

**AN EXPERT SYSTEM OF ENERGY SAVING TECHNOLOGIES  
FOR THE PROCESS INDUSTRIES  
(EXSYS)**

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## ABSTRACT

In Rational Use of Energy (RUE) problems, engineers have to identify the energy Best Available Technologies (BAT) that will satisfy the energy process requirements and constraints at minimum cost. This is a complex task for any engineer since he has to know: a) what are the BATs, b) what are the conditions and limits of their application, and c) what are the conditions of their optimal integration to the industrial system.

The objective of this project was to develop an expert system that will: a) propose the Best Available Technologies (BATs) by taking into account the energy requirements and the constraints of an industrial system, b) optimize the design parameters for each chosen BAT in a way that they comply with the energy requirements, and c) integrate the BATs in the model of the whole industrial process and select the Best Achievable process Configuration (BAC).

The expert system that was developed in this project consists of: i) the Expert System Shell, ii) the Energy BAT Database that is the "background knowledge" of the Expert System, and iii) the optimization modules that attached to the Expert System will perform the necessary optimization tasks.

The expert system shell is a classic one based on rules of the form "if ... then ...". In order for the shell to be able to select the BATs, the proper rules for the expert system were specified and inserted in it. These rules were identified from the analysis of existing studies conducted by experts for finding the BATs.

Databases of currently available technologies in several areas like combustion, utility networks, diesel engines, gas turbines, etc. were developed. These databases were not developed to be exhaustive, but rather being a good starting point for the development of an exhaustive database. They were developed both in ASCII format, and Microsoft EXCEL format, for higher transportability between different computer systems.

Supporting algorithms were developed for the expert system, that: a) identify the optimal design parameters for the chosen BATs, and then b) find the BAC. These algorithms are based on existing optimization techniques (e.g., MINLP, EMO, Pinch Analysis, etc.). Moreover, a module that provides basic explanations for the choices of the expert system shell was developed.

An alternative expert system shell was also developed, that is based on the optimization method of Genetic Algorithms (GAs). This GA-based expert system shell a) selects the BATs to replace the existing ones in a given industrial process and then b) calculates the optimal design parameters of the selected BATs in such a way that they comply with the energy requirements of the given process.

Finally, the developed classic expert system shell, along with the database, was applied by the EXSYS partners in four industrial test cases for testing its capabilities. These industrial test cases were: i) a petrochemical site, ii) an ethylene plant, iii) an industrial test case of sulfur dioxide conversion to sulfuric acid, and d) a chemical plant. The GA-based expert system shell was applied to the case that was thought of more complexity, the petrochemical site.

The output of the project was:

- The classic expert system shell of energy saving technologies for the process industries, along with supporting software (optimization routines, interfaces, etc.) that will determine the BAC.
- The Genetic-Algorithm-based expert system shell of energy saving technologies.
- The database of energy saving technologies.

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## **OBJECTIVES OF THE PROJECT**

The main objective of the EXSYS project was to provide an expert-system-based tool for:

- a) the selection of the Best Available Technologies (BATs) for an industrial system,
- b) the calculation of the optimal design parameters of their integration to the industrial system, and finally
- c) the calculation of the Best Available process Configuration (BAC) of the industrial system.

In order for this main objective to be achieved, the technical objectives of the EXSYS project consisted in the following:

- The development of an Expert System shell for the selection of the energy Best Available Technologies (BATs). By the term energy BATs are meant the available equipment in the market that will satisfy the energy requirements of the process at the minimum cost.
- The development of an energy BATs database that will be used by the Expert System. Since the scope of the project is to provide mainly the selection tool (expert system shell) along with the necessary optimization tools and prove the feasibility of its application, the developed database would not be exhaustive but representative of the available technologies.

- The development of the necessary optimization tools that will be used, in combination with the Expert System, for the calculation of i) the optimal design parameters for the selected BATs and ii) the BAC.
- The development of special tools that will provide explanations concerning the selections of the expert system, giving to the users-engineers an insight of the selection process.

The above mentioned expert system was applied and validated to the following four industrial test cases:

- A petrochemical site.
- An ethylene plant.
- A industrial test case for the production and usage of compressed gases.
- A chemical plant.

These cases were based on existing cases in the industrial partners' plants, or data collected from industrial plants. The application of the expert system to the four industrial test cases was performed in collaboration with the industrial partners. From this collaboration, the developers of the expert system were able to incorporate the opinions and suggestions of the directly interested parties.

## **TECHNICAL DESCRIPTION OF THE PROJECT**

### *The expert system*

With respect to the goals of the project, a general methodology to solve the problem of selecting the BATs in order to obtain the BAC of a process, has been developed. The major steps of the developed methodology are :

1. Define the process requirements in terms of quality and quantity.
2. Analyse the process requirements and identify the energy savings opportunities.
3. Study the side processes integration
4. Identify the type and the size of the technologies to be used to satisfy the process needs. (“Required technologies”)
5. Identify the energy saving technologies (“Marketed technologies”)
6. Compute the optimal integration of the selected technologies
7. Generate multiple solutions and perform a preliminary economical study of the process configurations
8. Synthesise and optimise the heat exchanger network
9. Take the final decision

The above methodology has been established and tested by solving examples in different industrial sectors : chemical and petrochemical plants. The applications used for validation purposes have also allowed to set up the overall structure of the software tool required to implement the methodology as given on Figure 1.

In order to allow the use of the software for all the partners of the RTD consortium, a WWW-interface has been developed by LASSC. This interface gives access to part of the software developed. The interest of the approach is to offer a platform independent interface (i.e. a WEB browser) to the users that always use the last version of the software that are running in a single place. For the next developments this approach will allow to use the pieces of software on the



integrated composite curves allows to identify the heat that has to be exchanged inside and between the processes of the plant in order to reach the minimum energy requirement of the system.

The optimisation method allows the use of more than one type of objective functions. All the possible objective functions, i.e. the operating cost, the exergy losses (up to now available for heat exchange and combined heat and power), the Net Present Value, the investment costs, are computed and are therefore given in the report as a given variable. These values can also be transferred into a spreadsheet (Microsoft Excel) file for comparison and for computing the Cost Break Even points of a technology.

In addition to the EMO-based optimization method, a Genetic Algorithm (GA) based optimization method was developed by LFME and was also applied to the industrial case of the cogeneration system of HAR, with excellent results. LFME developed a model of the HAR cogeneration system that was necessary for the application of the GA-based expert system shell. The developed GA-based expert system shell selects the BATs for a given industrial plant and then calculates the optimal design parameters of these BATs in such a way that they comply with the energy requirements of the given process. Since the selection of the BATs may be considered as an optimization task, the GA-based expert system shell performs optimization in two levels: In the first optimization level it finds the optimal (best) available technology for a given technology to be substituted, and then in the second level it calculates its optimal design parameters.

### ***Data bases***

Technology data bases have been developed, mainly by partners SEE, AL and HAR, for the application of the expert system and optimization tools. The following technology areas have been covered :

1. gas turbines
2. gas, diesel and dual fuel engines
3. recovery boilers
4. steam turbines
5. compressed gases technologies

The approach used by the partners SEE, HAR and AL in collecting the necessary energy technologies information for the EXSYS data base, is indicated by the following paragraph, which illustrates the constitution of the compressed gases technologies data base, by AL.

Air Liquide has constituted the compressed gases technologies data base including the technologies for producing both nitrogen and oxygen from atmospheric air. Compressed gases can be provided in tonnage quantities as liquid phase, gaseous phase produced by adsorption or membrane processes (non-cryogenic ways) and gaseous phase via cryogenics. Firstly, to satisfy a requirement of industrial gases (oxygen and/or nitrogen), it is necessary to know the most adapted gas supply mode according to the need: periodic cryogenic truck delivery, continuous pipeline delivery or on site supply by a dedicated unit. The main industrial on-site technologies for atmospheric gases separation to produce nitrogen and oxygen can be divided in three parts : cryogenic processes, pressure swing adsorption processes, permeation through hollow fibers processes. These technologies allows to produce the gases on site and to benefit from the synergies with the processes they are supplying. Each technology has its own range of applicability which is influenced by flowrate, purity, pressure and usage pattern. For each previous type of technology, the nature of the main products (oxygen and/or nitrogen), the quality of the main products (purity range and moisture), the economical capacity

range, the nature of the by-products, the advantages and drawbacks and the industrial application area have been identified. For each standard process, the following parameters have been collected : standard capacity (t/d), purity (mol. %), adsorbent or hollow fibers consumption (t/y), investment cost and size (floor space and vertical space). Each typical run of these standard processes (design, max. gaseous oxygen, max. gaseous nitrogen, max. liquid nitrogen, low purity, high purity, ...) have been referred in the data base : feed (air flowrate, temperature, pressure, moisture), product (flowrate, temperature, pressure, moisture), co-products (gaseous and/or liquid flowrate, temperature, pressure, purity, moisture), electricity consumption (compressor, vacuum pump, etc.) and cooling water consumption ( flowrate, inlet and outlet temperature, inlet and outlet pressure).

### *The industrial case studies*

The developed expert system and tools, were validated in the following industrial test cases:

#### *A. Petrochemical Site:*

The classic expert system shell for the energy BATs developed by LASSC, was applied to the cogeneration and utility systems of HAR. The expert system was used by HAR through the WWW interface, which was developed by LASSC. The first solution of the expert system, reflects excellently the situation of the base case, and thus, results in an excellent verification of the developed expert system.

Further solutions of the expert system, consisting of removing units from the cogeneration system or adding new ones, were able to not only provide remarkable energy savings, but also to produce excess of electricity, which can be exported to the grid. These solutions resulted in a substantial profit, both from steam production and electricity export.

#### *B. Olefins Plant:*

The analysis of the energy integration of an olefins plant has been performed using the new tools developed under the EXSYS project. The goal of the application was to validate the approach used and to identify the possible integration of energy savings technologies in the olefin plant.

The application of the methods shows the potential for energy savings in :

1. the refrigeration cycle, where 40 % of the mechanical power might be saved by computing a better integration with the Process heat exchanger network;
2. the importance of high temperature minimum approach : an increase of the reaction heat exchange area should allow to reduce the fuel consumption ;
3. the choice of the fuel used : a higher adiabatic temperature of combustion leads to a reduction of the fuel flowrate
4. the use of air preheating, that allows to save up-to 42 % of the fuel used ;
5. the use of oxygen enrichment allows to save 5.2% of fuel and an additional 4.4 %, when it is combined with air preheating..
6. the importance of the electricity price that leads to a less rational use of energy when it is too high :
7. the possibility of integrating a high temperature heat exchange gas turbine that leads to an energy saving of 69% and that allows to export electricity to the grid.
8. the possibility of using a partial oxidation gas turbine to retrofit the furnaces and that has to be used in conjunction with the air preheating. This solution leads to a reduction of

41.4 % of the fuel consumption and allows to produce twice the mechanical power produced in the solution with air preheating.

As a final remark, it is worth to stress out that the tools developed under the EXSYS project allow to compute an energy saving target by considering the possibility of exchanging energy among all the effects. The results obtained by this study form a necessary preliminary first step for the design of new process configurations: in fact heat exchangers and utilities network remain to be defined and the integrated structure of the technologies has to be designed. The interest of EXSYS approach stands, therefore, in the possibility to evaluate the energy saving which makes feasible the completion of the engineering task.

### *C. Sulfuric acid contact process*

The industrial application proposed by Air Liquide concerns oxygen boosting of a sulphuric acid contact process in order to increase the sulphur dioxide conversion and consequently to decrease the sulphur dioxide release to the atmosphere. Oxygen injection in such a process modifies greatly the energetic balance of the process because of the exothermicity of the oxidation reaction : additional steam is produced from the heat of reaction and energy (mainly electricity) is consumed by the oxygen producing process. The latter can be a vacuum swing adsorption process or a cryogenic one. The acid plant process is itself integrated to another industrial production plant and the aim of this application is to optimize the integration of side processes : a new facility to produce gaseous oxygen, a retrofitted production of sulphuric acid and another industrial plant.

The sulphuric acid plant has been dimensioned to produce 630 t/d sulphuric acid 100%, it is a single-absorption contact process in which the sulphur dioxide containing gas is produced by burning elemental sulphur. The sulfur dioxide containing gas coming from a sulfur burner is fed to the sulfuric acid process, this process can be divided into four main steps :

- the drying of the sulfur dioxide containing gas,
- the catalytic conversion of sulfur dioxide to sulfur trioxide,
- the sulfur trioxide absorption,
- the cooling of the sulfuric acid produced.

The second step is the main one ; after being dried in a drying column in which concentrated acid absorbs its moisture, the sulphur dioxide containing gas enters the first of four catalytic beds in the reactor. In this latter, sulphur dioxide reacts with oxygen to form sulphur trioxide.

Energy integration and more particularly effect modelling (EMO) approach shows ways for process improvement. It quantifies the possible energy savings but technical feasibility constraints have to be considered. It also optimises process intensification and computes possible benefits.

An academic gas turbine has been integrated to the industrial site. It is academic because the technologies necessary to implement it in industrial site do not exist. But energy integration and EMO approach quantify the possible benefits due to this academic technology. Those benefits are so important that they must be a very high incitement to interest new technology developments.

A real gas turbine has also been integrated to the industrial site. The results have been computed on medium values for the industrial site. A supplementary study must be done to analyse the daily values and thus highlight variations. Size of the gas turbine has to be computed knowing those variations, benefits depending on them (gas turbine has to work 95 % of the time). This study has not to be provided in the EXSYS project.

Concerning the absorber in the sulphuric plant, the project has also highlighted a process behaviour which was not expected. When the process is analysed without the another industrial plant, new technologies allow to increase the electricity production from 0.51 GJ/ton acid to 0.61 GJ/ton acid. But when the process is analysed with the connected industrial plant, this benefit disappears and the electricity production decreases and faster than the fuel reduction. The steam network is fitted depending on the solution.

Finally, the net efficiency, defined as the ratio of the electricity produced over the supplementary fuel necessary to produce it, has be computed. This efficiency varies form 84 % to 94 %. This is superior to all the technologies (to produce electricity) known at that time. It do demonstrate (if it is still necessary) the opportunity CHP on industrial site.

The energy integration techniques developed during the EXSYS project to define the process requirements. have proven to be efficient to understand the integration of energy saving technologies. The studied example concerning the integration of an oxygen production technology in a sulphuric acid plant shows that these techniques oriented towards the satisfaction of process requirements do take into account the proper definition of the operating constraints of the existing industrial processes.

The use of oxygen and enriched air for organinc or inorganic compound oxidations provides smaller equipment and increased throughput, simpler and more-efficient product recovery, improved catalyst performances, greater energy efficiency and reduced vent-gas volume. In the future, oxygen should play a larger role in chemical oxidations as its cost continues to decrease due to advances in compressed gas production technologies. Additionally, the creative and synergistic supply of industrial gases in conjunction with utilities such as steam, electricity, cooling water and compressed air will further promote the use of oxygen. This new kind of approach is mutually advantageous for the chemical firm and the gas supplier (Air Liquide). In general, chemical complexes do not exist in isolation ; usually, they are in close proximity to a refinery or other related petrochemical plants which may provide the opportunity for the synergistic supply of multiple products (oxygen, nitrogen, cooling water, steam, electricity, compressed air,...) to multiple processes.

#### *D. Application by SEE*

The application proposed by SEE, helped to :

1. define the problem
2. state the rules in the expert system
3. validate the approach developed.

This application mainly concerned the test of the expert system for selecting the gas turbines. The application of the expert system has been performed by partner SEE using the WWW interface, developed by LASSC.

## **RESULTS AND CONCLUSIONS**

It is obvious from the results of the industrial applications described above, that the expert system and tools developed in EXSYS project, will be valuable to the engineering community for the following reasons:

- The expert system will offer to the engineers a solution to the difficult problem of designing, or redesigning, an industrial system without the need of specialized knowledge. Moreover, a tool accompanying the expert system will provide explanations for the selections made giving to the engineers more insight to the process and helping them to identify possible problems. Finally, this tool may be valuable for educational purposes.
- Exhaustive knowledge of the state-of-the-art in industrial equipment will not be necessary because this knowledge will be included in the database of the expert system.
- The industrial systems designed with the use of this tool will operate at the optimal point a) using in this way less energy and b) contributing less to the environmental pollution.

The industrial applications of the developed expert system and tools, helped also to derive important conclusions concerning the sensitivity of the optimal design of a process to parameters other than the technologies and units utilized in the process.

For example, the applications of the developed expert system have shown the influence of the electricity price on the optimal solutions. When the ratio between the fuel cost and the electricity cost is lower than the marginal efficiency of a cogeneration technology, i.e. when the cost of the extra fuel required for producing electricity is lower than the cost of the electricity produced, the electricity production is driven to its maximum. In this case the electricity production will be preferred to the rational use of energy in the system. These situations are easily identified using the integrated composite curves.

The above, is an important conclusion that demonstrates that high electricity cost leads to lower energy efficiencies of the processes.

## **EXPLOITATION PLANS AND ANTICIPATED BENEFITS**

The results of the project will be valuable tools for the selection of the new technologies that have to be installed in the refinery of HAR, in order to meet the new electricity and steam demands arising from the Auto Oil directive.

Air Liquide by participating to the EXSYS project has found specific technological arguments to commercialize its own advanced technologies and to validate its new gas/utilities approach. The aim to demonstrate the validity and the profitability of the new synergistic supply of industrial gases in conjunction with utilities for an industrial site is clearly reached. With the conclusion of the industrial case studied, Air liquide wants to convince its customers of the primal importance that a gas technology inserted in their processes has a real potential of making profit in terms of both production and utility optimizations. The use of the data bases developed, the optimization tools and the expert system will allow Air Liquide to develop the sales of industrial gases (oxygen, nitrogen, ...) not only for their uses as process gases but also for optimizing the utility requirement of its customers.