td>4</td>
<td>89524.86</td>
<td>1.97</td>
</tr>
<tr>
<td>5</td>
<td>7688.95</td>
<td>1.85</td>
</tr>
<tr>
<td>6</td>
<td>15859.74</td>
<td>1.99</td>
</tr>
<tr>
<td>7</td>
<td>9597.01</td>
<td>1.99</td>
</tr>
<tr>
<td>9</td>
<td>4961.93</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Table 5.7: Computing times for efficient solutions. D(a)

<table>
<thead>
<tr>
<th>Solution</th>
<th>time (s)</th>
<th>gap %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>226.12</td>
<td>1.73</td>
</tr>
<tr>
<td>2</td>
<td>1281.18</td>
<td>1.87</td>
</tr>
<tr>
<td>3</td>
<td>2737.14</td>
<td>1.55</td>
</tr>
<tr>
<td>4</td>
<td>12244.80</td>
<td>1.99</td>
</tr>
<tr>
<td>5</td>
<td>5146.15</td>
<td>1.99</td>
</tr>
<tr>
<td>6</td>
<td>11059.00</td>
<td>1.97</td>
</tr>
<tr>
<td>7</td>
<td>5184.00</td>
<td>1.92</td>
</tr>
<tr>
<td>8</td>
<td>15099.47</td>
<td>1.97</td>
</tr>
<tr>
<td>9</td>
<td>737</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Table 5.8: Computing times for efficient solutions. D(b)

As in the previous experiment, the efficient solutions found reveal a clear trade-off between financial and environmental results. Figure 5.8 illustrates total cost and emissions of non-dominated solutions; however, due to the growing nature of the demand forecast in this dynamic model, investments are not only driven by emissions minimization but also by higher production necessities. A second figure was constructed including fixed, production and transportation average unitary costs (investments in technological updating, capacity expansion or plants shut-down are not considered in this figure). In this case, it is possible to compare results with operational unitary costs of the initial state of the system as it is indicated in Figures 5.9 and 5.10.
Figure 5.8: Pareto solutions for Total Cost vs. Emissions of $CO_2$
Figure 5.9: Average production and transportation unitary costs and CO$_2$ emissions for current state and solutions for D(a)
Computational results

Along the planning horizon, obsolescent technologies are replaced by new kilns with pre-heater and pre-calciner systems, higher energy efficiency and larger production capacity. In spite of the growth in global production capacity, most of the solutions suggest shutting down one or more production facilities. Figures 5.11 and 5.12 describe the updating or shut-down cost for each period. These cash flows aim at being an input for a subsequent financial analysis that should also include amortization and savage values; an analysis that is out of the scope of this work. Note that investments are described as present values, not as annuities, thus, the amortization period need not to coincide with the planning horizon, as it is proposed in previously published models [64, 62, 79, 63].
<table>
<thead>
<tr>
<th>Solution 1.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3180</td>
<td>18.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| Solution 2. | 1840 | 15.1 | 0  | 0  | 0  | 0  |

| Solution 3. | 2490 | 13.3 | 0  | 0  | 0  | 0  |

| Solution 4. | 1040 | 19   | 0  | 0  | 0  | 0  |

| Solution 5. | 915  | 19.1 | 0  | 0  | 0  | 0  |

| Solution 6. | 692  | 18.3 | 0  | 0  | 0  | 0  |

| Solution 7. | 568  | 15.6 | 3.43 | 0 | 0 | 0 | 0 |

| Solution 8. | 424  | 10.6 | 68.6 | 0 | 0 | 0 | 0 |

| Solution 9. | 358  | 8.16 | 5.4  | 0 | 0 | 0 | 0 |

Figure 5.11: Present value of cash flow corresponding to update and shut down costs for every planning period [10⁶ USD]. D(a)
<table>
<thead>
<tr>
<th>Solution 1.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2480</td>
<td>418</td>
<td>407</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

| Solution 2. | 1900 | 416 | 404 | 0.189 | 0 |

| Solution 3. | 1770 | 17.5 | 403 | 0.842 | 0 |

| Solution 4. | 1510 | 19.2 | 274 | 0 | 0 |

| Solution 5. | 1040 | 157 | 4.23 | 0 | 0 |

| Solution 6. | 833 | 17.2 | 0.961 | 0.141 | 0 |

| Solution 7. | 834 | 17.4 | 180 | 0.094 | 0 |

| Solution 8. | 623 | 9.25 | 2.48 | 0.189 | 0 |

| Solution 9. | 558 | 13.6 | 2.62 | 0 | 0 |

Figure 5.12: Present value of cash flow corresponding to update and shut-down cost for every planning period [10^9 USD]. D(b)

Figures 5.13 and 5.14 show main differences in cost composition of each solution, from cleaner solutions at the bottom to low-cost solutions at the top.
Figure 5.13: Cost description of efficient solutions D(a). $[10^9 \text{ USD}]$
What are the planning strategies associated to financial or environmental oriented solutions? Main differences are found in updating or shutting down decisions for the kiln process. All of the raw and cement mills are updated not only in cleaner but also in low-cost scenarios; thus, further analysis is focused on the kiln process. The figures 5.15 and 5.16 describe the percentage use of the different kiln technologies for every efficient solution. Cleaner production schemes privilege the use of preheater and pre-calciner technologies at the highest possible production capacities; however, some solutions in the cleaner extreme of the Pareto frontier imply pointless decisions so as to update the production technology in a process that will be shut down within the next few planning periods. As an example, the solution that corresponds to emissions minimization for (a) demand growth scenario -see Annex 4-, describes updating projects for kilns 1, 4, 5, 8, 9, and 10, which are out of operation in the subsequent planning period. A similar case for (b) demand growth scenario, kilns 2, 4, and 5 are updated to very low emissions operational technologies and are later closed. These kind of solutions disappear as the financial constraints are tightened.

Figure 5.15: Percentage production of clinker, with the corresponding kiln. D(a)

Differences in operating costs are highly dependent on the energy efficiency of the installed tech-
Figure 5.16: Percentage production of clinker, with the corresponding kiln. D(b)

nology, but also on the fuel used. Figure 5.17 shows important differences in the parameters that describe the cost and emissions of the fuels considered. From lower emissions to the left, to lower cost to the right, Figures 5.18 and 5.19 describe the percentage of use of each fuel in relation to total production. Cleaner solutions privilege the use of fuel (2) and (4) whereas fuel (3) and fuel (1) are mostly used in lower cost solutions.

Finally, Figures 5.20 and 5.21 allow to identify the most appealing solutions with respect to investment and consequent operational savings and emissions reduction. Investment and operational cost and emissions are expressed as average per unit -emission values are multiplied by 10, in order to allow its visualization.

Control technologies to mitigate NO\textsubscript{x} and SO\textsubscript{x} are out of the scope of this experiment; however, the resulting emissions of every solution can be computed and resultant emissions data are available. Using the same order, from the lower CO\textsubscript{2} emission to the left, to the highest to the right, Figure
Figure 5.17: Costs vs. Emissions of different fuels

Figure 5.18: Percentual production of clinker, with the corresponding fuel. D(a)
Figure 5.19: Percentual production of clinker, with the corresponding fuel. D(b)

Figure 5.20: Investments, operational savings and emissions reduction by cement ton. D(a)
Figure 5.21: Investments, operational savings and emissions reduction per cement ton. D(b)

show $NO_x$ and $SO_x$ emissions for solutions in D(a) and D(b) scenarios. Unlike the previous case in Section 5.2, $SO_x$ and $NO_x$ are directly related to $CO_2$ emissions because their emission control technologies were not included as updating projects in this experiment.
Figure 5.22: $NO_x$ and $SO_x$ pollutant emissions for non dominated solutions D(a) and D(b)
Carbon abatement costs

Despite the important financial advantages of most obtained solutions when compared against the current operation, differences in cost among cheaper and cleaner solutions are significantly high. The inefficiency of the current operational scheme implies that even minimum cost solutions convey operational changes that also come with lower emissions, but as the solutions move to the left in the pareto frontier - Figures 5.8 and 5.9, very important investments are required. The abatement cost calculation allows to recognize financial differences among lower and cleaner solutions.

Carbon abatement costs were computed using the formula proposed in [26] as described in Eq. 5.1. In such expression the abatement cost \( A \) depends on the complete cost and emissions of abatement option -respectively named \( (CCO) \) and \( (E_{sol}) \)-, the base line cost \( (BLC) \), and the base line emissions \( (BLE) \). The \( CCO \) is computed as in Eq. 5.2 and depends on the total investment of the solution \( (CE) \), the total production \( (P) \), and operational revenues, defined as the difference between the unitary operational costs of the abatement option \( (UCO_{sol}) \), and the unitary cost of the base line state \( (UCO^{BL}) \). Tables 5.9 and 5.10 illustrate abatement costs for each solution under both demand scenarios. Abatement costs are notoriously lower in the scenario of higher demand growth; as mentioned in Section 3, improvement investments have higher return when they are driven by the need of production capacity growth. The comparisons among Tables 5.9 and 5.10 and Figures 5.20 and 5.21 evidence that the lowest abatement cost does not mean the highest emission reduction.

\[
A = \frac{(CCO - BLC)}{(BLE - E_{sol})} \tag{5.1}
\]

\[
CCO = \frac{CE}{P} + (UCO_{sol} - BLC) \tag{5.2}
\]
<table>
<thead>
<tr>
<th>Base line costs $UCO^{BL}$ (USD/ton)</th>
<th>79.68</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base line emissions BLE (CO$_2$ ton/ton)</td>
<td>0.76</td>
</tr>
<tr>
<td>Total production P (ton)</td>
<td>58745470</td>
</tr>
<tr>
<td>Efficient solutions</td>
<td>Sol 1</td>
</tr>
<tr>
<td>Average op costs (USD/ton)</td>
<td>74.31</td>
</tr>
<tr>
<td>Average op emissions (CO$_2$ ton/ton)</td>
<td>0.572</td>
</tr>
<tr>
<td>Operational savings (USD/ton)</td>
<td>5.33</td>
</tr>
<tr>
<td>Total investment by unit (USD/ton)</td>
<td>56.25</td>
</tr>
<tr>
<td>Revenue CCO (USD/ton)</td>
<td>50.92</td>
</tr>
<tr>
<td>Emission reduction CO$_2$ ton/ton</td>
<td>0.188</td>
</tr>
<tr>
<td>Abatement cost A (USD/CO$_2$ ton)</td>
<td>271.19</td>
</tr>
</tbody>
</table>

Table 5.9: CO$_2$ Abatement cost calculation D(a)

<table>
<thead>
<tr>
<th>Base line costs (USD/ton)</th>
<th>79.68</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base line emissions (CO$_2$ ton/ton)</td>
<td>0.76</td>
</tr>
<tr>
<td>Total production (ton)</td>
<td>45624929</td>
</tr>
<tr>
<td>Efficient solutions</td>
<td>Sol 1</td>
</tr>
<tr>
<td>Average op costs (USD/ton)</td>
<td>74.40</td>
</tr>
<tr>
<td>Average op emissions (CO$_2$ ton/ton)</td>
<td>0.572</td>
</tr>
<tr>
<td>Operational savings (USD/ton)</td>
<td>-5.24</td>
</tr>
<tr>
<td>Total investment by unit (USD/ton)</td>
<td>70.16</td>
</tr>
<tr>
<td>Emission reduction CO$_2$ ton/ton</td>
<td>0.195</td>
</tr>
<tr>
<td>Abatement cost A (USD/CO$_2$ ton)</td>
<td>333.46</td>
</tr>
</tbody>
</table>

Table 5.10: CO$_2$ Abatement cost calculation D(b)
5.4 A tax to carbon emissions model

A tax to carbon emissions allows to transform $CO_2$ emissions into cost, therefore, a single objective function including the previously described costs along with the carbon tax was developed. The following results correspond to such experiments. Three accepted carbon payment systems are described: (i) Tax payment systems describes a direct tax for every ton of $CO_2$ emitted, (ii) cap-and-trade system is a market-based approach with interchangeable emissions allowances, (iii) cap-and-tax system is a hybrid approach, where emissions below a predefined cap are allowed, and those over this cap are subject to taxes [112, 113]. For this experiment, the cap-and-tax system is used.

The emission cap values are defined as the lowest feasible emissions for cement production; while tax values are defined as the current common carbon payments in the international market. These tax values vary significantly depending on the country where they are applied, and are not necessarily comparable because of the differences in the number of sectors covered, specific exemptions, and different compensation methods [114]. The following results correspond to cost minimization (first case) and profit maximization (second case). Some tax values around the world are described in Figure 5.23. The circle to the left of the figure represents the interval that contains tax values found in Poland, Mexico, New Zeland, Portugal, Korea, Iceland, UE, Beijing, Kasakhastan, Estonia, Japan and some provinces of China; while the remaining values are marked along the horizontal line.

![Figure 5.23: Values for carbon taxes around the world](image_url)

Figure 5.23: Values for carbon taxes around the world
5.4.1 Cost minimization

The cost of $CO_2$ emissions is represented in Equation 5.3 where $Z_t^{EO}$ and $Z_t^{ET}$ respectively represent the operational and transportation emissions of period $t \in T$; $cap_t$ is equivalent to the maximum amount of $CO_2$ that can be emitted without incurring in a tax, and $C$ represents the payment applied to each ton of $CO_2$ emitted over the cap. For this experiment, carbon caps are defined as the minimum emission obtained for each demand scenario, as computed in the experiments described in Section 5.3—see Table 5.11. Note that this cap corresponds to the use of the best available technologies and optimal network design for this case study, hence, when using the values described in Table 5.11 it is not technically possible to fulfil the estimated demand and to obtain emissions below this cap. It guarantees that the emission cost value $Z^C$ will never be negative. At this point, the work of [55] can be referenced. Using a similar mathematical structure, in the context of a cap and trade system, the authors suggest that negative values are equivalent to emission allowances that can be sold if the operation achieves emissions below the established cap.

$$Z^C = C_t \cdot (Z_t^{EO} + Z_t^{ET} - cap_t) \quad \forall t \in T$$

<table>
<thead>
<tr>
<th>Period / Demand</th>
<th>D(a)</th>
<th>D(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.186</td>
<td>4.806</td>
</tr>
<tr>
<td>2</td>
<td>5.549</td>
<td>5.058</td>
</tr>
<tr>
<td>3</td>
<td>6.222</td>
<td>5.181</td>
</tr>
<tr>
<td>4</td>
<td>7.800</td>
<td>5.305</td>
</tr>
<tr>
<td>5</td>
<td>8.856</td>
<td>5.438</td>
</tr>
</tbody>
</table>

Table 5.11: Carbon cap for each scenario and period $1 \cdot 10^6$ ton

The solutions described in Figures 5.24 and 5.25 were obtained using different tax values. Computational times are described in Tables 5.12 and 5.13. Detailed results are included in Annex 5.
<table>
<thead>
<tr>
<th>Tax value</th>
<th>time (s)</th>
<th>gap %</th>
</tr>
</thead>
<tbody>
<tr>
<td>t15</td>
<td>1798.61</td>
<td>1.76</td>
</tr>
<tr>
<td>t25</td>
<td>5468.75</td>
<td>1.96</td>
</tr>
<tr>
<td>t35</td>
<td>836.75</td>
<td>1.98</td>
</tr>
<tr>
<td>t45</td>
<td>320.92</td>
<td>0.58</td>
</tr>
<tr>
<td>t55</td>
<td>3843.37</td>
<td>1.95</td>
</tr>
<tr>
<td>t150</td>
<td>3101</td>
<td>2.91</td>
</tr>
</tbody>
</table>

Table 5.12: Computational times and gaps for different tax values. D(a)

<table>
<thead>
<tr>
<th>Tax value</th>
<th>time (s)</th>
<th>gap %</th>
</tr>
</thead>
<tbody>
<tr>
<td>t15</td>
<td>550.51</td>
<td>1.94</td>
</tr>
<tr>
<td>t25</td>
<td>2035.89</td>
<td>1.55</td>
</tr>
<tr>
<td>t35</td>
<td>1124.05</td>
<td>1.62</td>
</tr>
<tr>
<td>t45</td>
<td>2498.93</td>
<td>1.68</td>
</tr>
<tr>
<td>t55</td>
<td>1961.07</td>
<td>1.96</td>
</tr>
<tr>
<td>t150</td>
<td>1169.19</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Table 5.13: Computational times and gaps for different tax values. D(b)

![Figure 5.24: Comparison between taxed and non taxed solutions. D(a)](image-url)
The results summarized in Figures 5.24 and 5.25 clearly demonstrate that (i) Only very high carbon taxes lead to cleaner scenarios, while low taxes have very low impact on emission reduction; and (ii) the effect of different carbon tax values on emissions reduction is not linear. Tables 5.14 and 5.15 provide further details on the relation between emission costs, other costs and total emissions in taxed scenarios.
5.15 describe in detail the cost structure of each solution found. Notice that total cost in 5.24 and 5.25 correspond to the sum of total cost without taxes and emission costs in Tables 5.14 and 5.15. These results demonstrate that frequently, low differences in taxes do not affect updating decisions, just lead to higher payments due to emission.

Clearly, solutions with equal emissions show higher costs in the context of a carbon tax system. The real sense of those payment systems can be explained based on Figure 5.26. In the figure, suppose that point b represents a solution under a carbon tax system. The extra cost, represented by the line segment ab (\(\Delta \text{cost}\)) should be paid to another organization capable of investing this amount in a strategy that leads to higher \(CO_2\) emissions reduction than that represented by the line segment bc (\(\Delta \text{emissions}\)). In other words, if production emissions minus avoided emissions are located along the segment ec, the carbon tax system makes sense. The projection of the taxed solutions over the efficient frontier is not an exact measure, as the frontier line is not a continuum of solutions, but it constitutes a useful tool for designing a carbon tax system. Tables 5.16 and 5.17 describe, for each case, the \(\Delta \text{cost}/\Delta \text{emissions}\) reference value. This can be interpreted as that any strategy that allows to avoid one ton of \(CO_2\) with lower costs than those described in Tables 5.16 and 5.17 leads to a global effective management scenario.
Efficient frontier ■ taxed solution

Figure 5.26: Comparison between taxed and non taxed solutions

<table>
<thead>
<tr>
<th>solution</th>
<th>Δcost/Δemissions USD/CO₂ t</th>
</tr>
</thead>
<tbody>
<tr>
<td>t150</td>
<td>485.18</td>
</tr>
<tr>
<td>t55</td>
<td>832.5</td>
</tr>
<tr>
<td>t45</td>
<td>370.74</td>
</tr>
<tr>
<td>t35</td>
<td>363.03</td>
</tr>
<tr>
<td>t25</td>
<td>190.22</td>
</tr>
<tr>
<td>t15</td>
<td>51.49</td>
</tr>
</tbody>
</table>

Table 5.16: Reference values for the design of CO₂ payment system, D(a)

<table>
<thead>
<tr>
<th>solution</th>
<th>Δcost/Δemissions USD/CO₂ t</th>
</tr>
</thead>
<tbody>
<tr>
<td>t150</td>
<td>201.19</td>
</tr>
<tr>
<td>t55</td>
<td>576.78</td>
</tr>
<tr>
<td>t45</td>
<td>407.54</td>
</tr>
<tr>
<td>t35</td>
<td>287.02</td>
</tr>
<tr>
<td>t25</td>
<td>93.88</td>
</tr>
<tr>
<td>t15</td>
<td>72.13</td>
</tr>
</tbody>
</table>

Table 5.17: Reference values for the design of CO₂ payment system, D(b)
5.4.2 Profit maximization

A final experiment considers profit maximization as a single objective function model, as expressed in Eq 5.4. The main difference with the previous model is that under a profit perspective, demand fulfilment is not required as the model should be able of choosing not to fulfil a given demand due to the high cost or emissions of doing so. In this equation, decision variables $V_{ct}$ denote the amount of cement sold to customer $c \in C$ in period $t \in T$; and the parameter $P_{ct}$ defines the price of cement for each customer. $CO$, $CT$ and $CF$ represent the operational, transportation and fixed costs of the period, as described in Section 4. The total updating investment is used as a constraint. Emissions were not used as objective function nor as a constraint as in the previous case, as the objective of these experiments was to evaluate the effectiveness of a carbon tax system on reducing the total emissions of the operation.

$$Pf = \sum_{c \in C} \sum_{t \in T} V_{ct} \cdot P_{ct} - \sum_{t \in T} CO_t + CT_t + CF_t$$ (5.4)

For this specific experiment, a new set of constraints was imposed to take into account that during the updating periods, production capacity at the kilns cannot be used at a 100% of its potential due to the complexity of these particular updating activities. The parameter $\Theta$ defines the percentage of reduction in the operational capacity of the kiln during this period. Constraint 5.6 implies that an updated equipment cannot be closed in the following periods, thus, avoiding absurd decisions mentioned in previous section. Despite that in previous experiments financial constraints were effective to avoid this kind of decisions, the inclusion of constraint 5.5 seems to be an incentive to induce updating projects because of its effect over production capacity constraints, thus, constraint 5.6 help in describing more realistic scenarios.

$$A^K_{bkt} \leq Q^K_{bk} \cdot x^K_{bkt} - Q^K_{ar} \cdot z^K_{bkt} \cdot \Theta \quad \forall b \in U^K, \forall k \in K, \forall t \in T$$ (5.5)
\begin{align*}
\sum_{b \in U^K} \sum_{t \in T} z_{b_{kt}} + \sum_{t \in T} o_{out_{bt}}^H \leq 1 & \quad \forall \ r \in R, \\
\end{align*}

Table 5.18 shows computational times for the profit maximization experiment, with and without constraints over the total investment (for this case, investments were constrained to be lower than 1E+009 USD). Figure 5.27 represents the obtained results, where the triangles corresponds to those solutions without investments constraints, and squares to those with investment constraints. A detailed description of the solutions obtained is presented in Annex 6.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>without investments constraint</th>
<th>with investment constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>time (s)</td>
<td>gap</td>
</tr>
<tr>
<td>t0</td>
<td>1178</td>
<td>2.97</td>
</tr>
<tr>
<td>t50</td>
<td>10374</td>
<td>2.84</td>
</tr>
<tr>
<td>t100</td>
<td>10278</td>
<td>2.85</td>
</tr>
<tr>
<td>t150</td>
<td>4761</td>
<td>2.99</td>
</tr>
</tbody>
</table>

Table 5.18: Computing times
Under the cost minimization scenario, it was found that taxes have an evident impact over the cost, but in order to have an important impact to reduce emissions, very high tax values are required. What are the maximum values that the cement sector could withstand? This experiment was designed to evaluate the impact of taxes over the profit of the firm, taking into account cement market prices. Different taxes were used to answer that question. The results in Figure 5.27 and Tables 5.19, 5.20 and 5.21 also demonstrate that taxes are effective to reduce emissions but have higher impact over the firm’s profit; however, this impact seems to be acceptable. This may imply that under current cement prices, firms are allowed to make important environmental improvement investment while maintaining acceptable profit levels.

Figure 5.27: Pareto solutions for profit Vs. emissions of CO$_2$
<table>
<thead>
<tr>
<th></th>
<th>t0</th>
<th>t50</th>
<th>t100</th>
<th>t150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cement production [10^7 ton]</td>
<td>4.55</td>
<td>4.54</td>
<td>4.54</td>
<td>4.54</td>
</tr>
<tr>
<td>Total tax payment [10^8 USD]</td>
<td>0</td>
<td>2.76</td>
<td>3.85</td>
<td>3.73</td>
</tr>
<tr>
<td>CO2 Emissions [10^7 ton]</td>
<td>2.83</td>
<td>2.82</td>
<td>2.65</td>
<td>2.47</td>
</tr>
<tr>
<td>Total investment [10^9 USD]</td>
<td>1.21</td>
<td>1.32</td>
<td>1.21</td>
<td>0.976</td>
</tr>
<tr>
<td>Profit [10^9 USD]</td>
<td>4.0</td>
<td>3.77</td>
<td>3.51</td>
<td>3.39</td>
</tr>
</tbody>
</table>

Table 5.19: Results for the profit maximization problem

<table>
<thead>
<tr>
<th></th>
<th>t0</th>
<th>t50</th>
<th>t100</th>
<th>t150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cement production [10^7 ton]</td>
<td>4.55</td>
<td>4.54</td>
<td>4.46</td>
<td>4.46</td>
</tr>
<tr>
<td>Total tax payment [10^8 USD]</td>
<td>0</td>
<td>2.77</td>
<td>2.94</td>
<td>3.74</td>
</tr>
<tr>
<td>CO2 Emissions [10^7 ton]</td>
<td>2.83</td>
<td>2.81</td>
<td>2.52</td>
<td>2.47</td>
</tr>
<tr>
<td>Total investment [10^9 USD]</td>
<td>9.03</td>
<td>9.02</td>
<td>9.59</td>
<td>9.75</td>
</tr>
<tr>
<td>Profit [10^9 USD]</td>
<td>4.00</td>
<td>3.74</td>
<td>3.51</td>
<td>3.38</td>
</tr>
</tbody>
</table>

Table 5.20: Results for the profit maximization problems, investments constraint I ≤ 1E+009 USD

<table>
<thead>
<tr>
<th></th>
<th>t50</th>
<th>t100</th>
<th>t150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission reduction</td>
<td>0.68</td>
<td>6.46</td>
<td>12.78</td>
</tr>
<tr>
<td>Profit reduction</td>
<td>6.11</td>
<td>12.44</td>
<td>15.61</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Investments ≤ [10^9 USD]</th>
<th>t50</th>
<th>t100</th>
<th>t150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission reduction</td>
<td>0.45</td>
<td>10.98</td>
<td>12.52</td>
</tr>
<tr>
<td>Profit reduction</td>
<td>6.61</td>
<td>12.27</td>
<td>15.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No investment constraint</th>
<th>t50</th>
<th>t100</th>
<th>t150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission reduction</td>
<td>0.68</td>
<td>6.46</td>
<td>12.78</td>
</tr>
<tr>
<td>Profit reduction</td>
<td>6.11</td>
<td>12.44</td>
<td>15.61</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Investments ≤ [10^9 USD]</th>
<th>t50</th>
<th>t100</th>
<th>t150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission reduction</td>
<td>0.45</td>
<td>10.98</td>
<td>12.52</td>
</tr>
<tr>
<td>Profit reduction</td>
<td>6.61</td>
<td>12.27</td>
<td>15.50</td>
</tr>
</tbody>
</table>

Table 5.21: Percentual reduction on profit and emissions due to taxes payment system
Chapter 6

Conclusions

A multi-objective mixed-integer linear programming model was proposed to improve the environmental and economical performance of a complex supply chain, by means of the execution of technological updating projects, production capacity growth and/or the selection of fuel and raw material suppliers. As these subjects cannot be considered without addressing the consequences that they entail on the configuration of the supply chain, the model simultaneously allows to make technical decisions regarding the manufacturing processes and the network design. By integrating these two levels, the aim of this project was to find an optimum production scheme in a short term planning period. The most important characteristics of the proposed model are the following: (i) it allows to recognize the current state of an operating supply chain and to select, among a defined set of technology-updating alternatives, those that better meet the objectives; (ii) the manufacturing process is decomposed into sub-processes, each with its own improvement alternatives; and (iii) the flow of sub-products between processes and facilities, and from facilities to customers is described. The following three extensions of the model were proposed and tested:

- A static four-objective model where total cost and the emissions of $CO_2$, $NO_x$, and $SO_x$ as objective functions. Due to the high computational requirements of a complete exploration
of the solution space, the test instance used to test the model only included a two-echelon supply chain and a single planning period.

- A dynamic bi-objective model that included five planning periods and a wider supply chain with tree manufacturing process and also external suppliers. Two objectives were considered for this experiment (i.e. total cost and CO$_2$ emissions).

- A dynamic single objective model, where CO$_2$ emissions were transformed into cost by considering a carbon cap and a carbon tax payment system. In this experiment, two financial objective functions were explored: cost minimization and profit maximization.

To illustrate the capabilities of this proposal, the model was applied to the cement industry, known to be responsible for 5 to 7% of global CO$_2$ emissions. These high carbon emissions of global cement production has motivated this industrial sector to develop road-maps to improve its environmental performance. The data used to describe each possible production technology, their costs and emissions were retrieved from a wide revision of published environmental improvement road-maps for the cement industry. A test instance with 10 production plants, 30 groups of customers (aggregated by its geographical location) and 70-110 improvement projects by plant, was used.

The results of the computational experiments conducted revealed that the environmental performance of the supply chain can be improved by shutting down most of the current operating equipment, an action that is offset by increasing the capacity in those that remain in operation. Energy efficiency of the new installed equipment contributes to reduce emissions and to achieve lower operational costs. Cleaner fuels are important in emission reduction but may increase the operational costs. Optimal potential capacity allocation is a simultaneous strategy to reduce logistics costs and transportation emissions.

As a multi-objective problem, not only one, but a set of efficient solutions was obtained. A summary of the obtained results is expressed in terms of three main conclusions that the computational experiments allowed to find: (i) it is possible to find a “win-win” scenario with respect to the current state of the system; very important improvements in the environmental performance are obtained
under low investments or even more, operational savings, (ii) the efficient solutions obtained represent a clear trade-off between costs and emissions, (iii) the cement industry is capable of absorbing the highest evaluated carbon tax values, maintaining acceptable profitability levels.

Notwithstanding the very common use of operations research methods to design sustainable supply chains and production processes, the problem of improving the environmental performance of an operating supply chain by means of technology-updating projects, specifically addressed for each sub-process of the manufacturing process, and how these projects convey changes in the supply chain design has not received due attention in the academic literature. The proposed tool demonstrated its usefulness to engage the complex challenge of simultaneously modeling operational and strategic decisions considering its environmental and financial implications.

This modeling exercise provides empirical evidence of the complexity of the decisions involved in the improvement of the environmental performance of an operating system. The results clearly demonstrate the effectiveness of using a multi-objective mathematical programming approach to design strategies towards a more sustainable supply chain.

The obtained results has significant implications for the firms but also for public polices design, described in following subsections. Future extensions of the problem are described in the last section.

### 6.1 Management implications

The current environmental state of the global system, implies a big challenge for companies. Profitability cannot be the unique goal, as to achieve long term sustainability, firms need to ensure local and global environmental quality. While current efforts to reduce environmental impacts of productive process preferably depend on the own management goals of each firm, the global awareness of the problem will lead to create non voluntary, but mandatory commitments. However, the change from a pollutant trajectory to a cleaner one, means breaking the “inertia” of a system and,
in turn, represents a financial challenge because of the costs involved in shutting down an operating process and disassembling, rebuilding or relocating facilities.

One of the key aspects of this research was to study the trade-offs between direct costs and pollutant emissions. Regarding the classical question “does it pay to be green?”, our results clearly show a positive answer. Dismantling older technologies and installing new ones entail high financial investments. In the case of operating supply chains with obsolete components, however, the benefits are evident, as technological updates can lead to simultaneous environmental and financial improvements. For this case study, it is clear that the “business as usual strategy” is suboptimal; it was demonstrated that an operating system that does not use the BAT, has the opportunity to achieve better environmental and financial operation strategies. Once efficient technologies are installed, differences among cleaner and lower cots operational strategies come form the supply chain network design. At this point, cleaner energy resources constitute a strategic subject, and their availability defines an essential advantage for production allocation decisions. Carbon taxes represent a direct response to the described trade-off. For the case study, its use clearly demonstrated that in the context of cost minimization, higher taxes necessary conduce to a cleaner production process.

The benefits of high-scale production and the consequent higher transportation intensity remain a strategic subject in sustainable management systems. Large-scale production advantages depend on the particular characteristics of each product and production system. Only the sum of the results of detailed studies, with enough environmental indicators, can lead to complete conclusions about the large-scale production advantages. Considering the cement supply chain, this case study demonstrates that better solutions in terms of emissions reduction are related to higher production scales. That effect is stronger in the case of the kiln, thus emphasizing the importance of modeling as many stages as possible in the supply chain.

All of those subjects justify the use of an advanced decision making tool that allows to involve a wide variety of variables such emissions, costs, taxes, production allocation, transportation intensity, supplier selection in the integral planning of the production process.
As stated in [9], a costing exercises such as the one conducted for this work is commonly based on a few case studies published, and it is hard to extend published cost data to the implementation of energy efficient technologies in other countries or contexts. Thus, the analyses of real production process demands a very intensive previous work of searching for specific improvement projects costs.

However, the challenge for the firms not only concerns to recognizing the importance of simultaneously consideration of all those subjects in their decision making process, but also to assemble the information that makes possible the use of such a complete tool. This means to obtain very detailed data related to cost and environmental impacts for all echelons of the production and supply chain, but also to identify, in detail, possible improvement projects for every component in the system. In this sense, the knowledge of the process becomes a very important key of success in the decision making process.

Finally, it is remarked that communication with real potential users of the proposed tool has demonstrated that their improvement projects portfolio seems narrow when compared with the amount of improvement projects included in the test instance of this case study. Taking into account that the construction of the test instance was referenced on technical road maps published for cement industry, it is feasible to conclude that firms could also build a wider improvement project portfolio. One of the stronger capabilities of the proposed tool is its feasibility to evaluate a wide set of improvement projects for each process, at each facility, in order to find global efficient solutions.

### 6.2 Public policy implications

Among the wide range of solutions that represent a clear trade-off between costs and emissions, the question of which to select depends on the firms management decisions, but also on the public policies that create external mechanisms to induce pollutant emission reduction. Natural goals of the firms have a financial nature, hence, public mechanisms are invited to impose environmental
goals. As stated in [112], “If the market is left to operate freely, greenhouse gas emissions will be excessive, since there is insufficient incentive for firms and households to reduce emissions”. Emissions can be limited through normative mechanisms like emission norms or through financial mechanism, appealing to the classical “pigouvian principle”: polluters pay.

The advantage of a financial mechanism over an emission limit or standard, is the recognition of significant differences among abatement costs for each firm or productive sector. For firms with lower abatement costs, emission reduction is the most attractive option, whereas for firms with higher abatement costs, they are induced to pay taxes or to buy emission allowances. To fix the value to pay is a difficult matter; too low and firms are likely to opt for paying and continuing to pollute. Too high and the costs will rise higher than necessary to reduce emissions, impacting profits, jobs and end consumers [112, 113].

In this case study the results indicate that only very high tax values could drive to cleaner production scenarios. This means that in the case of common current taxes, the option of pay and pollute would be probably selected by the firms. Considering the very important role of cement sector in global CO₂ emissions and also, the very high levels of consumption of this product, this scenario is not desirable and thus, it is necessary to explore how to induce technological updating.

The test instance of the case study was based on a five-year planning horizon; an extended horizon would mean lower abatement costs. In a real business case, better financial conditions to achieve lower emission could imply (i) to use public incentives to reduce the capital cost for environmental improvement investments, and/or (ii) to induce companies to merger in order to achieve wider markets and use high scale economies.

Of course, it is necessary to mention a tacit subject in every planet vs. profit trade-off analysis: environmental damages always cause externalities. These financial costs that are technically out of the financial balance constitute an important key issue to consider when favouring more efficient and cleaner production technologies.
Future work

This work constitutes another application of the concept of EWO (enterprise wide optimization) introduced by Grossman in [12]. As authors exposed in their original work, results demonstrate that current computational capacity supports the simultaneous modeling of a very wide set of subjects. In the same sense, it has been ratified that multi-objective solution methods are the right tool to address the challenge of decision making in the frame of sustainability. The high real applicability of this problem invites to keep working on its multiple possible extensions, considering more echelons in the supply chain as well as other key performance indicators. Major subjects in relation to future work are now highlighted:

Uncertainty

Literature review evidence a very wide treatment of uncertainty in supply chain management. In this work, the particular subject of uncertainty with respect to demand forecast was addressed by running the model for two demand growth scenarios. This multiple-scenario modeling strategy could be applied to other parameters such as fuel costs, inflation, raw materials cost, etc. However, it is also possible to aim for a systematic treatment of uncertainty. This is a crucial subject in middle or long term decision making tools, that deserves to be tackled in future works.

Linearization

The natural structure of the proposed model is non linear, due to the set of decisions that should be simultaneously undertaken and together define the objective function: main production technologies, complements, fuels and operating capacity. The proposed linearization strategy described in Section 4 demonstrated to be effective but demands complex data pre-processing. Other solution approaches, maintaining the non linear structure of the problem, could be explored.

Technological updating problem

Costs and environmental effects due to technological updating decisions, depend on the current state of the system; multiple changes imply to update, period by period, the description of the state of the system. This entails a more complex mathematical formulation, or to introduce the constraint
proposed by authors in [89] and used in this work: to allow only one change per process along the planning horizon. Considering the costs and complexity of updating projects, this constraint is acceptable with its real implications, but for a set of lower scope updating projects, it could be useful to design a modeling strategy that allows to adopt more than one change along the planning horizon, making it possible to update, period by period, the operational state of the supply chain and redefine its updating possibilities.

**Extensions of the problem for the cement industry case**

The case of the cement industry is particularly important because of the high energy inefficiency of production plants around the world and its very significant participation in global GWP emissions. After technological updating, the use of alternative cementing materials is a subject that should necessarily be involved in the environmental improvement process, and could be included in the model using the structure of an optimal mixture problem.

Despite the application of the model to the case of cement production, its structure can be perfectly applied to any supply chain. Technological updating opportunities in iron and steel, glass, paper, ammonia and motor systems sectors, published by the Institute for industrial efficiency -http://ietd.iipnetwork.org-, constitute an interesting target for other applications.

**Non exact solution methods**

Using the test instance designed for the case study and the described computing capacity, the proposed dynamic model cannot be solved for the four-objective problem; therefore, to propose a heuristic solution method seems to be a necessary option to execute the dynamic formulation with more than two-objectives. Non exact solution methods could also be useful to explore solutions methods for the non-linear original formulation of the problem.

**planning period length Vs. Amortization period of the investment**

The dynamic formulation of the model has an horizon defined by the number of planning periods, which mainly represent a defined demand forecast; however, selected updating projects to execute during this time, implies assets acquisition and investments with amortization periods that are
much longer than the planning period. Hence, a more rigorous financial management of these investments during the planning period could be the subject of future work.

**Carbon emissions payment systems** The subject of the carbon emission payment system and its impacts over emission reduction and profitability of the firms is strategic. The presented approach is a brief contribution to the development of tools that could allow to design effective emissions payment mechanisms, but more experiments need to be conducted. Using the developed mathematical model, the following steps are proposed: (i) consider tax values as decision variables, and (ii) test tax and cap-and-trade systems with different cap and tax values.
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