Analysis of Multi-Company Collaborative Supply Chain Management Using MILP

by

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This is to certify that I have examined this copy of a master's thesis by

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This study is dedicated to the real owners of my success in life:

To my mother, father and sister

ABSTRACT

Production systems must interact with other systems for a better performance. The interaction among production systems is usually established when these systems exchange materials. Integrated analysis of different production systems can provide valuable insight and identify improvements in the financial and environmental performance of industrial supply chain systems. The optimal integration of production systems at an industrial zone for multi-period operation has been addressed in this thesis. A systematic approach to identify the synergy among different companies at the strategic level has been developed. The proposed approach uses three steps; the generation of standardized models for process equipment in the production systems, integration of these models that make up the supply chain system, and solution of the model and analysis of the results. The approach includes detailed MILP models for each production system to realize collaboration in a multi-period setting. The approach is illustrated with an example that is a simplified version of a real problem and tested on an industrial problem. It is shown that important improvements in the cost and release of environmentally harmful emissions can be accomplished by collaboration in supply chain systems.

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NOMENCLATURE

x_{ijklt}	amount of material *k* in unit *j* of company *i* in state *l* at period *t*
η_{ijk}	boiler efficiency
IN	indicator of input material to a process
OUT	indicator of output material from a process
CON	indicator of consumed material in process
GEN	indicator of generated material in process
a_{ijk}	coefficient of HP steam consumption
BC_{ijk}	constant that represents the amount of electricity or MP steam consumption independent from the HP steam generation
b_{ijk}	coefficient of input material to a turbine
g_{ijk}	coefficient of output material from a turbine
TC_{ij}	electricity generation constant
x^{L}_{ijkl}	lower bound for the amount of material k in unit j of company i in state l
x^{U}_{ijkl}	upper bound for the amount of material k in unit j of company i in state l
N_{ij}	initial fuel inventory of tank j of company i
I_{ijt}	amount of fuel in tank j of company i at period t
Yf_{ijkt}	binary variable which is 1 if fuel k is purchased for tank j of company i in period t
CPO_{ijk}	fixed cost of purchase order that incurs whenever a purchase order is given
Cp_{ijkt}	total purchase cost of fuel *k* that is purchased for the tank *j* of company *i* in period *t*
H_{ijk}	cost of carrying one unit of fuel *k* for one period in tank *j* of company *i*
I_{ijt}	amount of fuel inventory in tank *j* of company *i* at the end of period *t*

$xe_{iji'j't}$	amount of material exchanged from unit *j* of company *i* to unit *j'* of company *i'* at time *t*
d_{ijt}	amount of material demanded by unit *j* of company *i* at time *t*
s^{U}_{k}	upper limit for emission of fuel k
C_{ijkt}	cost of fuel used in the boilers
$XEC_{iji'j'}$	maximum amount of material that will be exchanged between unit *j* of company *i* and unit *j'* of company *i'* over the total time horizon
$\beta_{jj'}$	cost coefficient for the variable cost of investment from unit *j* to unit *j'*
$\alpha_{jj'}$	fixed cost of investment from unit *j* to unit *j'*
E_k	calorie content of fuel k
s_k	sulfur content of fuel k
c_k	cost of fuel k
P^{U}_{ijk}	upper limit for the purchase amount of fuel k for fuel tank j of company i
P^{L}_{ijk}	lower limit for the purchase amount of fuel k for fuel tank j of company i
CPT_{ijk}	capacity of tank j of company I
CR_k	unit cost of harmful substance k (e.g. SO_x) release
SSF	safety stock parameter
HP	high pressure steam
MP	medium pressure steam
LP	low pressure steam

Chapter 1

INTRODUCTION

Supply chain management (SCM) is the management of material and information flows both in and between facilities such as vendors, manufacturing process and assembly plants, distribution centers and retailers. The supply chain management decisions incorporate the behavior of the systems that use deterministic or stochastic models. The development of realistic models and excersizing the decisions that are derived from these models is an important challenge in supply chain management. Conceptual studies on supply chain management emphasized the importance of the strategic relationships between companies in order to increase financial and operational performance of these companies by reductions in the total cost and inventories throughout the supply chain, and increased levels of shared information.

One of the most significant paradigm shifts of modern business management is that individual organizations no longer compete as solely autonomous entities, but rather as supply chains. Supply chain management has entered the era of internetwork competition. In this emerging competitive environment, the ultimate success of the single organization will depend on its ability to integrate the intricate network of supply chain relationships. Increasingly, the management of multiple relationships across the supply chain is being referred to as supply chain management (SCM). Strictly speaking, the supply chain is not a chain of businesses with one-to-one, business-to-business relationships, but a network of multiple businesses and relationships. SCM offers the opportunity to capture the synergy of intra- and intercompany integration and management. In that sense, SCM deals with total business process excellence and represents a new way of managing the business and relationships with other members of the supply chain.

Most of the organizations have focused their attention to the effectiveness and efficiency of their functions separately. As a new way of managing their functions, a growing number of organizations have begun to realize the strategic importance of planning, controlling, and designing a supply chain as a whole. It is important for the organizations to capture the synergy of inter-functional and inter-organizational integration and coordination across the supply chain and to subsequently make better supply chain decisions. Decision makers are becoming aware that the successful coordination, integration and management of key decision processes across members of the supply chain will determine the ultimate success of the single organization.

In the last decade, the increase in energy demand, the technological advances in the supply devices, the financial cost evolution and the current concern to mitigate the environmental impact of the energy consumption have changed and, probably will continue changing the methods to supply and spread energy in order to fully satisfy the energy demand[1]. Models can be developed for the energy supply systems, which generally have complex structures, in order to make analysis and optimization on these systems. Modeling and optimization of the energy supply systems helps to reduce the energy consumption and the harmful effects of these energy systems to the environment, while satisfying the energy demands of the production facilities. The generated models are the tools for the analysis of energy systems that allow the decision makers to make an efficient use of energy in the production facilities.

Financially and environmentally performance improvement is a must for survival and growth of industrial organizations. In every industrial sector, companies compete to produce their products at lower costs, with high quality and without harming the environment. Industrial organizations carry out their industrial activities usually at designated areas called industrial zones. An industrial zone is a collection of production systems belonging to different companies with distinct characteristics in the same area. Some of the production systems in the industrial zone have close interaction among each other due to supplierproducer relationships. The industrial zone is classified as the overall system while the individual production systems (organizations) can be considered as subsystems that are integral part of the overall system in this study. There is a high level of supply chain integration among these production systems. A strong interaction among production systems can be observed in the supply chain integration of the energy at an industrial zone. Since all production systems use energy for production, energy is an important candidate for supply chain integration. There are some other reasons for energy to be considered as an important material for integration: Since all of the subsystems require energy for production, there is almost always a central power production facility in the industrial zone, and also a number of subsystems may produce their own energy in their own utility plants. Production rate is proportional to the supply amount of energy; therefore, capacity and efficiency of a production facility is closely related to the supply amount of energy. A distinct feature of energy that differentiates it from the other materials is the inventory management: energy cannot be inventoried in its most effective form, as electricity or steam. For this reason careful attention must be paid for the production, storage, and transfer of all materials in energy systems. Another important characteristic of energy is the fact that energy generation systems release a large quantity of environmentally harmful substances such as SO_X, NO_X, and CO_X.

The objective of this thesis is to develop a quantitative assessment to the question: "Does the multi-organization collaborative SCM create a synergy to overcome financial and environmental obstacles and difficulties for survival and growth?". In this thesis, it is shown that a systematic approach can be very useful in identifying the synergy among a number of supply chain systems and detect improvements in the financial and environmental performance of these systems. The problem of integrating the energy production systems in an industrial zone by making necessary investments is formulated as a multi-period, mixed-integer linear programming problem. The model is formulated as a multi-period and multi-scenario model, so that energy generation planning and scenario analysis can be studied using the same model. The model simultaneously takes into account operation conditions, utility demands and material prices of all planning periods in the optimization process. The model is also used for budget planning, investment decision-making, electricity contract optimization and unit shutdown scheduling.

Linear programming and non-linear programming methods are generally used for such industrial optimization problems. But these methods can only handle the current operating conditions of the system. Therefore minimum operating or investment costs for longer periods cannot be guaranteed by these methods. Such problems usually require major computational effort with nonlinear models. Furthermore, solutions of nonlinear models can result in local optimum or may be unable to provide solution. Such unfavorable conditions, however, can be eliminated by using linear models. The linear models can be used to solve large scale industrial problems efficiently and accurately.

There are also some discrete decisions such as turning on and off some equipment or decisions about making an investment in the energy generation systems. Linear programming and non-linear programming methods cannot handle such discrete decision problems. For these reasons integer variables are employed in the model for determining equipment on/off, and investment decisions. The problem includes the solution of systems of disjunctions. Using a convex hull representation of each of the disjunctions, these equations are converted into an MILP problem. Detailed information about disjunctive programming is presented in Chapter 2.

The proposed approach has three main steps. The first step is the development of process models. The process units are modeled using fundamentals of thermodynamics, conservation of mass and energy, and by statistical analysis of existing process data. The process models for the most common equipment in the energy systems are given in Chapter 3. The second step is the development of a multi-period, mixed-integer linear programming model for each process system that is a collection of process equipment. The optimization model integrates the production systems in the industrial zone that involves systems of disjunctions. The last step is the analysis of the solution to identify financial and environmental improvements if the production systems are integrated through exchange of material and energy. The mathematical models and the formulation used to solve the integration problem are given in Chapter 3. In this chapter, all the components of the energy generation systems are modeled one by one and the formulations are presented explicitly. The application of this approach is illustrated through an example that is a simplified version of a real problem in Chapter 4. It is shown that important improvements in the cost and release of environmentally harmful substances can be accomplished by integration of different process systems at an industrial zone. In addition, application to an industrial problem is presented at the end of Chapter 4. Main conclusions and recommendations for future work are summarized in Chapter 5.

Chapter 2

LITERATURE REVIEW

Supply chain management has attracted a lot of attention recently due to its role involving all of the activities in industrial organizations ranging from raw material procurement to final product delivery to customers. Conceptual studies on supply chain management emphasized the importance of the strategic relationships between organizations in order to improve financial and operational performance of these organizations by reducing the total cost and inventories throughout the supply chain, and increased levels of shared information. The essence of this relationship is concerned with coordination between the participants: Reyniers[2], Whang[3], Sox et al.[4]. Partnering between industrial organizations is an increasingly common avenue for these organizations to find and maintain competitive advantage as mentioned by Mentzer[5] and Mohr and Spekman[6]. The nature of inter-firm partnering in supply chain management has been studied by Mentzer et al.[7]. These authors suggest a continuum of strategic and operational partnering based upon the orientation of the partners and the degree of implementation of partnering between two independent industrial organizations. This work also argued that implementation of strategic partnering leads to sustainable competitive advantage. Maloni and Benton[8] mentioned that extensive literature exists about concepts of supply chain management, but there are very few reports describing more rigorous quantitative approaches to address issues related to supply chain management. Lee and Kim[9] proposed a hybrid approach combining analytical and simulation models for planning production and distribution operations of supply chain systems considering capacity constraints and operation times.

A growing number of industrial organizations started to realize the strategic importance of planning, controlling, and designing supply chain networks as a whole rather than a collection of disconnected subsystems. Min and Zhou[10] reviewed the efforts in modeling supply chain operations, and identified key challenges and opportunities in modeling the operations in supply chain systems. They mentioned that synergy among industrial organizations is needed to overcome challenging issues about supply chain systems and this synergy is created by inter-functional and inter-organizational integration. Integrated process management was discussed by Scheifer[11] to deal with economic, quality and environmental aspects of supply chain systems and link its subsystems to make better decisions in the organization and control of the processes.

Energy systems have also attracted a lot of attention due to its role and importance in the performance of all industrial systems. Marechal and Kalitventzeff[12] mentioned the importance of the integration of multi-period utility systems for site scale process integration. In one of their previous studies in 1998 they determined the optimal configuration of utility systems for minimization of energy requirements. Rogers and Rowse[13] analyzed the gains from system integration using a multi-period multi-regional linear programming model of Canadian electric power supply. Tari and Söderström[14] developed a method for creating optimization models for industrial energy systems including material stores. The authors also determined the influence of the existence of material stores in an industrial energy system on the total system cost. Saeed et al.[15] addressed fuel consumption reduction by applying a pinch-point implementation. These approaches targeted minimization of the total cost of supplying energy to process systems.

Gonzales-Monroy and Cordoba[1] mentioned the importance of financial costs and environmental impact of energy generation. They considered a single energy production system that satisfies electricity demand in a city and recommended a solution to this problem using simulated annealing. Zhou et al.[16] integrated two multi-objective decision making methods, goal programming and analytic hierarchy process, to address sustainable supply chain optimization of continuous process industries.

Environmental impact is another important issue for energy production systems. An important issue in the industrial supply chain management is the satisfaction of all production requirements to achieve high profits while observing environmental regulations. Performance improvement, both financially and environmentally, is a must for survival and growth of industrial organizations. There is a high level of competition in all industrial sectors that are composed of several companies competing to produce the same or similar products at lower costs while trying to achieve higher levels of quality. There are also some environmental protection laws and protocols, like Kyoto Protocol that organizations have to follow that could impose significant restrictions on individual organizations' ability to sustain production levels. Bullinger, Steinaecker and Weller[17] mentioned that environmentally clean products and processes will represent a competitive factor of strategic impact to producing companies. They worked on modeling environmental aspects of products and processes. Liu and Sahinidis[18] modeled the problem of selecting processes and capacity expansion policies for a chemical complex as a multi-period, mixed integer linear programming problem. They developed a polyhedral approach to avoid addition of unnecessary variables and constraints.

Generalized disjunctive programming has been used as the modeling framework by Turkay and Grossmann[19] in the optimization of discrete continuous systems. Generalized disjunctive programming (GDP) is a natural modeling framework in which discrete decisions and discrete behaviors of units in a process network are represented. Another important characteristic of GDP is the ability to represent units as separate modules that allows flexibility in model generation, model analysis and custom solution algorithm development.

The mathematical model in this study includes a set of conditional constraints that are expressed as disjunctions. These disjunctions are given by equations and inequalities where the inequalities define the domain of validity for the constraints. The solution of such a system is defined by variable values satisfying the constraints, and exactly one set of constraints for each of the disjunctions. Using a convex hull representation of each of the disjunctions these constraints are converted into an MILP problem. Using the convex hull formulation for the systems of linear disjunctive constraints gives rise to a tight MILP model which has the important feature that it does not involve big-M constraints.

Several engineering design, synthesis and operation problems involving discrete choices and continuous variables can be modeled with the following generalized disjunctive programming model.

$$\min Z = \sum_{j \in D_k} \sum_{k \in K} c_{ik} + f(x)$$

$$s.t.$$

$$g(x) \leq 0, \tag{2.1}$$

$$\bigvee_{i \in D_k} \begin{bmatrix} Y_i \\ h_{ik}(x) = 0 \\ r_{ik}(x) \leq 0 \\ c_{ik} = \gamma_{ik} \end{bmatrix} k \in K,$$

$$x \in X, c_{ik} \geq 0, Y = 0,1$$

The above problem involves both continuous variables x, c_{ik} and boolean variables Y_i, that are to be selected so as to optimize an objective function Z that satisfies global constraints, g(x)≤0, and a set of disjunctions $k \in K$. The global constraints are independent of the discrete choices. Each disjunction involves several terms $i \in D_k$ and the OR operator, $\vee$, requires that at least one of these terms to be true. This means that the corresponding equations and inequalities must be satisfied for that term. For the terms that are false, neither the equations nor the inequalities need to hold.

The mathematical model is handled with a similar approach as explained above, and the problem is converted into an MILP problem, which is explained in detail in Appendix A.

Chapter 3

ENERGY GENERATION SYSTEMS

3.1 Introduction

Energy generation systems utilize fuel, air and some other materials to produce steam and electricity demanded by other process equipments in industrial systems. An example of an energy generation system is given in Figure 4.1. In such a system there are some common units such as fuel tanks, boilers, turbines, and mixers. Materials such as fuel, steam, and electricity are transferred between these processing units. The flow of materials in the system is modeled with variables x_{ijklt} representing the amount of material k in unit j of company i in state l at period t. The index l, which represents the state of the material k is included to model the mass and energy conservation equations effectively and takes one of the values *IN*, *OUT*, *CON*, or *GEN* according to the state of the material which can be an input to a process or output from a process, or consumed, or generated in a process equipment. Specific materials and states of a material are indicated with subscripts in constraints for easy understanding.

As a whole, the energy generation systems are constrained to verify a number of conditions associated with technical characteristics of the devices or to the way chosen to supply the energy. Therefore, a set of constraints must be taken into account in the optimization problem. Some of the common conditions are as follows:

- Demand must be fulfilled.
- Units have limited capacities. Thus, for a given unit, the capacity must range from a maximum to a minimum.
- The amount of material transfers should be greater than or equal to zero.

- Material balances around the units should be satisfied.
- Environmental regulations should be obeyed.
- Inventory levels should be monitored at each period.

There are also some other conditions and constraints that are specific to the process equipments in the systems.

As previously mentioned, there exist some common units in an energy generation system, some of which will be explained in the following subsections. These models use the templates that are developed for common processing equipment in production planning and scheduling[20]. In this thesis, these models are modified for multi-period operation and also on/off decisions for the energy system equipment are introduced. The multi-period MILP models are presented and explained in these subsections.

3.2 Boiler Models

A steam generating unit is one of the most important components of a fossil-fuel power plant, in which chemical energy of fossil fuels are utilized to obtain electrical work. Components in a steam generating unit are so arranged that they absorb heat efficiently from the products of combustion, i.e. hot gases that comes out of burning of coal or fuel oil. One of the important components in a steam generating unit is the burner which provides complete burning of coal or fuel oil with sufficient amount of pre-heated air. The purpose of pre-heating the input air is to increase the overall efficiency of the unit. The hot gases of combustion first meet the water tubes in the furnace where water undergoes the boiling phenomena. What leaves the furnace wall and screen tubes is usually a water-steam mixture and they lead to the main section of the boiler. The term "boiler" may sometimes refer to the whole steam generating unit. It is actually the part of the unit where water is boiled and steam is separated. Steam leaving the unit should have as high a thermal energy as possible so that it can be transferred to mechanical work in the turbines. Also the steam in turbines should be free from water droplets since they may cause corrosion. Hence a superheater is a necessary integral part of a steam generating unit. From heat transfer point of view, they should be in such a location where the combustion gases are quite hot. So they are placed right after the boiler screen tubes. Reheaters are essentially the same as superheaters in that they both heat up steam to economize and provide better turbine performance. Only the steam flow is from the high pressure turbine to the low pressure turbine. They are usually placed right after the superheater in the flow passage of hot gases. The hot gases of combustion after passing through the superheater, reheater, and boiler, still contain high thermal energy; so, if they are thrown out of the stack it would be a waste of energy. There are two ways employed to use the excess thermal energy: one is to heat up the feed water close to the saturation temperature in the so called economizer and the second one is to heat up the air in an air heater for combustion which also helps efficient burning of the fossil fuel. Although a steam generating unit can be considered to have a complex structure, in this study it is handled as a simplified unit because the details of what goes on in the steam generating unit is not the principal concern of this study.

In brief, boilers generate high pressure steam by burning fuel. As a consequence of burning fossil fuels, boilers generate environmentally harmful substances such as SO_X, NO_X, and CO_X. Boilers require electricity for operating the mechanical equipment and lower pressure steam for heating the boiler feed water. In general, two types of lower pressure steam are considered. These are LP (low pressure) and MP (medium pressure) steam. In the equations lower pressure steam will be represented by MP. Material flow around a typical boiler is illustrated in Figure 3.1.

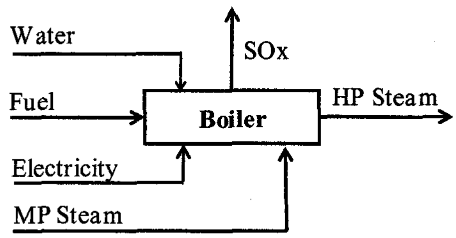


Figure 3.1 Schematic diagram of a boiler.

Boiler models include the following equations:

$$x_{ijk_{HP}l_{gen}t} = \frac{1}{\eta_{ijk_{fuel_m}}} cc_{k_{fuel_m}} x_{ijk_{fuel_m}l_{con}t} \qquad \forall_{ijt} \qquad (3.1)$$

$$x_{ijk_{MP}l_{con}t} = a_{ijk_{MP}} x_{ijk_{HP}l_{gen}t} + BC_{ijk_{MP}} \qquad \forall_{ijt} \qquad (3.2)$$

$$x_{ijk_{EL}l_{con}t} = a_{ijk_{EL}} x_{ijk_{HP}l_{gen}t} + BC_{ijk_{EL}} \qquad \forall_{ijt} \qquad (3.3)$$

$$x_{ijk_{SO_x}l_{gen}t} = s_{f_{fuel}} x_{ijk_{fuel}l_{con}t} \qquad \forall_{ijt} \qquad (3.4)$$

$$x_{ijkl_{in}t} + x_{ijkl_{gen}t} = x_{ijkl_{out}t} + x_{ijkl_{con}t} \qquad \forall_{ijkt} \qquad (3.5)$$

$$x_{ijkl't} = 0 \qquad \forall_{ijkl't} \qquad (3.6)$$

$$C_{ijk_{fuel}t} = c_{f_{fuel}} x_{ijk_{fuel}l_{con}t} \qquad \forall_{ijt} \qquad (3.7)$$

$$x^{L}_{ijk_{HP}l_{gen}} \leq x_{ijk_{HP}l_{gen}t} \leq x^{U}_{ijk_{HP}l_{gen}} \qquad \forall_{ijt} \qquad (3.8)$$

The amount of HP steam generation as a function of the fuel consumption is modeled in equation (3.1) which shows that the amount of steam generation is proportional to the consumption of the particular fuel used in the boiler. In addition, boiler efficiency, η_{ijk}, is a function of the fuel type. The parameter $cc_{k_{fuel_m}}$ represents the calory content of fuel m. Equations (3.2) and (3.3) model the electricity and MP steam consumption in the boiler as a function of the amount of HP steam generated. In these equations, a_{ijk} is the coefficient of produced and consumed entities depending on the particular boiler and BC_{ijk} is a constant representing the amount of material consumed regardless of the production quantity. These constants and coefficients are obtained by statistical analysis of the existing process data. The generation of SO_X as function of sulfur content of the particular fuel and the amount of fuel consumption in the boilers is given in equation (3.4). Equation (3.5) relates the states of materials in the boiler considering conservation of mass. In order to maintain consistency in the material balances, equation (3.6) fixes some of the states of materials to zero (e.g., since there is no HP steam consumption and HP steam input to the boilers, corresponding states of HP, *CON* and *IN*, are fixed to 0 in the boilers). Equation (3.7) models the total cost of fuel as function of the unit cost of fuel and fuel consumption in the boilers. Finally equation (3.8) enforces the upper and lower bounds for HP steam generation.

3.3 Turbine Models

The function of a steam turbine is to convert heat energy contained in high pressure steam into mechanical energy. The source of the high pressure steam is a boiler, in an energy production system. Fossil fuel (i.e. coal), or nuclear energy is consumed to provide the thermal energy in the boiler.

In a typical turbine, steam at higher pressures is expanded to steam at lower pressure and electricity is generated by the conversion of the mechanical energy, released during expansion, into electricity. A typical multi-stage turbine receives HP steam and produces electricity. The expanded steam which loses its energy leaves the turbine as lower pressure steam at different levels such as MP and LP steams. A typical turbine, and its inputs and outputs are illustrated in Figure 3.2.

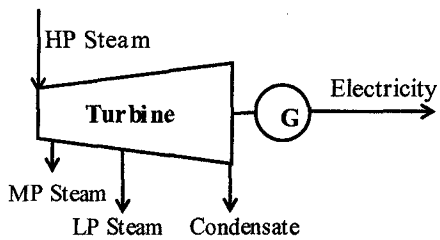


Figure 3.2 Schematic diagram for a turbine.

The operation of a turbine can be modeled using the following constraints.

$$x_{ijkl_{in}t} + x_{ijkl_{gen}t} = x_{ijkl_{out}t} + x_{ijkl_{con}t} \qquad \forall_{ijkt} \qquad (3.9)$$

$$x_{ijkl't} = 0 \qquad \forall_{ijkl't} \qquad (3.10)$$

$$x_{ijk_{EL}l_{gen}t} = \mathrm{b}_{\mathrm{ijk}_{\mathrm{HP}}} x_{ijk_{HP}l_{in}t} - \mathrm{g}_{\mathrm{ijk}_{\mathrm{MP}}} x_{ijk_{MP}l_{gen}t} - \mathrm{g}_{\mathrm{ijk}_{\mathrm{LP}}} x_{ijk_{LP}l_{gen}t} - \mathrm{TC}_{ij} \qquad \forall_{ijt} \qquad (3.11)$$

$$x_{ijk_{HP}l_{in}t} = x_{ijk_{MP}l_{gen}t} + x_{ijk_{LP}l_{gen}t} \qquad \forall_{ijt} \qquad (3.12)$$

$$\mathrm{x}^{\mathrm{L}}_{\mathrm{ijk_{EL}l_{gen}}} \leq x_{ijk_{EL}l_{gen}t} \leq \mathrm{x}^{\mathrm{U}}_{\mathrm{ijk_{EL}l_{gen}}} \qquad \forall_{ijt} \qquad (3.13)$$

Equation (3.9) relates the states of materials in the turbines considering conservation of mass. In order to maintain consistency in the material balances, equation (3.10) fixes some of the states of materials to zero (e.g., since there is no electricity consumption and electricity input to the turbines, corresponding states of electricity, *CON* and *IN*, are fixed to 0 in turbines). Electricity generation in a turbine is a function of the amount of HP steam feed and the amounts of MP and LP steam generation as shown in equation (3.11). The coefficients b_{ijk} and g_{ijk}, and the constant TC_{ij} in equation (3.11) are obtained by statistical analysis of the existing process data. The material balance around turbines is expressed in equation (3.12). The upper and lower bounds on the amount of electricity generated in turbines are given in equation (3.13).

3.4 Fuel Tank Models

Boilers receive fuel from fuel tanks which contain different kinds of fuel for generation of steam. The fuel tanks have finite capacity and contain an initial inventory, N_{ij}. The amount of fuel in tank j of company i at period t is represented by variable I_{ijt}. Tank models include the following equations:

$$x_{ijk_{fuel}l_{out}t} = \sum_{j' \in Boilers} x_{ij'k_{fuel}l_{in}t} \qquad \forall_{ijt} \qquad (3.14)$$

$$x_{ijk_{fuel}l_{IN}t} \leq \mathrm{P}_{\mathrm{ijk}}^{\mathrm{U}} * Yf_{ijkt} \qquad \forall_{ijt} \qquad (3.15)$$

$$x_{ijk_{fuel}l_{IN}t} \geq \mathrm{P}_{\mathrm{ijk}}^{\mathrm{L}} * Yf_{ijkt} \qquad \forall_{ijt} \qquad (3.16)$$

$$Cp_{ijk_{fuel}t} = \mathrm{CPO}_{\mathrm{ijk}} * Yf_{ijkt} \qquad \forall_{ijt} \qquad (3.17)$$

$$I_{ij(t-1)} + x_{ijk_{fuel}l_{IN}t} - I_{ijt} - \sum_{j' \in Boilers} x_{ij'k_{fuel}l_{in}t} = 0 \qquad \forall_{ijt} \qquad (3.18)$$

$$I_{ijt} \geq \mathrm{CPT}_{\mathrm{ijk}} * SSF \qquad \forall_{ijt} \qquad (3.19)$$

$$I_{ijt} \leq \mathrm{CPT}_{\mathrm{ijk}} \qquad \forall_{ijt} \qquad (3.20)$$

$$I_{ijt_0} = \mathrm{N}_{\mathrm{ij}} \qquad \forall_{ij} \qquad (3.21)$$

$$Hc_{ijk_{fuel}t} = \mathrm{H}_{\mathrm{ijk}} * I_{ijt} \qquad \forall_{ijt} \qquad (3.22)$$

The total amount of fuel that leaves a fuel tank must be equal to the total amount of fuel that is received by the boilers that are connected to that particular fuel tank. Equation (3.14) models the material balance between a fuel tank and the boilers that use the particular fuel in the fuel tank. The amount of a particular fuel used at every period may vary from period to period due to multi-period nature of the problem. For this reason the amount of fuel that remains in the tank must be updated at every period. Material balance around a fuel tank is modeled by equation (3.18), which updates the amount of inventory in a fuel tank. There is a safety stock that is the minimum level of fuel that must be available in a fuel tank. Equation (3.19) enforces the inventory at any period to be less than or equal to the total storage capacity of the fuel tank multiplied by the safety stock level as a fraction of the total storage capacity. The safety stock parameter, SSF, defines the fraction of the storage capacity. The amount of fuel in a fuel tank can not exceed the capacity of the tank, as illustrated in equation (3.20). The amount of fuel inventory in a tank at the beginning of the first period is equal to the initial inventory of that fuel given by N_{ij} as shown in equation (3.21). It is also possible to purchase fuel from other sources when there is insufficient inventory in the fuel tanks. Binary variable Yf_{ijkt} is 1 if fuel k is purchased for tank j of company i in period t. There is an upper and a lower limit for the fuel purchase amount as shown in equations (3.15) and (3.16) respectively. The parameter $\mathrm{CPO}_{\mathrm{ijk}}$ is fixed cost of purchase order that incurs whenever a purchase order is given. The variable $Cp_{ijk_{fuel}t}$ represents the fixed cost for purchasing fuel *k* that is purchased for the tank *j* of company *i* in period *t*. Equation (3.17) models the fixed cost of purchase in terms of the fixed cost of purchase and the binary variable Yf_{ijkt}. Finally, equation (3.22) models the holding cost of fuel inventory in terms of H_{ijk}, which is the cost of holding one unit of fuel *k* for one period in tank *j* of company *i* and I_{ijt} which is the amount of fuel inventory in tank *j* of company *i* at the end of period *t*.

3.5 Mixer/Splitter Models

Mixers/splitters are the units that receive and send the same type of material from and to different units. There is a mixer/splitter for each material in the system (e.g., HP steam mixer, LP steam mixer, MP steam mixer, electricity mixer). Material flow around a typical steam mixer is shown in Figure 3.3.

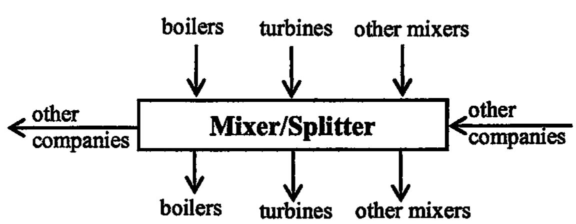


Figure 3.3 Schematic diagram for a mixer.

A mixer/splitter receiving material from the units that produces this particular material, from other mixers and from other companies, sends it to certain units that use this material to other mixers and to other companies. The flow of materials around a mixer/splitter is modeled by equation (3.23).

$$\sum_{j} x_{ijk_{b}ut} + \sum_{j} xe_{iji'j't} = \sum_{j} x_{ijklt} + \sum_{j} xe_{i'j'ijt} + \mathrm{d}_{ijt} \qquad (3.23)$$

The variable $xe_{iji'j't}$ represents the amount of material exchanged from unit j of company i to unit j' of company i' at time t. The amount of particular material demanded by unit j of company i at time t is represented by parameter d_{ijt}. The demand for any material is satisfied from mixers.

3.6 Fuel Selection

There are different types of fuels used in energy production systems. These fuels differ in price, availability or their content of environmentally harmful substances. Boilers can utilize different fuels with minimal adjustments in the settings of boiler equipment. There are many reasons for considering alternative fuels; one of the most important reasons is the insufficient amounts of fuel available in the inventory forcing the system to use an alternative fuel. Other reasons include the selection of economically and/or environmentally attractive fuel among the available alternatives. The use of alternative fuels in boilers is modeled using disjunctions as shown by Turkay and Grossmann[19].

$$\underset{m \in D_{ij}}{\vee} \begin{bmatrix} Y_{ijk_{fuel_m}t} \\ x_{ijk_{HP}l_{gen}t} = \dfrac{1}{\eta_{ijk_{fuel_m}}} \mathrm{cc}_{k_{fuel_m}} x_{ijk_{fuel_m}l_{con}t} \\ x_{ijk_{MP}l_{con}t} = \mathrm{a}_{ijk_{MP}} x_{ijk_{HP}l_{gen}t} \\ x_{ijk_{MP}l_{con}t} = \mathrm{a}_{ijk_{EL}} x_{ijk_{HP}l_{gen}t} \\ x_{ijk_{SO_x}l_{gen}t} = \mathrm{s}_{k_{fuel_m}} x_{ijk_{fuel_m}l_{con}t} \\ C_{ijk_{fuel_m}t} = \mathrm{c}_{k_{fuel_m}} x_{ijk_{fuel_m}l_{con}t} \\ \mathrm{x}^{L}_{ijk_{HP}l_{gen}} \le x_{ijk_{HP}l_{gen}t} \le \mathrm{x}^{U}_{ijk_{HP}l_{gen}} \end{bmatrix} \tag{3.24}$$

The above disjunction is included in the optimization model after the convex hull formulation as shown by Turkay and Grossmann[19]. The derivation of the convex hull formulation for equation (3.24) is given in Appendix A. The boilers can use only one type of fuel at a time for generating HP steam as indicated by equation (A.28). In addition, the HP steam generation (and fuel consumption as consequence of equation (A.20)) in the boilers is restricted to between an upper bound and lower bound with equations (A.25) and (A.26).

As a result of some environmental protection laws, there are some restrictions on the total emission of harmful chemicals for industrial organizations. At each period of time, there is an upper limit for the emission of SO_X, which is expressed in equation (3.25).

$$\sum_i \sum_j x_{ijk_{SO_x}l_{gen}t} \le \mathrm{s}^{U}_{k_{SO_x}} \tag{3.25}$$

3.7 Objective Function

The objective function of the problem is the minimization of the total cost, which is composed of operating cost and investment costs. The following subsections give detailed information about the formulation of the operating costs and the investment costs.

3.7.1 Operating Costs

Operating costs consist of the cost of fuel that is used in the boilers, fixed cost of purchasing fuel, holding cost of fuel inventory, cost of purchasing electricity from the utility company and penalty cost of harmful gas release. The first term in the objective function is the cost of fuel used in the boilers which is represented by the variable $C_{ijk_{fuel}t}$. The second and the third terms of the objective function which is the total fuel purchase cost and the fuel inventory holding costs were mentioned in equations (3.17) and (3.22) respectively. The fourth term is the cost of electricity purchase from the utility company which is a function of the amount of electricity purchased and the price of the electricity. Finally, the fifth term is the penalty cost of SO_x release.

3.7.2 Investment Costs

Investment has to be made for inter-company material exchanges, in order to integrate the system. For example, pipelines with certain capacities must be constructed to transfer material (e.g., steam) from one company to another. Similarly, investment has to be made to exchange electricity between companies. The capacity of the investment is determined by the following inequality.

$$XEC_{iji'j'} \geq XE_{iji'j't} \tag{3.26}$$

The variable $XEC_{iji'j'}$ represents the maximum amount of material that will be exchanged between unit *j* of company *i* and unit *j'* of company *i'* over the total time horizon. Therefore, the investment cost should be proportional to the variable $XEC_{iji'j'}$. Equation (3.27) gives the total cost of investment which is the second term in the objective function.

$$XEC_{iji'j'} * \beta_{jj'} + \alpha_{jj'} \tag{3.27}$$

In equation (3.27), the first term is the variable cost of investment where $\beta_{jj'}$ is the cost coefficient, and the second term is the fixed cost of investment where $\alpha_{jj'}$ is a constant.

Therefore, the objective function is defined as the minimization of the summation of all cost terms explained above, and is defined as follows:

$$\begin{aligned} \min Z = &\sum_i \sum_j \sum_k \sum_t C_{ijkt} \\ &+ \sum_i \sum_j \sum_k \sum_t CP_{ijkt} \\ &+ \sum_i \sum_j \sum_k \sum_t Hc_{ijkt} \\ &+ \sum_i \sum_j \sum_{i'} \sum_{j'} \sum_t (XE_{iji'j't} * CE_{iji'j'}) \\ &+ \sum_i \sum_j \sum_t X_{ijk_{SOX}l_{GEN}t} * CR_{k_{SOX}} \\ &+ \sum_i \sum_j \sum_{i'} \sum_{j'} (XEC_{iji'j'} * \beta_{jj'} + \alpha_{jj'}) \end{aligned} \tag{3.28}$$

The optimization model and the analysis of the results are illustrated in the following chapter with an example that is derived from an industrial system.

Chapter 4

EXAMPLES AND RESULTS

4.1 Illustrative Example

The illustrative example considers two energy systems with each system having two fuel tanks with different fuels, two boilers, two turbines, and one mixer for each type of material as shown in Figure 4.1.

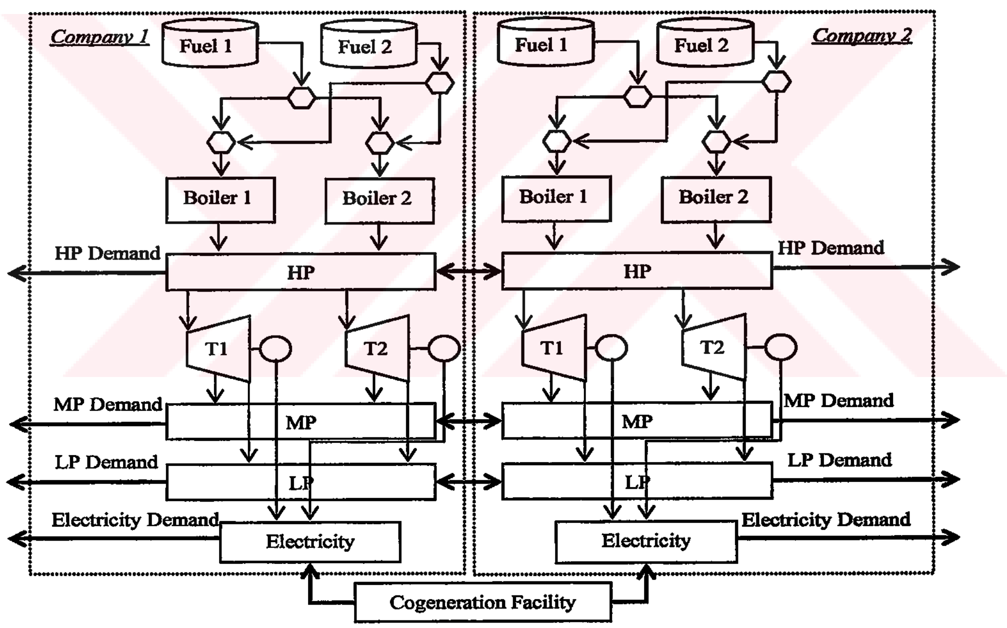


Figure 4.1 Flow sheet of the illustrative example.

The energy systems must fulfill the electricity and steam requirement of production systems they serve. The demand for steam (HP, MP, and LP) and electricity is a function of production rate and energy requirement characteristics of the processes that the energy systems are serving. The parameters about the operating characteristics of the utility system and the investment costs to integrate the system are given in Table 4.1 and 4.2 respectively. Energy requirements for the processes at each period in the example are given in Table 4.3.

Table 4.1 Operating characteristics for the utility system in the illustrative example.

	Company 1		**Company 2**	
	Fuel 1	*Fuel 2*	*Fuel 1*	*Fuel 2*
E_k	10.5	9.65	6.65	10.2
N_{ijk}	100	40	120	100
s_k	7.8	1.42	1.2	5.13
c_k	200	135	83	95
P^U_{ijk}	25	40	40	30
P^L_{ijk}	0	0	0	0
CPO_{ijk}	100	100	100	100
CPT_{ijk}	120	50	130	110
H_{ijk}	10	15	10	15
	Boiler 1	*Boiler 2*	*Boiler 1*	*Boiler 2*
$\eta_{ijk_{fuel1}}$	0.6	0.58	0.58	0.57
$\eta_{ijk_{fuel2}}$	0.6	0.58	0.58	0.57
$a_{ijk_{MP}}$	0.11	0.12	0.11	0.12
$a_{ijk_{EL}}$	0.002	0.003	0.0025	0.0028
$x^u_{ijk_{HP} l_{gen}}$	550	550	600	600
	Turb. 1	*Turb. 2*	*Turb. 1*	*Turb. 2*
$b_{ijk_{HP}}$	0.150	0.175	0.160	0.170
$g_{ijk_{MP}}$	0.070	0.080	0.070	0.075
$g_{ijk_{LP}}$	0.009	0.010	0.012	0.010
$x^u_{ijk_{FT} l_{gen}}$	70	60	70	65
$x^u_{ijk_{St\_MP} l_{gen}}$	300	300	400	400
$x^u_{ijk_{St\_LP} l_{gen}}$	300	300	300	300

Table 4.2 Fixed and variable cost of investment.

Source Mixer	Destination Mixer	Fixed Cost	Variable Cost
HP1	HP2	0	0.4
HP2	HP1	0	0.4
LP1	LP2	0	0.2
LP2	LP1	0	0.2
MP1	MP2	0	0.3
MP2	MP1	0	0.3
LP1	LPU	0	0.4
LP2	LPU	0	0.4
LPU	LP1	0	0.4
LPU	LP2	0	0.4

Table 4.3 Energy demand in the example problem.

Demand	Period	Company 1	Company
Electricity	1	150	140
	2	200	180
	3	180	160
HP Steam	1	10	10
	2	13	15
	3	8	12
MP Steam	1	620	300
	2	423	345
	3	510	385
LP Steam	1	300	680
	2	260	500
	3	350	570

The problem is modeled in OPL Studio and solved using ILOG CPLEX[21]. The number of constraints and variables included in the problem are given in Table 4.4. The multi-period mixed integer linear programming problem is solved in 421 nodes with 2007 iterations in 5.1 CPU seconds on a computer with Pentium 4 processor at 1.4 GHz speed and 512 MB of RAM memory.

Table 4.4 Statistics of problem size and solution for illustrative example.

Number of constraints	912
Number of variables	16,919
Number of nodes	421
Number of iterations	2,007
CPU time (sec)	5.1

The same problem is also solved after eliminating the exchange of materials between companies. In the non-integrated problem, the amounts of materials exchanged between companies are set to zero. The comparison of the results of the integrated problem and the non-integrated problem clearly shows the synergy generated by integration of the companies through exchange of materials. It is observed that steam expansion that means lost energy decreased and exchange of steam and electricity exists as shown in Tables 4.5 and 4.6. For example, in the optimal solution for non-integrated system there is a large quantity of steam flow from the higher pressure steam mixers to the lower pressure steam mixers of the same company. The flow of steam between two steam mixers is called steam expansion, when steam that is at a higher energy level loses its energy and becomes steam at a lower energy level without its energy being extracted in the steam turbines. The expansion of steam from a higher pressure mixer to a lower pressure mixer means that the energy is lost between two mixers. Since exchange of materials is not allowed in the non-integrated problem, it is observed that boilers produce more HP steam than the required amount for fulfilling the MP and LP steam requirement through expansion. On the other hand, since there is material exchange between the equivalent mixers of different companies, the energy integrated solution fulfills the energy requirement of both of the companies at a lower cost. In other words, as a result of the integration, the amount of lost energy decreases and the system meets the demand more efficiently.

Table 4.5 Material exchange in the nonintegrated solution

Company i	**Unit j**	**Company *i'***	**Unit *j'***	**Period**	**Amount**
Company1	HP1	Company1	MP1	1	141
Company1	HP1	Company1	MP1	3	23.5
Company2	HP2	Company2	MP2	1	7.3
Company2	MP2	Company2	LP2	1	80
CompanyU	ElecU	Company1	Elec1	1	55.5
CompanyU	ElecU	Company1	Elec1	2	117.4
CompanyU	ElecU	Company1	Elec1	3	78
CompanyU	ElecU	Company2	Elec2	1	7.9
CompanyU	ElecU	Company2	Elec2	2	66
CompanyU	ElecU	Company2	Elec2	3	31

Table 4.6 Material exchange in the integrated solution.

Company i	Unit j	Company i'	Unit j'	Period	Amount
Company1	LP1	Company2	LP2	1	98.9
Company1	LP1	Company2	LP2	3	62.67
Company2	HP2	Company1	HP1	1	38.7
Company2	HP2	Company1	HP1	2	38.7
Company2	HP2	Company1	HP1	3	25.4
Company2	HP2	Company2	MP2	1	13.3
Company2	LP2	Company1	LP1	2	31
Company2	MP2	Company1	MP1	1	132.2
Company2	MP2	Company1	MP1	2	132.2
Company2	MP2	Company1	MP1	3	132.2
Company2	MP2	Company2	LP2	1	37.8
CompanyU	ElecU	Company1	Elec1	1	41.4
CompanyU	ElecU	Company1	Elec1	2	135
CompanyU	ElecU	Company1	Elec1	3	78
CompanyU	ElecU	Company2	Elec2	1	8.1
CompanyU	ElecU	Company2	Elec2	2	48
CompanyU	ElecU	Company2	Elec2	3	28

Financial and environmental improvements as a result of the integration are illustrated in Table 4.7. The integration of the system leads to 2.42% reduction in the total cost at the optimal solution. It is also important to notice that 7.23% reduction in the SO_X emission is obtained through supply chain integration.

Table 4.7 Comparison of the results.

	Nonintegrated	Integrated	Change (%)
Total Cost	57,438.54	56,047.89	2.42
SO_x Release	1,146.65	1,063.72	7.23

4.2 Industrial Example

The approach proposed in the paper is applied to an industrial problem which is a significantly larger problem compared to the illustrative example. There are three companies and a cogeneration facility in the system which can be described as the energy production systems in an industrial zone. There are different tanks, boilers, turbines, mixers, and splitters in the energy systems of each of these companies: 3 boilers, 6 turbines, 5 types of steam in Company 1; 7 boilers, 6 turbines, 6 types of steam in Company 2; 6 boilers, 5 turbines, 3 types of steam in Company 3; 6 types of steam in the Cogeneration facility. There are 11 types of steam that have different pressures generated and used in the overall system. The boilers are fed with different types of fuels with different characteristics such as calorific value, cost, and SO_X emission. There are 10 different types of fuel feeding the boilers which has different characteristics such as cost, calorific value, and SO_x emission. Each company has 5 different fuel tanks which contain the alternative fuels for the boilers in that company. The details of operating and design data for the industrial problem cannot be disclosed due to confidentiality. The statistics about the model size and the two-period solution are given in Table 4.8.

Table 4.8 Statistics about the problem size and the solution for the example.

Number of constraints	3,198
Number of variables	309,464
Number of nodes	0
Number of iterations	274
CPU time (sec)	143

As for the illustrative example, the industrial problem is solved to optimality for both the integrated and the non-integrated system, and the solutions are compared in order to emphasize the synergy by the systems integration. When the optimal solutions for the integrated and nonintegrated systems are compared, it is observed that the nonintegrated solution fulfills the energy requirement of the companies at a higher cost than the integrated solution. The difference in the cost between the optimal solutions for the integrated and nonintegrated cases is very large. In addition it is also observed that there is a substantial reduction in the SO_X emission levels. Therefore, energy-integrated solution fulfills the energy requirement of the companies at a lower cost while reducing SO_X emission to satisfactory levels.

The amounts of reductions in the total cost and the total SO_X emission are shown in Table 4.9.

Table 4.9 Comparison of the results of the industrial problem.

	Nonintegrated	**Integrated**	**Change (%)**
Total Cost	39,272,673	26,381,600	32.8
SO_x Release	11,457	7,909	30.9

Chapter 5

DATABASE INTEGRATION & GRAPHICAL USER INTERFACE

The decision makers may have major difficulties in modeling their problems and analyzing the solution effectively. Therefore, the model and the solutions derived from the model described in this thesis are communicated to decision makers through self sufficient software. The developed software has modules for entering data, creating a topology of the supply chain systems, interface to database and CPLEX solver, and display and reporting of the results.

5.1 Main Features of the Graphical User Interface

The software integrates a graphical user interface developed using Visual Basic, a relational database developed using ACCESS, and a mathematical programming solver (ILOG CPLEX) providing a flexible and user friendly environment for solving large-scale problems. The GUI employs a structure that allows users to define their model in different levels of detail. The problem is structured using the graphical user interface which is user friendly and the data is stored in tables in Visual Basic environment. These data tables are then linked from the GUI to a relational database (ACCESS). The data handling ability of the database is efficiently used by the model environment users. By this environment, the users don't have to deal with difficult database structures. Special constraints and the objective function are input in a standard optimization model (ILOG OPLStudio) file. The standard model can be modified according to requirements of different problems. After the data is completely entered into the data tables, GUI executes the solver to optimize the problem and capture the optimized results. A summary of the modeling environment is shown in Figure 5.1.

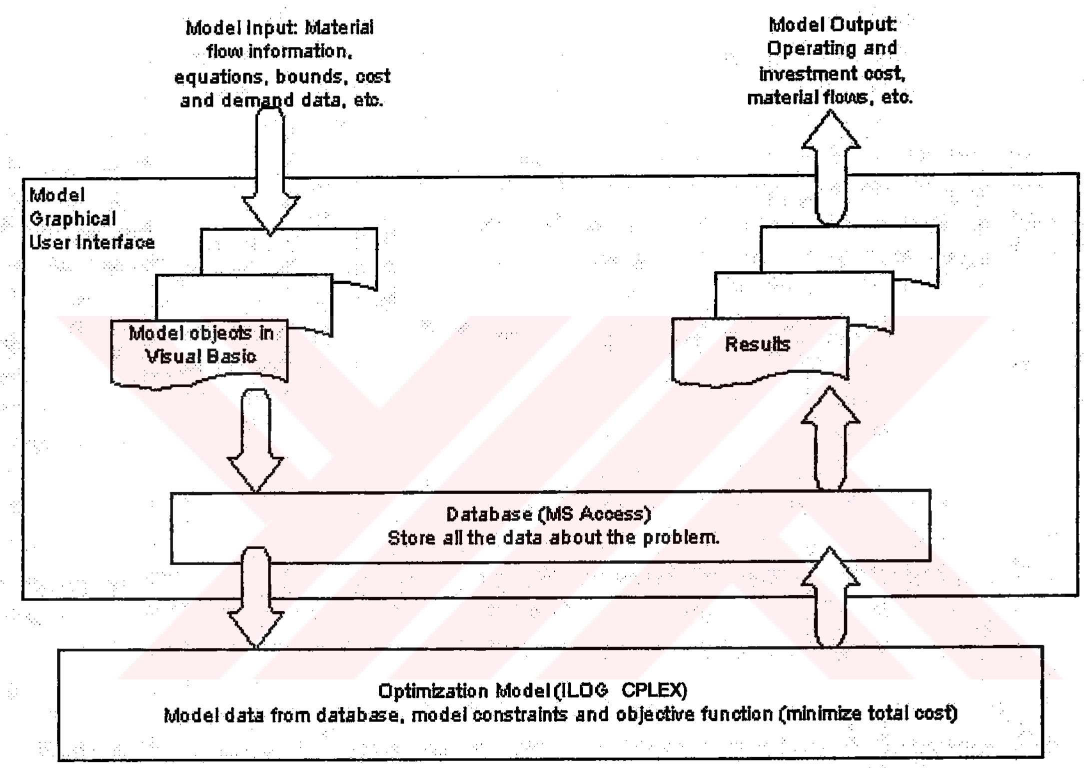


Figure 5.1 Modeling environment data flow diagram.

5.2 Main Menu and Topology Builder

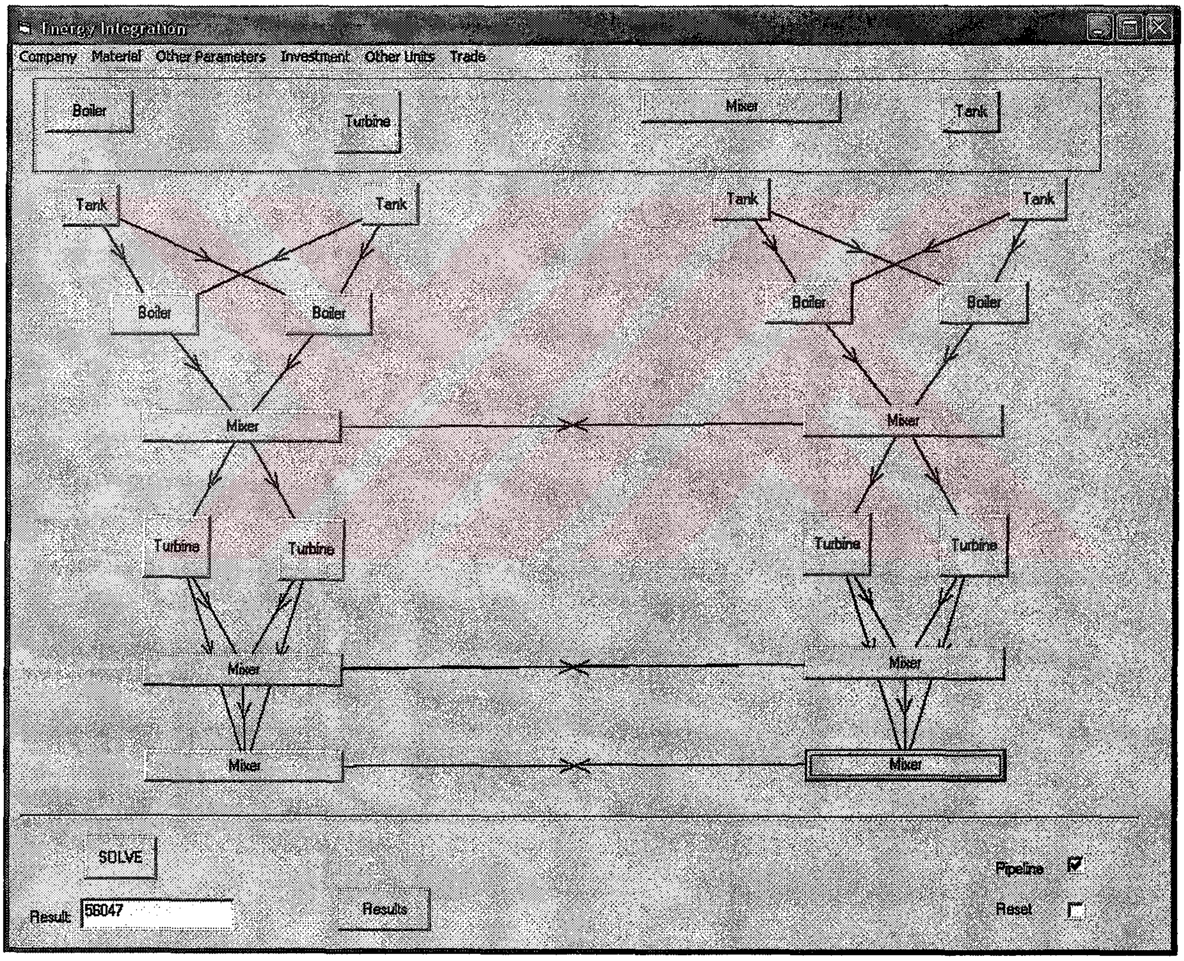


Figure 5.2 Main menu and the material flow diagram

The topology builder form appears when the software as shown in Figure 5.2. The toolbar at the top of the form contains some commands which are used for storing the system information in the database. These commands are "Company", "Material", "Other Parameters", "Investment", "Other Units", "Trade". The forms behind these command buttons are given below. Below this toolbar there are 4 groups of buttons which represent boilers, turbines, mixers and tanks respectively. The user drags and drops these buttons wherever he wants on the form and designs the energy system by creating the units and the material flows between these units as shown on the figure above. When the user clicks on any of the buttons representing a different unit on the form, the respective form about the unit opens and the data about the unit is entered and stored in the database via this form. After designing the system, the user clicks the "Solve" button which triggers the solver engine. ILOG CPLEX solves the model and gives the results. The objective value appears in the textbox at the bottom of the form. The resulting values of the variables are stored in tables in the database which can be viewed by clicking on the results button on the form.

5.3 Data Entry Forms

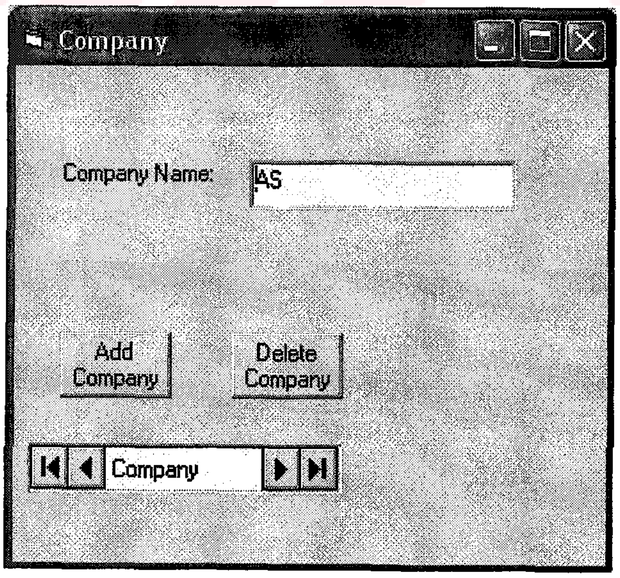


Figure 5.3 Company Form

The data entry form given in Figure 5.3 is used to store the company information. New companies can be added or existing companies can be deleted via "Add Company" and "Delete Company" buttons.

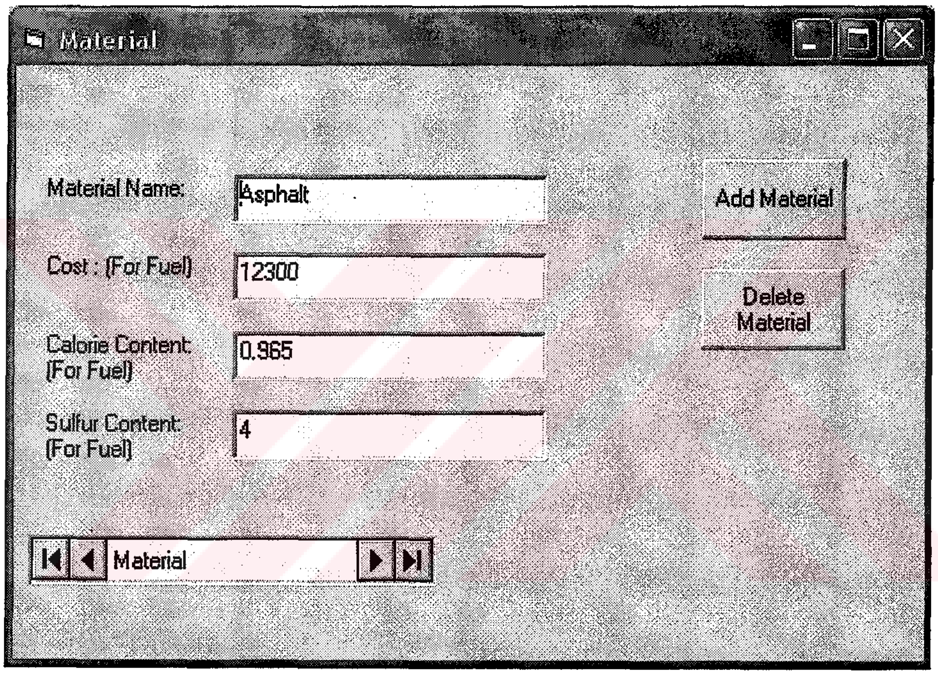


Figure 5.4 Material Form

By the above form in Figure 5.4, the specifications of the materials such as cost, calory content and sulfur content can be stored in the database.

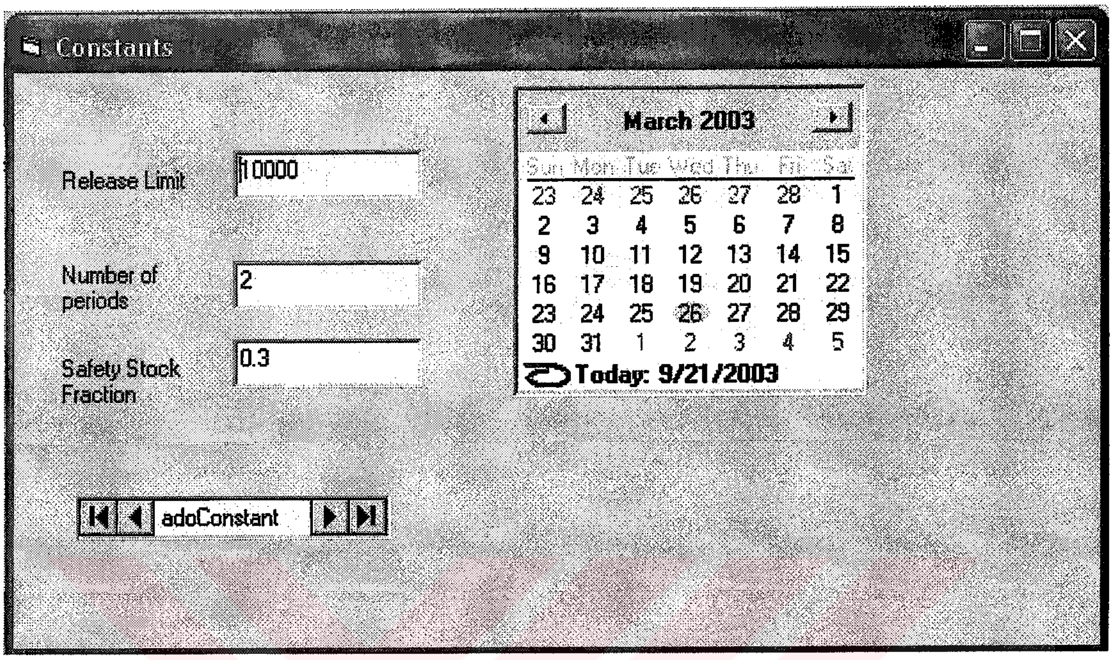


Figure 5.5 Constants form

The form given in Figure 5.4 is used for entering values of some constants such as the upper limit for harmful gas emission and the safety stock fraction for the fuel storage tanks. Also, by using the calendar at the right hand side of the form, the user can determine the number of periods (days) that the problem is solved for.

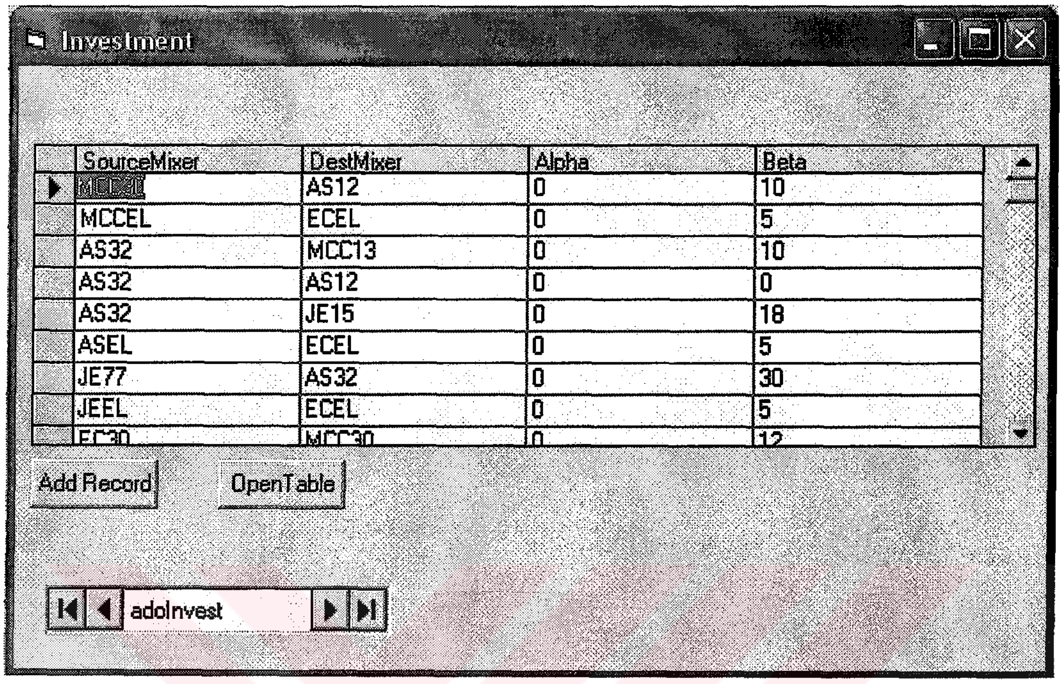


Figure 5.6 Investment form

The form in Figure 5.6 is used for entering the investment information, specifically fixed cost and variable cost of investment between the units in the system.

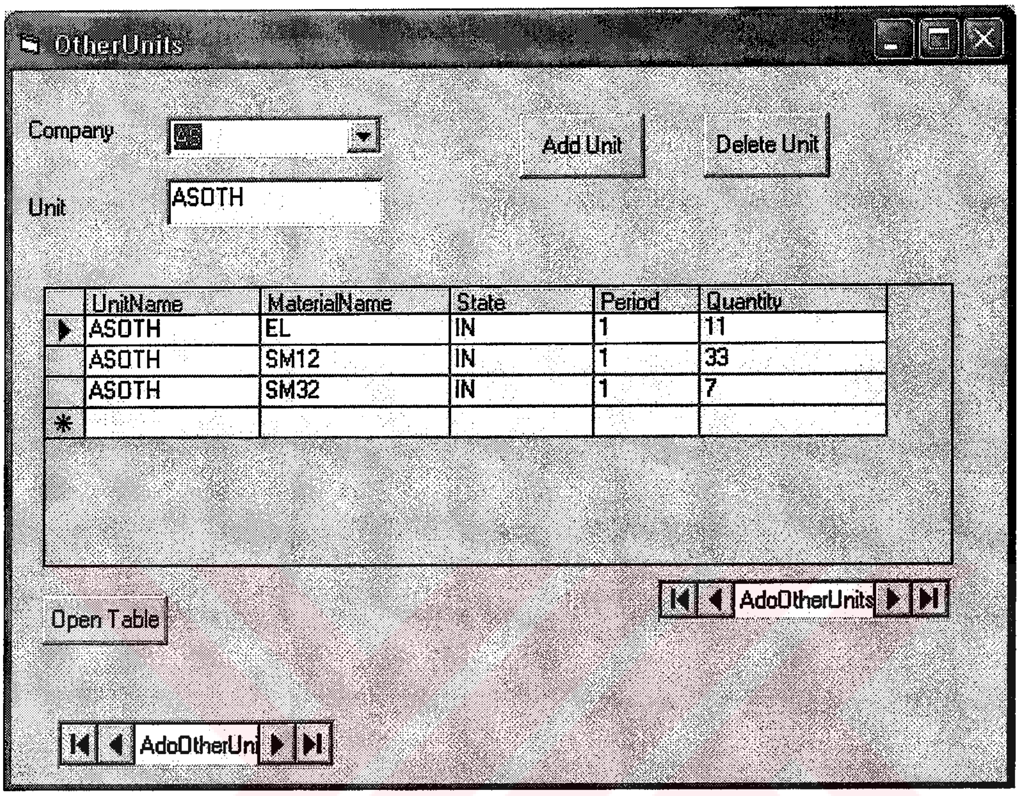


Figure 5.7 Other units form

"Other Units" form which is shown in Figure 5.7 is used for storing the material requirements of the other plants in the system.

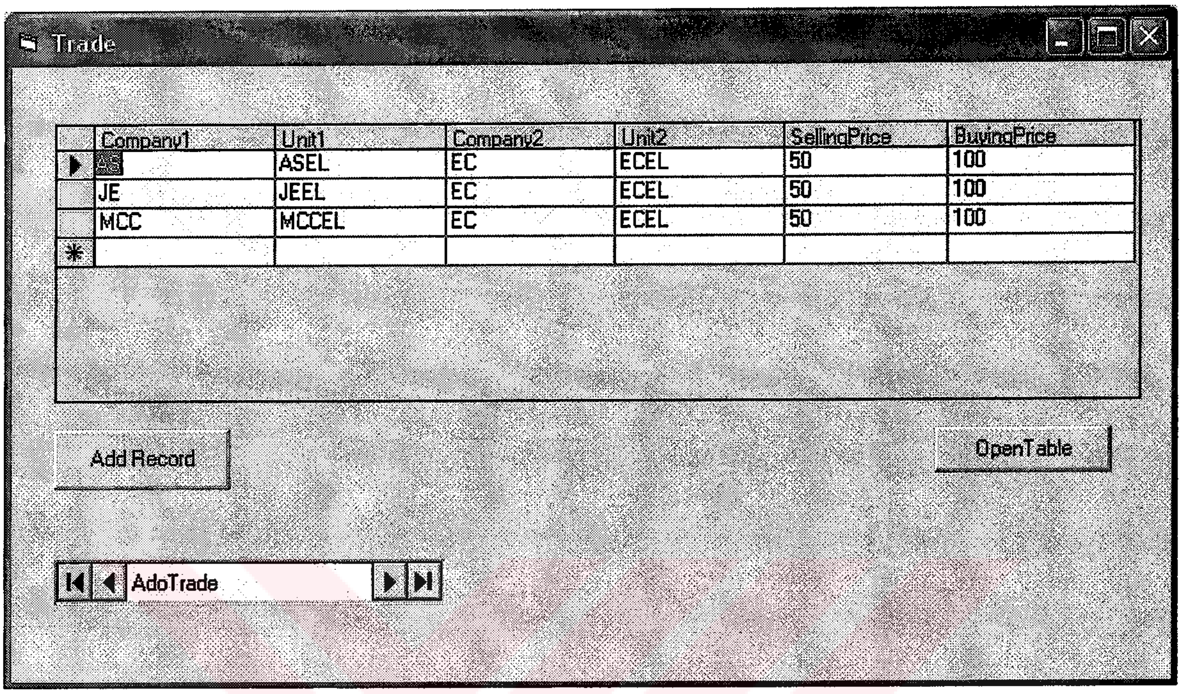


Figure 5.8 Trade form

By the "Trade" form, shown in Figure 5.8, the electricity selling and buying prices between the utility company and the other companies are stored in the database.

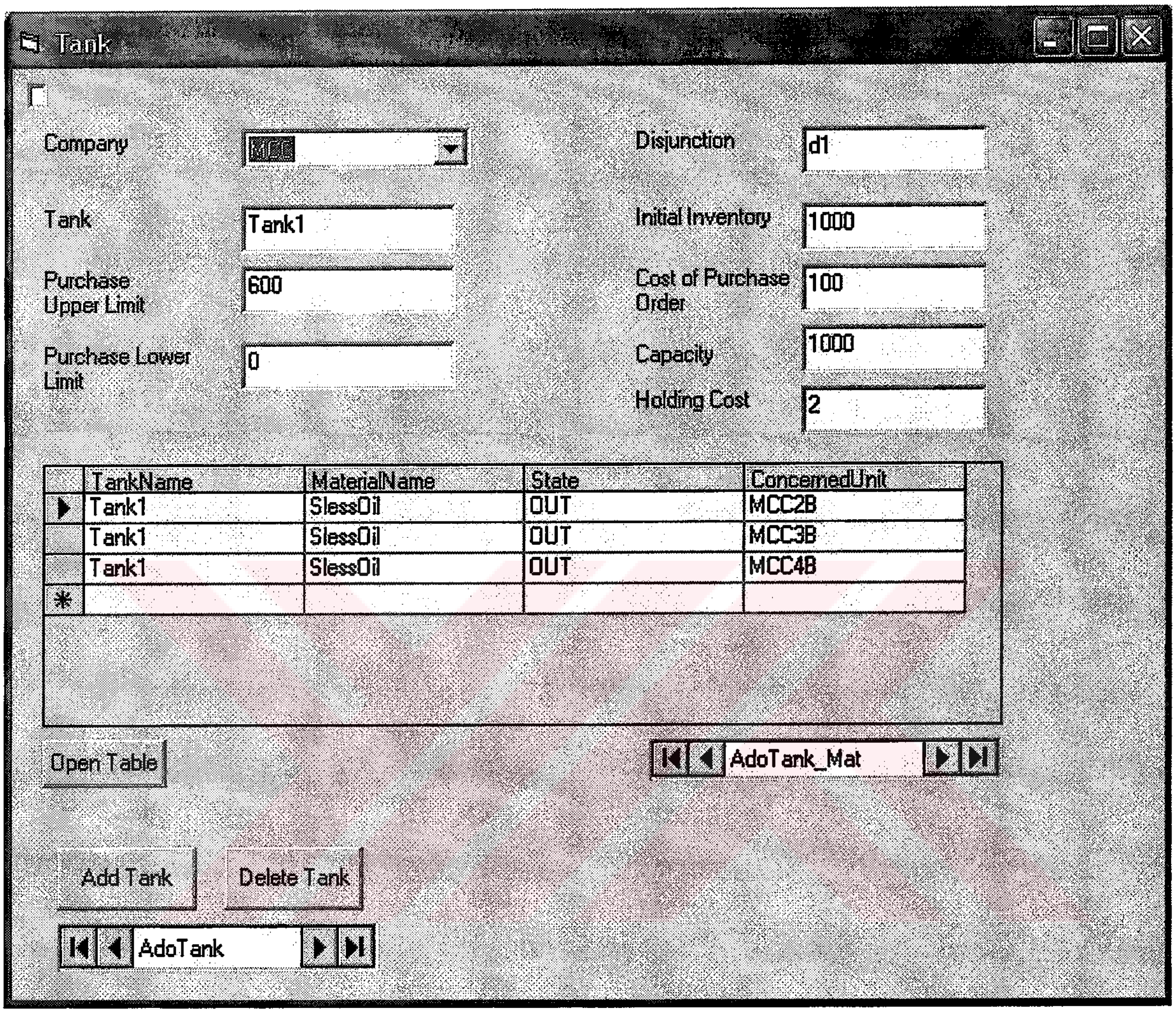


Figure 5.9 Tank form

In the "Tank" form, some specifications of the fuel storage tanks such as purchase upper and lower limits, the initial inventory, the cost of giving a purchase order, the capacity and the cost of holding a unit of fuel for a period of time are stored in the database as shown in Figure 5.9. In the lower sub-table, the material flow data between the fuel tanks and the boilers are stored in the database.

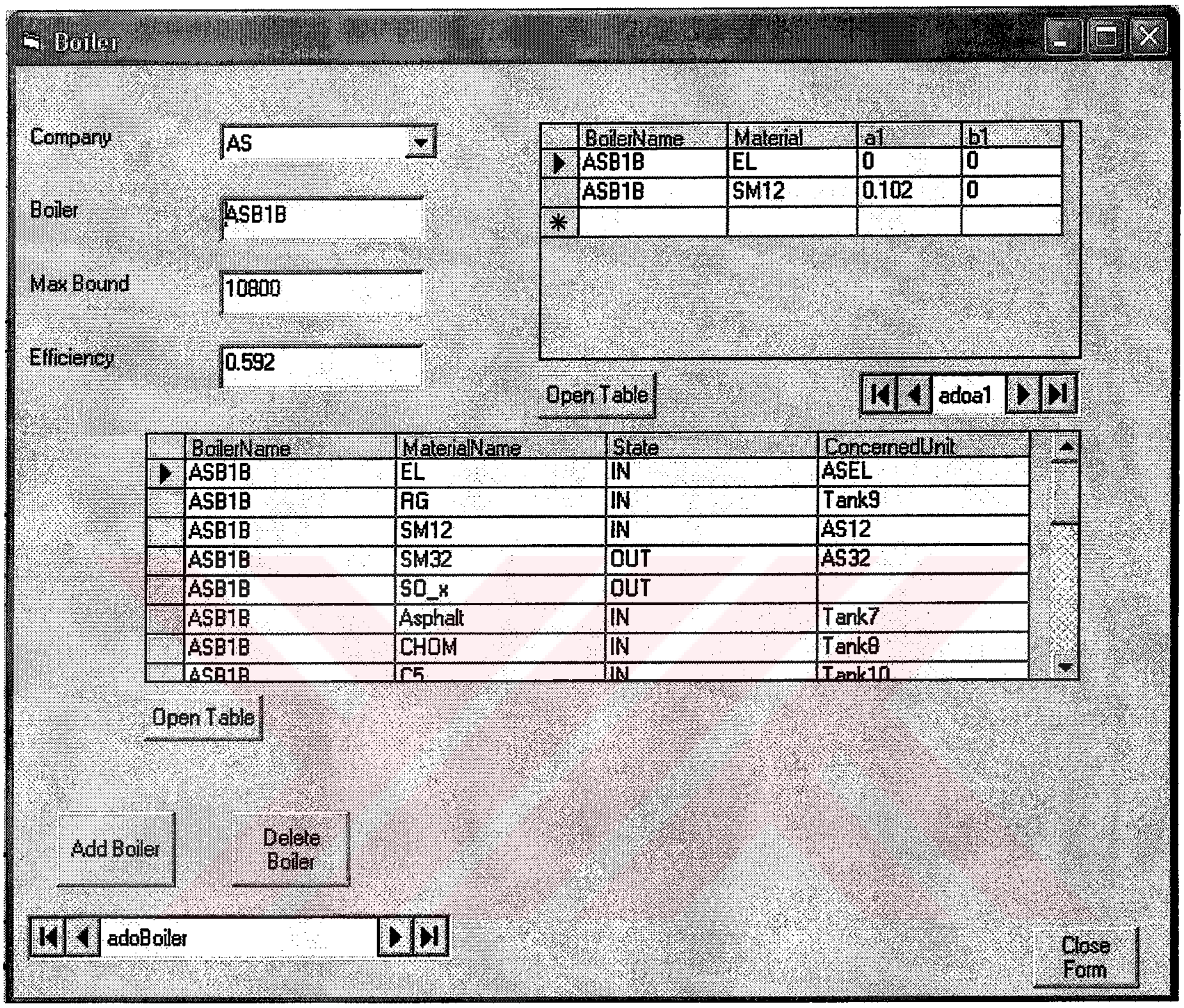


Figure 5.10 Boiler form

By the above "Boiler" form, the specifications such as maximum steam generation bound and the steam generation efficiency of the boilers are stored in the database, as shown in Figure 5.10. In the sub-table on the upper right of the form, some predetermined constants about the boilers that are specific to the materials are stored. In the lower sub-table, material flow data between the boilers and the other units in the system are stored.

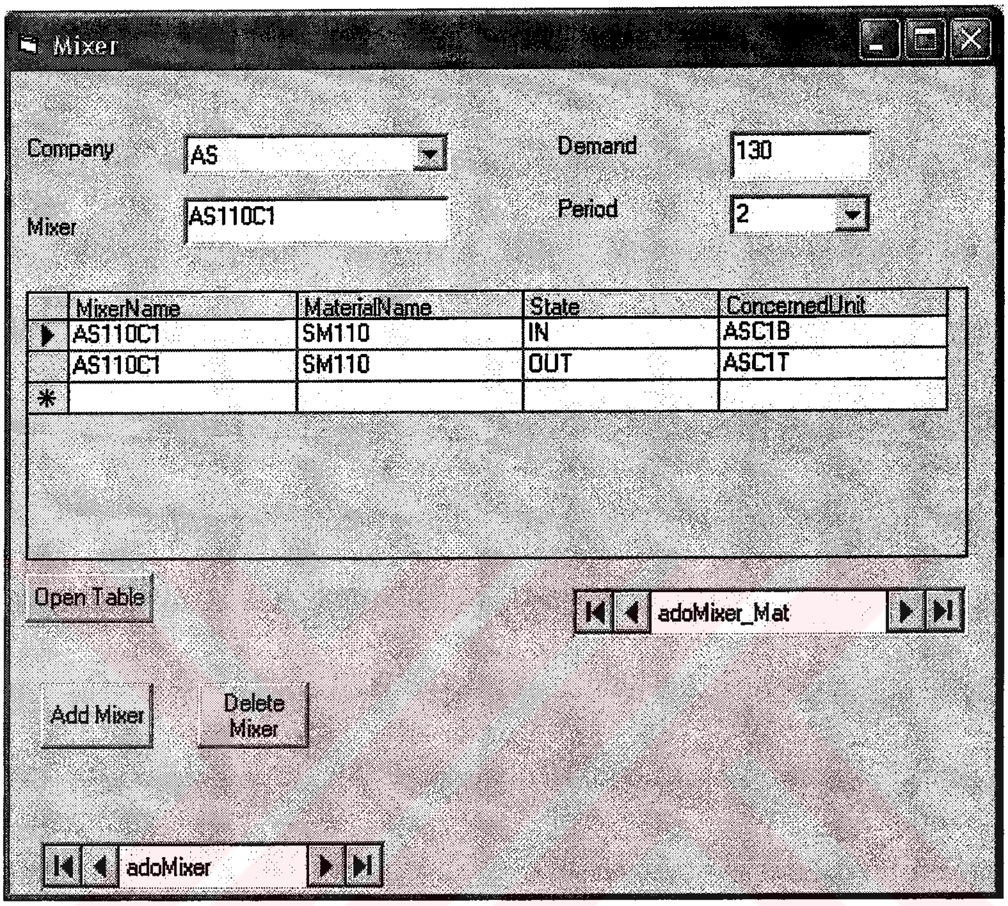


Figure 5.11 Mixer form

The "Mixer" form stored the demand data of the mixers at each period and the material flow data of these mixers as shown in Figure 5.11.

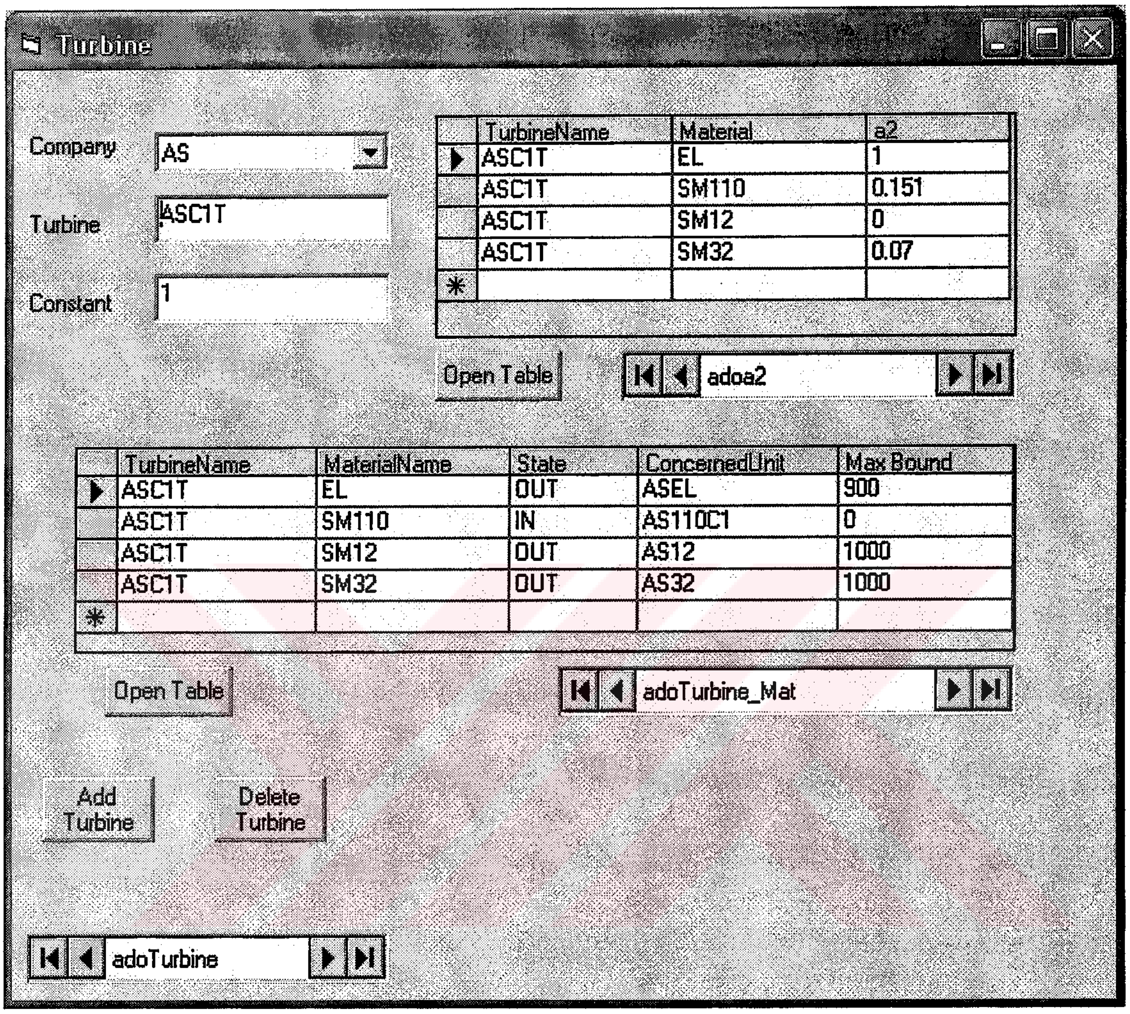


Figure 5.12 Turbine form

Data about the turbines are stored via the "Turbine" form as given in Figure 5.12. In the upper sub-table, material related constants about turbines are stored. In the lower table, material flows around the turbines and upper bounds for material generation of turbines are stored.

5.4 Database Structure

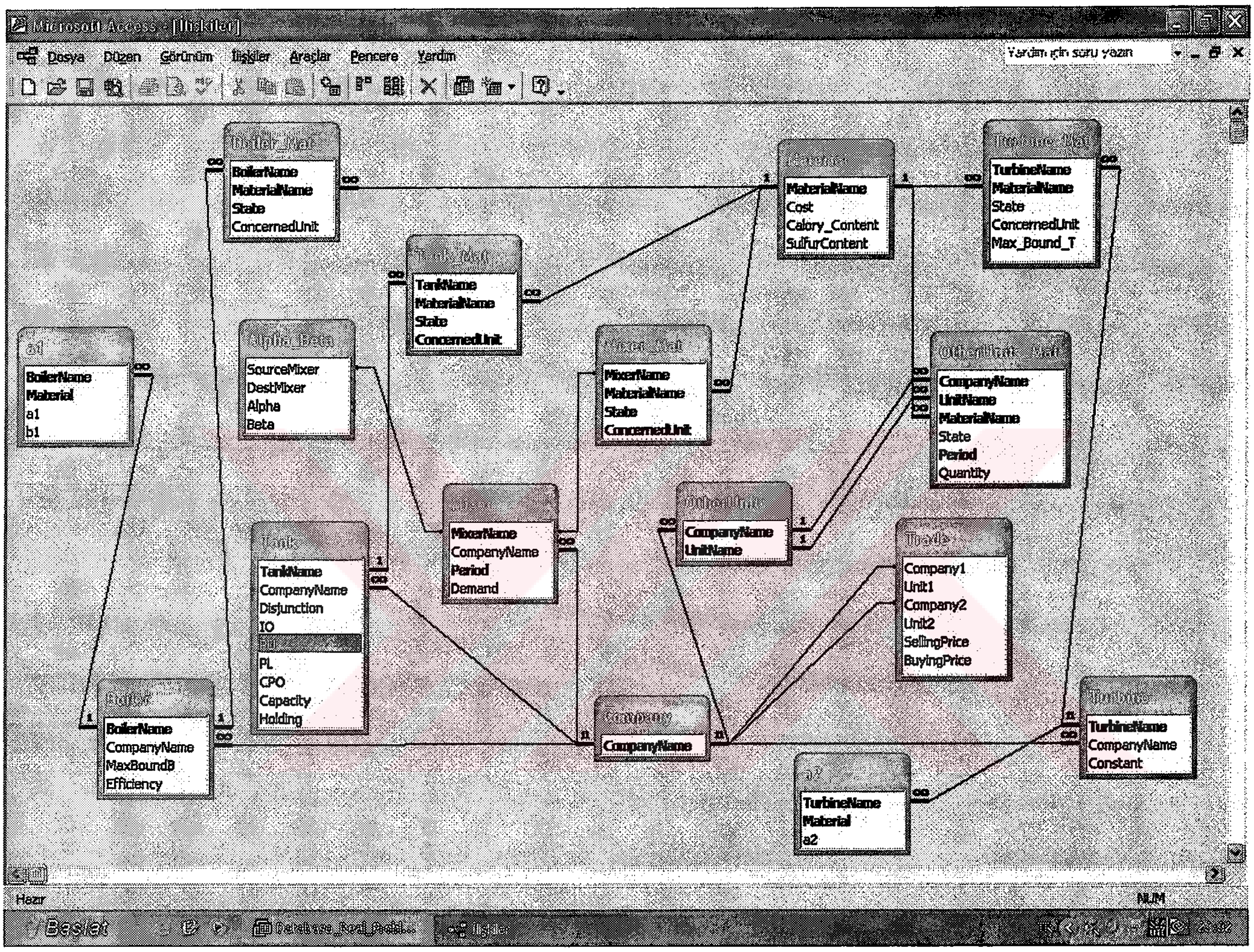


Figure 5.13 Relational database management system design

Figure 5.13 illustrates the structure of the relational database management system developed for handling the problem data. The data of the problem are stored in the tables shown in Figure 5.13, which are linked together through relationships. The database system design is so robust and so effective that it doesn't let any inconsistency or replication of data, and lets the queries run efficiently on the problem data.

5.5 Reporting Results

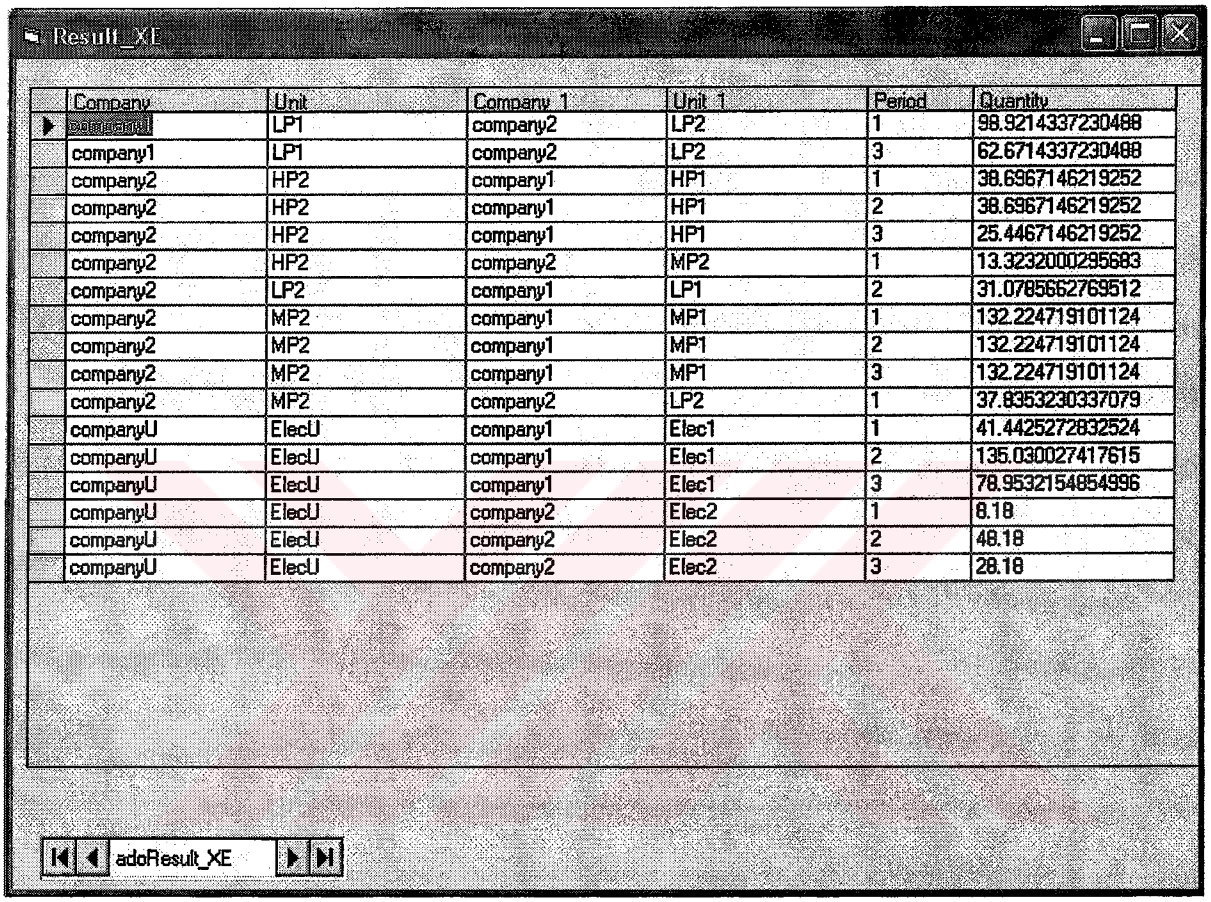
Result_X

Company	Unit	Material	State	Period	Quantity
company1	B1	EL	CONS	1	0.840449438202247
company1	B1	EL	CONS	2	0.22
company1	B1	EL	CONS	3	0.649438202247191
company1	B1	EL	IN	1	0.840449438202247
company1	B1	EL	IN	2	0.22
company1	B1	EL	IN	3	0.649438202247191
company1	B1	Fuel1	CONS	2	6.28571428571429
company1	B1	Fuel1	IN	2	6.28571428571429
company1	B1	Fuel2	CONS	1	26.1279618093963
company1	B1	Fuel2	CONS	3	20.1897886708971
company1	B1	Fuel2	IN	1	26.1279618093963
company1	B1	Fuel2	IN	3	20.1897886708971
company1	B1	SO_x	GEN	1	37.1017057693427
company1	B1	SO_x	GEN	2	49.0285714285714
company1	B1	SO_x	GEN	3	28.6694999126739
company1	B1	SO_x	OUT	1	37.1017057693427
company1	B1	SO_x	OUT	2	49.0285714285714
company1	B1	SO_x	OUT	3	28.6694999126739
company1	B1	St_HP	GEN	1	420.224719101124
company1	B1	St_HP	GEN	2	110

adoResult_X

Figure 5.14 Results table showing the flow of material

The table in Figure 5.14 gives information about the material flow within a company. For example the first row of data indicates that boiler B1 that belongs to Company1 consumes 0.84 units of electricity in the first period. Similarly, other rows show the flow of material around the units of the production systems.



Company	Unit	Company 1	Unit 1	Period	Quantity
company1	LP1	company2	LP2	1	98.9214337230488
company1	LP1	company2	LP2	3	62.6714337230488
company2	HP2	company1	HP1	1	38.6967146219252
company2	HP2	company1	HP1	2	38.6967146219252
company2	HP2	company1	HP1	3	25.4467146219252
company2	HP2	company2	MP2	1	13.3232000295683
company2	LP2	company1	LP1	2	31.0785662769512
company2	MP2	company1	MP1	1	132.224719101124
company2	MP2	company1	MP1	2	132.224719101124
company2	MP2	company1	MP1	3	132.224719101124
company2	MP2	company2	LP2	1	37.8353230337079
companyU	ElecU	company1	Elec1	1	41.4425272832524
companyU	ElecU	company1	Elec1	2	135.030027417615
companyU	ElecU	company1	Elec1	3	78.9532154854996
companyU	ElecU	company2	Elec2	1	8.18
companyU	ElecU	company2	Elec2	2	48.18
companyU	ElecU	company2	Elec2	3	28.18

Figure 5.15 Results table for displaying exchange of material

The table in Figure 5.15 gives information about the material flow between the companies in the system. For example the first row of data indicates that about 98.9 units of low pressure steam flows from LP1 of Company1 to LP2 of Company2 in the first period.

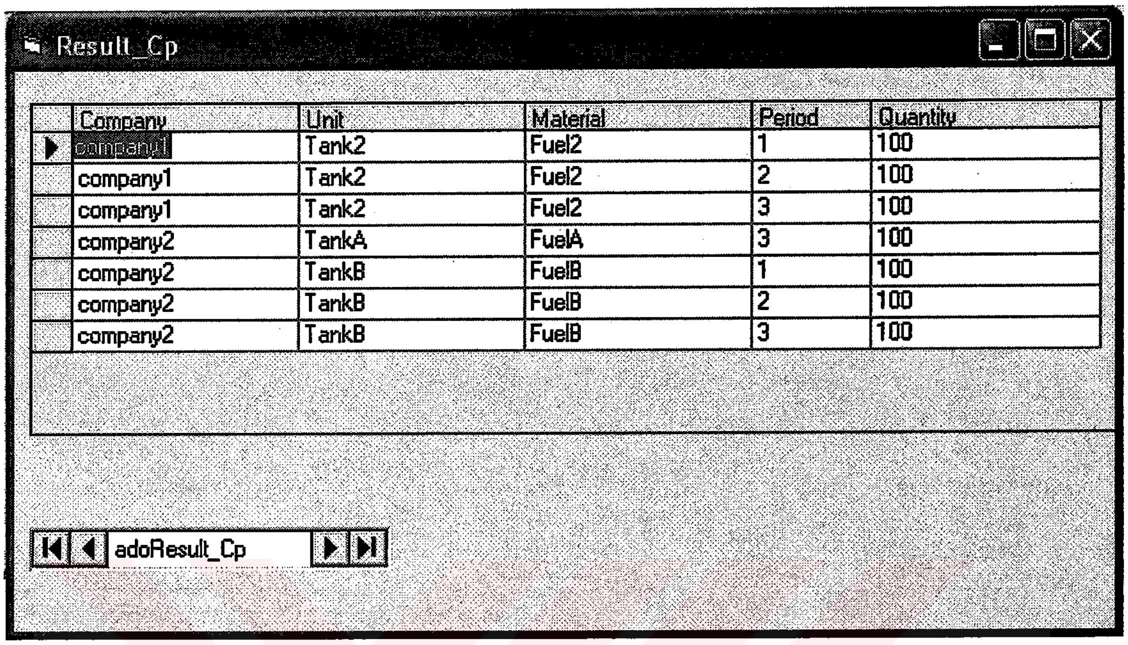
Result_Cf

Company	Unit	Material	Period	Quantity
company1	B1	Fuel1	2	1257.14285714286
company1	B1	Fuel2	1	3527.2748442685
company1	B1	Fuel2	3	2725.62147057111
company1	B2	Fuel2	1	4462.69430051813
company1	B2	Fuel2	2	3652.21738106453
company1	B2	Fuel2	3	4462.69430051813
company2	BA	FuelA	1	4343.45864661654
company2	BA	FuelA	3	4343.45864661654
company2	BA	FuelB	2	3241.17647058824
company2	BB	FuelA	2	4.42312853010662E-
company2	BB	FuelB	1	3185.29411764706
company2	BB	FuelB	2	3185.29411764706

Result_Cf

Figure 5.16 Results table showing the fuel cost

The table in Figure 5.16 gives information about the cost of fuel used in the boilers at each period. For example the first row gives the cost of Fuel1 used in B1 of Company1 in the second period.



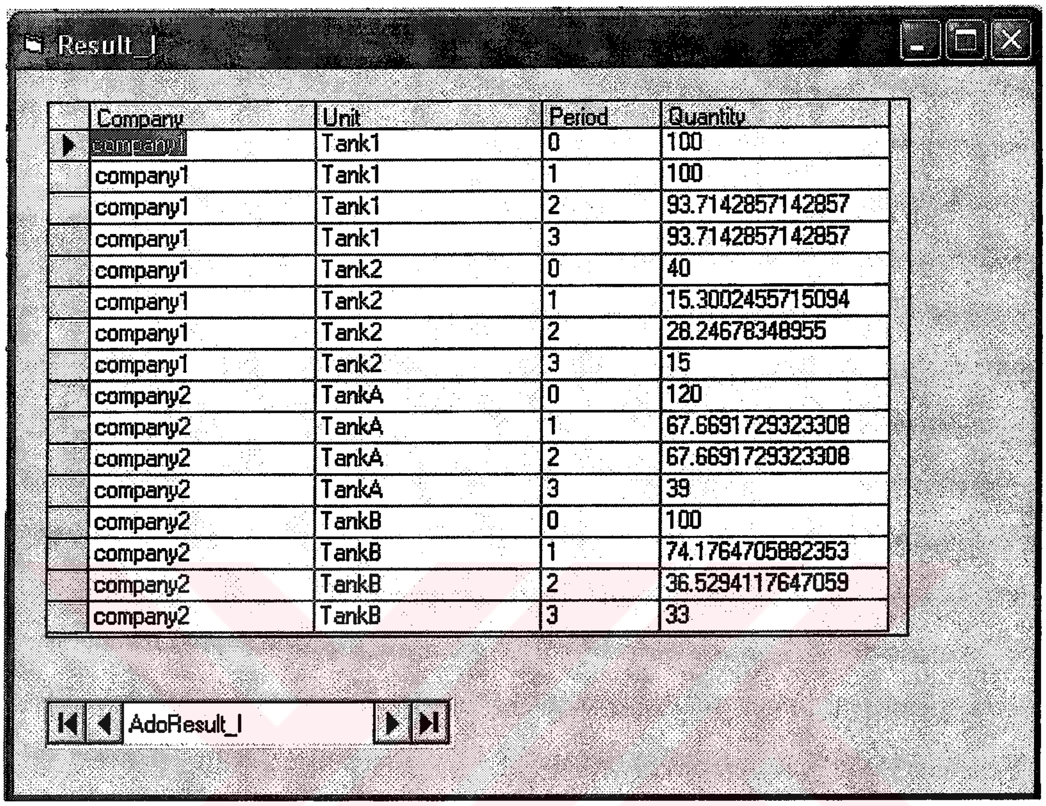
Result_Cp

Company	Unit	Material	Period	Quantity
company1	Tank2	Fuel2	1	100
company1	Tank2	Fuel2	2	100
company1	Tank2	Fuel2	3	100
company2	TankA	FuelA	3	100
company2	TankB	FuelB	1	100
company2	TankB	FuelB	2	100
company2	TankB	FuelB	3	100

adoResult_Cp

Figure 5.17 Results table showing the fixed cost of purchasing fuel

The table in Figure 5.17 gives information about the fuel purchase and the corresponding cost. For example the first row says that Fuel2 is purchased for Tank2 of Company1 in the first period and a fixed cost incurred for this purchasing operation.



Company	Unit	Period	Quantity
company1	Tank1	0	100
company1	Tank1	1	100
company1	Tank1	2	93.7142857142857
company1	Tank1	3	93.7142857142857
company1	Tank2	0	40
company1	Tank2	1	15.3002455715094
company1	Tank2	2	28.24678348955
company1	Tank2	3	15
company2	TankA	0	120
company2	TankA	1	67.6691729323308
company2	TankA	2	67.6691729323308
company2	TankA	3	39
company2	TankB	0	100
company2	TankB	1	74.1764705882353
company2	TankB	2	36.5294117647059
company2	TankB	3	33

Figure 5.18 Results table for monitoring inventory levels in storage tanks

The table in Figure 5.18 gives information about the fuel inventory levels in the fuel storage tanks. For example the third row says that about 93.7 units of fuel exist in Tank1 of Company1 at the end of the second period.

Chapter 6

CONCLUSIONS & RECOMMENDATIONS FOR FUTURE WORK

6.1 Conclusions

The multi-company collaborative supply chain management and a method for the optimal integration of the energy production systems of an industrial zone for multi-period operation have been addressed in this thesis. A systematic approach which helps to identify the synergy among different companies at the strategic level has been developed and illustrated in the energy integration of companies in the same industrial zone. The proposed approach consists of modeling process units using fundamentals of thermodynamics, conservation of mass and energy and process data; development of an MILP model for the supply chain integration of different process systems; and comparative analysis of the results.

The proposed approach has been illustrated with an example that is a simplified version of a real problem. First, the problem is solved for the integrated system and the results are saved in a database. The same problem is also solved after eliminating the exchange of materials between companies. In the non-integrated problem, the amounts of materials exchanged between companies are set to zero. The comparison of the results of the integrated problem and the non-integrated problem clearly shows the synergy generated by integration of the companies through exchange of materials. It is observed that steam expansion that means lost energy decreased and exchange of steam and electricity exists. In other words, as a result of the integration, the amount of lost energy decreases and the system meets the demand more efficiently. It is shown that important improvements in the financial and environmental performance of the industrial organizations can be accomplished by integration of different process systems at an industrial zone. The proposed approach includes MILP models for each company to realize collaboration in a multi-period horizon. The same approach is applied to a complex real world problem. The results and the improvements upon integration are also illustrated for this real problem. Significant reductions in the amount of energy wasted due to strong constraints in the industrial systems are eliminated.

A quantitative approach can be valuable in analyzing the synergy among multiple organizations in improving their financial and environmental performance. The application of the proposed approach that aims to asses the synergy among a number of companies in an illustrative example and an industrial problem showed that significant improvements in the financial and environmental performances of the organizations can be realized.

6.2 Contributions of the Thesis

The model is formulated as a multi-period and multi-scenario model, so that planning and scenario analysis can be studied using the same model for energy production. The model takes into account operation conditions, utility demands and material prices of all planning periods in the optimization process simultaneously. The investment costs, operating costs and the amount of environmentally harmful substance release are included in the objective function and they are minimized simultaneously in the problem.

There are some discrete decisions such as turning on and off some equipment or investment decisions for the production systems considered in this thesis. Linear programming and non-linear programming methods cannot handle such discrete decision problems. For these reasons integer variables are employed in the model for determining equipment on/off, and investment decisions. The problem includes the solution of systems of disjunctions. Generalized disjunctive programming has been used as the modeling framework in the optimization of this system. Using a convex hull representation of each of the disjunctions, the constrraints are converted into an MILP problem. Using the convex hull formulation for the systems of linear disjunctive constraints, gives rise to a tight MILP model which has the important feature that it does not involve big-M constraints and therefore enables the optimal solution to be found in a short time and efficiently even if the problem size is very large.

The decision makers may have major difficulties in modeling their problems and analyzing the solution effectively in general. Therefore, the model and the solutions derived from the model described in this thesis are communicated to decision makers through a self-sufficient software. The developed software has modules for entering data, creating a topology of the supply chain systems, interface to database and CPLEX solver, and display and reporting of the results. The module for creating the topology of the system helps the model developer and the other people understand the interactions within the system in a better an easier way. The module for entering the data helps the user to define or modify the problem data easily without modifying the model code written in OPL Studio. By the interface to the database and the CPLEX solver, the users don't need to directly work on the database system and the model itself. This feature is especially important for real life problems which usually contain a large number of variables and constraints. After running the model, CPLEX solves the problem and thousands of rows of data are generated. These bulks of data are meaningless without converting them to meaningful information reports. The reporting module of the software takes all the output data and converts them into meaningful reports that are easy to understand by the users of the software.

6.3 Recommendations

The amount of SO_x release only is considered as the environmental impact measure in this study. But there may be other substances that must be controlled for the performance of the system. As an extension of this study, other harmful substances can be considered as additional measures of environmental impact. Furthermore, transition from fossil fuels to greener fuels is another important issue that may be handled as an extension of this study.

Another important issue is the scope of the problem considered so far. Instead of the integration of only the energy systems, total material integration can be performed as an extension of this study. This further study requires more effort to design the system and to define the interactions between and within the systems in the modeling phase. Nevertheless, the concept and the definitions remains the same, only some new unit types, new variables and new structures must be involved for the extension of this thesis.

Although the software developed for this thesis meets the demands of a standard user and performs most of the required functions, the graphical user interface may be improved by information technology specialists. The aim in developing this software was to illustrate the concept and initialize some efforts in this field.

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VITA

Cihan Oruç completed the high school in Bursa Anadolu Lisesi, Bursa, in 1997. He received his B. Sc. degree in Industrial Engineering from Marmara University, Istanbul, in 2001. As his graduation project, he completed a project on modeling and projection of retailing industry in Turkey using statistical models. He analysed data and proposed strategies on where to open a store, for one of the biggest retailing companies in Turkey. Since 2001, he is in the Master of Science program in Industrial Engineering of Koc University as a teaching/research assistant. For the completion of the program he has taken part in an industrial engineering project with the title Analysis of Multi-Company Collaborative Supply Chain Management Using MILP.

APPENDIX A:

Convex hull formulation of Equation (3.24)

A.1 Disaggregating the continuous variables for each term of the disjunction and expressing the original continuous variables as the sum of disaggregated variables.

$$x_{ijk_{HP}l_{GEN}t} = \sum_{m\in D_{ij}} xd^{m}_{ijk_{HP}l_{GEN}t} \tag{A.1}$$

$$x_{ijk_{fuel_m}l_{CON}t} = \sum_{m\in D_{ij}} xd^{m}_{ijk_{fuel_m}l_{CON}t} \tag{A.2}$$

$$x_{ijk_{MP}l_{CON}t} = \sum_{m\in D_{ij}} xd^{m}_{ijk_{MP}l_{CON}t} \tag{A.3}$$

$$x_{ijk_{EL}l_{CON}t} = \sum_{m\in D_{ij}} xd^{m}_{ijk_{EL}l_{CON}t} \tag{A.4}$$

$$x_{ijk_{SO_x}l_{GEN}t} = \sum_{m\in D_{ij}} xd^{m}_{ijk_{SO_x}l_{GEN}t} \tag{A.5}$$

$$C_{ijk_{fuel}t} = \sum_{m\in D_{ij}} Cd^{m}_{ijk_{fuel}t} \tag{A.6}$$

A.2 Replication of constraints with the disaggregated variables.

Replication of the constraint 3.1 with the disaggregated variables:

$$xd^{m}_{ijk_{HP}l_{gen}t} = \frac{1}{\eta_{ijk_{fuel_m}}} cc_{k_{fuel_m}} xd^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall m \in D_{ij} \tag{A.7}$$

Replication of the constraint 3.2 with the disaggregated variables:

$$xd^{m}_{ijk_{MP}l_{CON}t} = \mathrm{a}_{\mathrm{ijk}_{\mathrm{MP}}} xd^{m}_{ijk_{HP}l_{gen}t} + \mathrm{BC}_{\mathrm{ijk}_{\mathrm{MP}}} \qquad \forall \mathrm{m} \in \mathrm{D}_{\mathrm{ij}} \qquad \text{(A.8)}$$

Replication of the constraint 3.3 with the disaggregated variables:

$$xd^{m}_{ijk_{EL}l_{CON}t} = \mathrm{a}_{\mathrm{ijk}_{\mathrm{EL}}} xd^{m}_{ijk_{HP}l_{gen}t} + \mathrm{BC}_{\mathrm{ijk}_{\mathrm{EL}}} \qquad \forall \mathrm{m} \in \mathrm{D}_{\mathrm{ij}} \qquad \text{(A.9)}$$

Replication of the constraint 3.4 with the disaggregated variables:

$$xd^{m}_{ijk_{SO_x}l_{gen}t} = \mathrm{s}_{\mathrm{f}_{\mathrm{fuel_m}}} xd^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall \mathrm{m} \in \mathrm{D}_{\mathrm{ij}} \qquad \text{(A.10)}$$

Replication of the constraint 3.7 with the disaggregated variables:

$$Cd^{m}_{ijk_{fuel}t} = \mathrm{c}_{\mathrm{f}_{\mathrm{fuel_m}}} xd^{m}_{ijk_{fuel_m}l_{con}t} \qquad \forall \mathrm{m} \in \mathrm{D}_{\mathrm{ij}} \qquad \text{(A.11)}$$

Replication of the constraint 3.8 with the disaggregated variables:

$$x^{L}_{ijk_{HP}l_{gen}} Y_{ijk_{fuel_m}t} \le xd^{m}_{ijk_{HP}l_{gen}t} \qquad \forall \mathrm{m} \in \mathrm{D}_{\mathrm{ij}} \qquad \text{(A.12)}$$

$$xd^{m}_{ijk_{fuel_m}l_{CON}t} \le \mathrm{x}^{\mathrm{U}}_{\mathrm{ijk}_{\mathrm{fuel_m}}\mathrm{l}_{\mathrm{CON}}} Y_{ijk_{fuel_m}t} \qquad \forall \mathrm{m} \in \mathrm{D}_{\mathrm{ij}} \qquad \text{(A.13)}$$

Summation of all binary variables is equal to 1.

$$\sum_{m} Y_{ijk_{HP}l_{fuel_m}t} = 1 \qquad \text{(A.14)}$$

A.3 Elimination of unnecessary variables and constraints:

$$x_{ijk_{HP}l_{GEN}t} = \sum_{m \in D_{ij}} xd^{m}_{ijk_{HP}l_{GEN}t} \qquad \text{(A.15)}$$

$$x_{ijk_{fuel_m} l_{CON} t} = \sum_{m \in D_{ij}} xd^{m}_{ijk_{fuel_m} l_{CON} t} \tag{A.16}$$

$$x_{ijk_{SO_x} l_{GEN} t} = \sum_{m \in D_{ij}} xd^{m}_{ijk_{SO_x} l_{GEN} t} \tag{A.17}$$

$$xd^{m}_{ijk_{HP} l_{gen} t} = \frac{1}{\eta_{ijk_{fuel_m}}} cc_{f_{fuel_m}} x_{ijk_{fuel_m} l_{con} t} \qquad \forall m \in D_{ij} \tag{A.18}$$

$$x_{ijk_{MP} l_{CON} t} = a_{ijk_{MP}} x_{ijk_{HP} l_{gen} t} + BC_{ijk_{MP}} \tag{A.19}$$

$$x_{ijk_{EL} l_{CON} t} = a_{ijk_{EL}} x_{ijk_{HP} l_{gen} t} + BC_{ijk_{EL}} \tag{A.20}$$

$$xd^{m}_{ijk_{SO_x} l_{gen} t} = s_{f_{fuel_m}} x_{ijk_{fuel_m} l_{con} t} \ \forall m \in D_{ij} \tag{A.21}$$

$$C_{ijk_{fuel} t} = c_{f_{fuel_m}} x_{ijk_{fuel_m} l_{con} t} \tag{A.22}$$

$$x^{L}_{ijk_{HP} l_{gen}} Y_{ijk_{fuel_m} t} \le xd^{m}_{ijk_{HP} l_{gen} t} \qquad \forall m \in D_{ij} \tag{A.23}$$

$$xd^{m}_{ijk_{HP} l_{gen} t} \le x^{U}{}_{ijk_{HP} l_{gen}} Y_{ijk_{fuel_m} t} \qquad \forall m \in D_{ij} \tag{A.24}$$

$$\sum_{m} Y_{ijk_{HP} l_{fuel_m} t} = 1 \tag{A.25}$$