EXSYS II: AN EXPERT SYSTEM FOR OPTIMAL INSERTION OF INTENSIFIED ENERGY SAVING TECHNOLOGIES (IEST) IN THE INDUSTRIAL PROCESSES

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Abstract

Offering more compact and more efficient unit operations that are usually more environmental friendly, the Intensified Energy Saving Technologies (IEST) are in good position for improving the energy efficiency and the performances of the industrial processes. The goal of the EXSYS II project has been to develop a new methodology and its implementation tools to quantify the potential of application of the IEST, determine their proper sizing and the conditions of their optimal insertion in industrial production processes. This has been done by integrating the expertise of the different consortium partners in a so-called "expert system" able to guide a user who has to solve the problem of selecting the most appropriate IEST for a given process. The tools are a set of technological databases quantitatively describing the IEST, an expert system to help the user to apply the methodology and integrated optimisation computer codes to compute and evaluate the optimal insertion of IEST in existing and new processes.

Eight technology areas are covered:

- heat transfer units;
- high temperature units;
- compressed gas technologies;
- organic Rankine cycles;
- refrigeration cycles;
- heat pumps and heat transformers;
- cogeneration systems;
- other intensified units, like reactors.

The consortium has developed a web accessible platform where new emerging technologies are compared to classical solutions in order to quantify their competitive advantage, their energy savings potential and to develop the possible synergies between technologies. The expert system is implemented on a web server that gives access to technical databases and allows engineers to solve IEST integration problems. Starting from the definition of the problem by the user, the software automatically formulates optimisation problems, transfers data between solving steps, organises access to the technical databases and gives results explanations, recommendations and information on the methods used. The expert system has been set up using the rules formulated by the technology experts and integrates optimisation methods for the insertion of energy technologies. These optimisation methods have also been implemented into the existing energy integration tools of the partners.

The development of the methods and tools has been supported and validated by industrial test cases in various fields of the process industry. A mean possible energy saving of 20% strongly related to the exploitation of synergies between IEST has been experienced. The application of the innovative methodology demonstrates a strong increase of the engineering work performance both in terms of creativity and time of realisation.

The experimental web server developed is an original development platform to be used for further R&D activities, for networking and for promoting the rational use of energy in the industry.

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2. Objectives of the project

The goal of the EXSYS II project was to develop a new methodology and its implementation tools to quantify the potential energy savings benefits of the optimal insertion of the Intensified Energy Saving Technologies (IEST), in existing and new processes. These tools had to integrate the expertise of the different consortium partners in a so-called "expert system" able to guide a user solving the problem of selecting the most appropriate IEST for a given process. The tools are a set of technological databases quantitatively describing the IEST, an expert system to help the user to apply the methodology and integrated optimisation computer codes to compute and evaluate the optimal insertion of IEST in existing and new processes. Eight technology areas are covered:

1) heat transfer units
2) high temperature units,
3) compressed gas technologies,
4) organic Rankine cycles,
5) refrigeration cycles,
6) heat pumps and heat transformers,
7) co-generation systems,
8) other intensified units.

The developed tools platform had to be accessible through the web. Industrial test cases had to be used to develop and validate the methodology and its implementation tools.

In addition to the methodology development, a critical review of the IEST developed in the EU had to be performed and potential of energy savings in the EU industry to be assessed.

3. Technical description

3.1.Introduction

Improvement of energy efficiency of industrial processes has been achieved in the last years thanks to the so called “pinch technology” and its improvements: the heat recovery was the central point and this did lead to “soft” changes in the processes. There is more to be gained in energy saving by inserting energy saving technologies in the processes although this may lead to more drastic changes in the structure of the process. To make this insertion efficient, major difficulties have been overcome.

1) The optimal insertion has to be examined at the global level considering the possible synergy or mutual exclusion of the candidate technologies to be inserted in a given industrial production site.

2) The R&D effort made in the development of new intensified energy saving technologies increases the number of technologies available on the market.

3) The size standardisation of the technologies on the market increases the difficulty of selecting the optimal technology, because this makes the match proces requirement / IEST more difficult.

4) The evolution of the prices on the market may influence the profitability of an ongoing project.

To overcome these difficulties the project consortium has developed an innovative methodology and has implemented it in software tools because of its complexity. This has been achieved in a context of higher process integration, at site scale, in terms of materials, energy and other utilities.

The consortium chose to develop a web-based platform to benefit from the advantages of inter-operability, data sharing, text standards and hyperlinks.

The contributions of the partners are of three different types:

1. Methodology and tools development

The development result is a web platform that is operated as a tool for analysing and selecting the possible insertion of IEST in the process industry. This mainly represents the contributions of UMIST, TNO and ULg, although the contributions of the other partners in the project have been necessary to state the problems and obtain meaningful solutions.

2. Detailed analysis of the Intensified energy saving technologies

Consortium members have developed structured knowledge and technology databases on the different IEST for technology areas under study. They have also developed tools allowing the identification, the selection and the optimal insertion of the technologies using the developed expert system web platform. For each technology domain, the responsible partner developed reports, databases and software to describe the state of the art, the available technologies, the technology selection procedures and the best sizing procedure. These contributions are given in a standardised format.

3. Applications

The developed tools have been tested and validated by solving applications in different industry areas. Results obtained and the energy savings that can be expected by using IEST demonstrate the interest of the tools developed. An attempt to extrapolate the results at the European level has also been made.

3.2.The EXSYS II web platform

Because the EXSYS II project did involve partners with different technology expertise in several areas and experts in technology insertion and in industrial processes, one of the challenging aspects of the project was to share the expertise and to try to implement it using an expert system. This system was to be accessed on a web platform also to be created.

In order to structure the web platform development, several co-ordinating tools have been developed: a databases system shared on the web to standardise and to ease the developments: e.g. the development of a database including the definition of all the databases, a bibliographic reference database, a manufacturer database, etc.

This expert system integrates rules for IEST selection and optimisation methods. Some of the rules are translated into parameters optimisation, others are "if then" rules, others are implemented in the sequence of problems to solve, others are simple queries in databases and of course some of them are pure expert system rules. The web offers the possibility of storing such an expertise in the form of a software tool that uses a unique interface even if the programs running are quite different and running on computers in different countries.

From the developer's point of view the use of HTML documentation allows developing how-to manuals to report the developments performed. This allowed us to have a coherent approach during the developments, speeding up the learning curves of the different partners.

Used for co-ordination purposes, the web site of the EXSYS II contract has a partners corner where useful information for the execution of the project is available; namely:

- A News section
- A downloadable reports section including minutes, reports, deliverables
- A how-to section where the partners find guidelines
- For co-ordination and developments purposes, the consortium did use E-mail lists.

The consortium has developed a web-based platform where new emerging technologies are compared to classical solutions in order to quantify their competitive advantage, their energy savings potential and to identify the possible synergies between technologies when inserted in a given process.

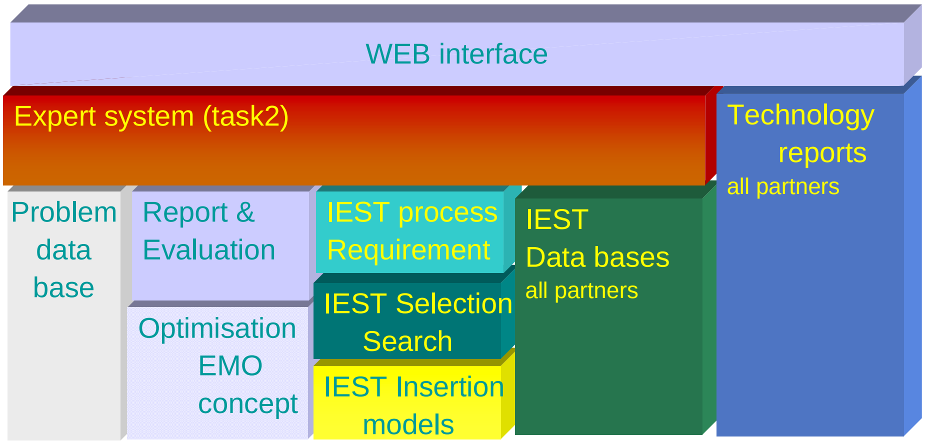

Figure 1: The building blocks of the system developed.

The system is built with the contributions of the different partners linked together by the contribution of University of Liège (ULg). Figure 1 describes the different building blocks. On top of the structure, ULg developed a web server that serves as the web interface of the system and organises the access to the different areas of information or tools of the system.

The building blocks are the following:

1. Descriptive report of the technologies and their evolution. The consortium developed the basis for an information web site on the evolution of the intensified energy saving technologies in the industry. The informative reports are organised by technology areas structured using identical templates using the hyperlinks techniques to browse the different aspects related to a given technology.
2. The technology (IEST) databases include the structured technical data concerning the technologies available on the market and all the necessary data to allow the selection of the technologies to satisfy a process requirement. Some common databases have also been developed.
3. Three partners have developed the optimisation tools: ULg, UMIST and TNO. These tools implement the optimisation concepts. The concepts use different objective functions (exergy, energy, operating cost, CO_2 emissions, total cost) and constraints that aim at representing the integration of the technologies to satisfy the requirement of a process. The optimisation concepts are used by different models to identify, select and optimise the insertion of the IEST in the system. The results of the project have been implemented using existing computer tools for energy integration of the three contributing partners as background.
4. IEST process requirement: this tool solves the problem of identifying the technologies to be used in a given process and their corresponding size. The method

combines optimisation models and rules for the different technologies.

5. IEST selection procedures have been developed for each type of technology to select in the technology databases, the technology to be used according to the process energy requirement and the process environment.
6. IEST insertion models that represent the interactions between the different technologies in an optimisation model that will select the technologies and compute their optimal sizes to satisfy the process requirements. The parameters of the model are obtained from the parameters stored in the databases.
7. A tool set for reporting and evaluation allows transforming the numerical results of the optimisers into understandable textual reports for evaluating the optimiser solutions. This tool generates also detailed cost evaluations including investment and operating cost. The use of the web interface allows producing both graphical and textual reports that can be directly printed.
8. In the system, each user defines its process data in its own reserved problem database for which a database interrogation tool set has been developed.
9. The expert system organises the data transfer and the use of the different tools and guides the user through the steps of the methodology. This system prepares the data for the requested step, executes the requested action, generates and saves the results and proposes the next steps. The communication to the user is made using HTML files with hyperlinks (for the next steps or for explanations) or forms (when user data are needed). The use of the tools is therefore transparent to the user.

The implementation of the EXSYS II web platform developed by ULg is shown on figure 2. HTML interface is used to define the problem, display and comment the results and suggest further calculations. The access to the web server is protected by user password and the different information areas are protected according to the user status (user or developer). The problem database has a proprietary data format preserving the confidentiality of the data sent by the users. The web server manages the user requests and organises the computations that may be performed in different locations. In this system different computers are used: e.g. a database server using FILEMAKER pro in Belgium, another in Portugal and a third one in the UK. This offered the advantage that each partner manages the information and tools he is responsible for on his computers while being integrated in the overall system.

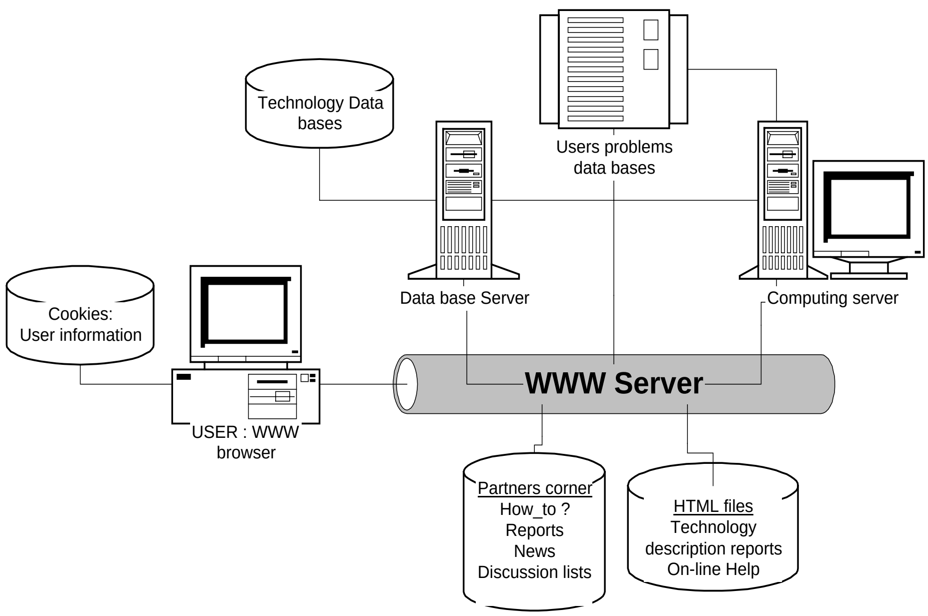

Figure 2: Implementation of the EXSYS II web platform.

3.3. Intensified Energy Saving Technology reports and databases

3.3.1. Generic technical information on the IEST

UMIST and their subcontractor DAR prepared a detailed report on intensified energy savings technologies in the following areas: Heat exchangers, Separation technologies, Miscellaneous, including reactors, Heat exchanger materials.

- Within each intensification technology, a number of aspects were discussed, including, but not limited to, energy efficiency, status, operating parameters and requirements (in a programmable form - i.e. equations, where possible), benefits and limitations, and synergy. References to further data were given as appropriate. Over 90 technologies were described in the Deliverables that was fully approved by the first project progress meeting as a base for the further research directions.

The Appendices also included data on the design of compact heat exchangers, and their cost. The database on intensification technologies has been built using these topics as the structure base. In addition, references to further data are given after each technology 'synergy' discussion. In the cases of the 'enabling' technologies and applications, the data presentations are in the form of discussions, differing from the normal format input required for the parameter database.

From this first report, the partners started collecting the technology information in the different technology areas. Partner ULg developed a structured web site to insert and access this information in two different ways: generic information and technology parameters.

Generic information

Generic information concerns the definition of state of the art of a given technology and its future development. This is available as descriptive structured report files in HTML format. ULg developed a canvas to structure the information and make uniform the access to the technology reports on the web site. In each technology area, the following items have been delivered: technical description, typical efficiencies, costs and operating ranges, limits of application, fluids (inputs and outputs), typical applications, advantages and drawbacks, future developments and time to commercialisation, manufacturers.

Technical data in databases

In addition to the review reports, the project partners have developed the technical databases they were responsible for. For helping in this development, partner ULg has defined the structure and the content of all the technology databases. The latter include technical structured data to be used for searching and selecting the best-suited technologies. The technical databases have been developed using "FILEMAKER pro" a relational database management system that allows databases sharing on the web site. This tool allows an easy interface with the other programs. It allows also programming selection rules and strategies in the databases. The partners have also developed the necessary query tools. The results are obtained as lists and detailed records.

A price conversion database has also been developed to convert the prices referenced in the technology databases into EURO values of today. This is done using the currency exchange rate and the chemical engineers plant index (CEPI). The competitive advantage of the platform developed is related to information certification given by technology experts and to structured technical data gathering, all being available on the same web site.

The table below gives the list of technology reports and technology databases built during the EXSYS II contract and that are accessible on the developed web server.

Technology reports	Description	Databases	Partner
Heat exchangers	Intensified heat exchangers	Intensified HTX	UMIST
ORC	Organic Rankine cycles and turbines	Components turbines	ULg
Co-generation gas turbines engines heat recovery boilers fuel cells.	Gas turbines, engines, fuel cells, steam turbines and boilers	Gas engines Steam turbines Recovery boilers Gas turbines Fuel cells	SEE

High temperature Cement Kilns and Glass Furnaces Burners; Air Preheaters Tube Inserts Gasifiers Fluidised Bed Separation Units Ceramic Membranes Activated Carbon	Preheaters, burners and other high temperature units	HTU databases Glass Furnaces Cement Kilns Glass Furnaces Pulverised_Coal_Burners Oil_Burners Gas_Burners Multi_Fuels_Burners; Porous_Burners; Gasifiers Air_Preheaters Tube_Inserts Fluidized Bed Separation Units Ceramic Membranes Activated Carbon	IST
Heat pumps	Compression heat pumps, absorption heat pumps, etc.	Heat pumps	TNO
Refrigeration cycles	Refrigerants, compressors, heat exchangers, refrigeration cycle structure	Components Compressors Generic compressors	ULG
Compressed gases	Technologies concerning the production and the utilisation of compressed gases: O2, N2, Ar, etc.	Generic compressed gases Technologies Compressed gases technologies	AL
Reactors	Intensified reactors technologies		UMIST
Separation units	Intensified separation units		UMIST

In each technology area, the partners did develop rules for selection and models to compute the technology requirement according to the process requirement and to compute the optimal insertion of the technology.

The following table gives the summary of the tools, set of rules and models developed by the consortium and integrated as part of the methodology on the web server.

Area	Partner	Content
Heat transfer units	UMIST	Developments of systems for selecting the appropriate intensified heat transfer technology according to the technology requirement.
High temperature units	IST ULg	Development of selection methodology and rating techniques for high temperature units. Development of insertion models and optimisation models for high temperature units. Developments of CFD models for turbulence, radiation have been developed to perform CFD predictions of combustion chambers. Optimal air preheating integration model
Compressed gases technologies	AL	Compressed gases technologies: applications, selection and performance prediction models. Development of a model for enriched air combustion allowing for computing the optimal enrichment value.
ORC	ULg	Organic Rankine Cycles: single cycle models including rating of the different elements: heat exchangers and turbines, models for identifying the best fluids and optimising the operating conditions (pressures and temperatures). Models for computing the optimal insertion: calculation of the integration performances and optimal rating, contributions to the different objective functions.
Refrigeration	ULg	Refrigeration cycles: single refrigeration cycle models including rating of the different elements: heat exchangers and compressors, models for computing the best fluids and optimising the operating conditions. Model for computing the optimal insertion in case of multiple pressure and fluids cascade. Model for selecting the optimal compressor type.
Heat pumps	TNO ULg	Heat pumps and heat transformers: Models of the different available techniques: compression, absorption, and adsorption. Model for selecting the most appropriate technology type. Model for evaluating the cost of the units.
Cogeneration	SEE ULg	Co-generation systems : Simulation models of gas turbines : adaptation of performances to the type of fuel used and derivation of an energy integration model Simulation models of partial oxidation gas turbine: simulation with adaptation of the type of fuel, derivation of an energy integration model. Model of combustion including the calculation of the most appropriate fuel. Model of gas turbine optimal integration of a given gas turbine

		Model of gas-diesel engine optimal integration including the different levels of heat available. Model of recovery boiler, furnace simulation allowing the rating of the boiler. Selection strategy in the gas-diesel engines and the gas turbine databases Detailed model for cost estimation of co-generation projects

3.3.2. Survey of European R&D in the IEST (partner LFME)

In relation with the development of the technology databases LFME was responsible for making a survey of the IEST developed with the help of EC funding. LFME created and updated a list of EC funded projects (ongoing or already completed) that deal with IEST, along with their contact information. LFME checked all sources available for the identification of IEST projects, but the main information was found at the WWW-based database of the Community Research and Development Information Service (CORDIS). The number of projects per technology area is presented below:

Heat transfer units:	19 projects
High temperature units:	16 projects
ORC and refrigeration cycles:	5 projects
Heat pumps and transformers:	12 projects
Cogeneration units:	11 projects
IEST / Specific applications:	11 projects
Fuel Cells technologies:	8 projects
Compressed gas technologies:	1 projects
	Total: 83 projects

LFME contacted all the co-ordinators of these 83 projects and requested information about the IEST researched in the corresponding projects. From the 83 co-ordinators, 46 (55.4%) responded, and from those, 20 (43.4%) provided some useful IEST information. The remaining 26 of those that responded and did not provide any information, either redirected LFME to the EC, or expressed their intention to not co-operate at all. The data gathered by LFME are consistent with the technical data gathered by the other consortium members. This information has been placed in a separate database on the EXSYS II Web Site.

Conclusions have been drawn concerning the R&D effort made in the field of IEST in the process industry.

- IEST are the key to a competitive European process industry.
- IEST offer more compact, more effective and more environmental units for the process industry
- A fair share of research on IEST (both to innovative and retrofitting technologies) is dedicated at a European level, in Funded Research Programs such as JOULE, THERMIE and BRITE-EURAM, although the results of this effort may not be efficiently disseminated.
- The basic drawback of IEST, which is their proper sizing and optimal insertion in existing processes, is addressed in funded projects of the EU, such as EXSYS and EXSYS II.
- The opening of most IEST that have been developed in the ‘90s, to the European market, is estimated to begin in the first decade of the next century.

3.4. The optimisation driven expert system for the selection of the optimal energy saving technologies.

The method developed aims at selecting the technologies on the market and at integrating these in an optimal way to satisfy the process requirements. The project consortium chose the exploitation of Internet technology to solve this problem in the optimal way, increasing in this way the efficiency of the research consortium. The use of the web allows running the different programs from different places. It allows also to always access the latest version of the tools. This was a big advantage during the system developments. The different optimisation tools are accessed through the web site. Using the forms display capabilities of the browsers and CGI (Common Gateway Interface) allows developing platform independent interfaces giving always the same appearance to the program independently of the software tools used. The use of the HTML (Hyper Text Meta Language) format allows developing on-line documentation of the program using hyperlinks, forms and graphics. Each entry is documented allowing guiding the user through the problem solving procedure.

The extended use of the HTML format (a standardised ASCII format) for text and hyperlinks and of GIF files for the graphics allows to document the results. Partner ULG developed a software tool that allows to transform numerical results of an optimisation method into valuable and comprehensible results for the user whose structure is given on figure 3.

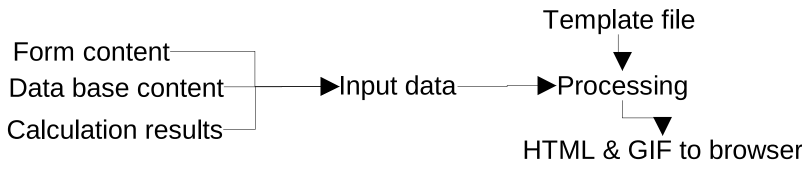

Figure 3 : algorithm of the reporting tool

Partner ULg developed an intelligent system to guide the engineer through the steps of the methodology. Using the web, little expertise is needed from the user for using the software: it is the developers who have to code the expertise (expert system) in intelligent documentation and software to transform the results of the optimisation into an understandable presentation.

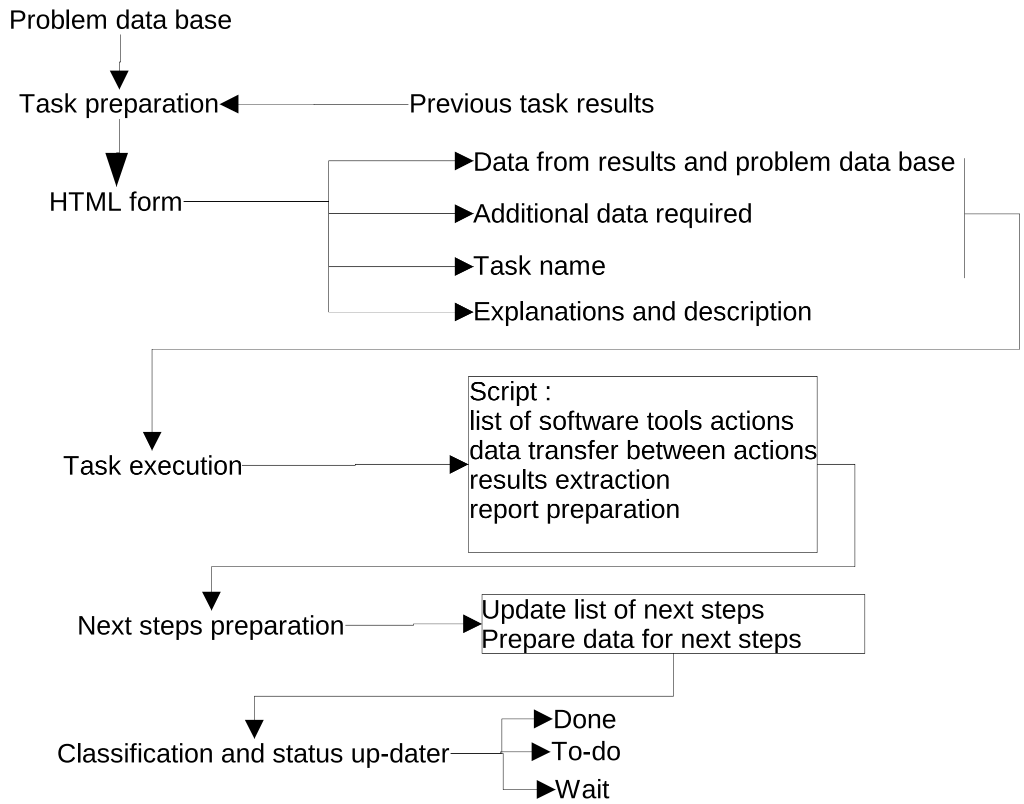

Figure 4 : expert system action description

The principle of the tools developed is to store in a problem database, the list of tasks to be performed and organise the links between the different software tools. To each task corresponds a list of calculations to be performed (application of optimisation formulations) and a list of data required to solve it. Part of the data is extracted from the problem database (definition of process requirement); the missing information is requested to the user using HTML forms. The tools developed implement the list of steps to be performed. This list is up-dated each time a computation is performed according to the results obtained. A follow-up tool (expert system) has been developed to record the state of the tasks and indicate the user the next tasks to do and prepare for each of them the data required. Each task has three status: done (task performed, or not necessary with respect to the problem definition), to-do (task to do now) or wait (task to do later, when other steps are completed). For each of the tasks, the available data that are required are recovered from the problem database and from the results of the previous calculations. The tool developed by ULg allows not only to ask the user the only necessary information required to solve a given task, but also, by the way of the HTML technology, to comment and explain the task performed or to be done and the results obtained. With this tool each application of the optimisation and of other techniques results in a list of tasks and a list of commented results where suggestions of improvements are given according to the results of the optimisation.

The method being implemented in the project proceeds with the different steps given below.

3.4.1. Identify the known IEST applications for a given process

In collaboration with partner AL, ULg has developed an IEST application database where the known applications of the IEST in given processes are recorded. A search procedure oriented towards the definition of the processes allows identifying from the definition of a process, the type of IEST to be used and the typical size of the known applications. The interest of this development resides mainly in the exploitation phase when the database will be filled by the technology developers to promote the use of the IEST in the process industry.

3.4.2. Definition of the process requirements

Starting from the definition of the process, the first step is the definition of the process requirements. The hot and cold streams are defined according to the level of detail required (in the implementation four levels of details have been considered). Different options are proposed to compute the energy requirement of the process. Beside the heat requirements, other data are also required to define the process requirements: e.g. the fuels available, the mechanical power requirement and the cost parameters. Partner ULg developed an on-line documentation system using hyperlinks to explain the signification of the data required and a web enabled problem database system to modify and visualise the data for a given process system under study.

3.4.3. Compute the minimum energy requirement of the process

The minimum energy requirement of the process is computed and the composite curves are obtained using the EASY software developed by partner ULg. The development mainly concerned the adaptation of software to interface it with the web and produce useful HTML reports including graphics. The report menu gives access to text reports, composite curves as well as the suggested next commands to be executed according the calculation results (next steps). It gives also access to the problem data using the database management system developed. There is also the possibility of using the software tools developed by TNO (Odessy) or by UMIST (CPEA :Combined Pinch Exergy Analysis) for this task.

3.4.4. Identify candidate generic energy saving technologies

This step aims at identifying the generic energy saving technologies offering an insertion opportunity for a given process. An exergy and energy optimisation procedure has been developed by ULg to determine the possible technologies to be inserted in the process. This step uses the specialised methods developed by partners for the different technology areas:

- TNO using exergy optimisation for heat pumps (heat pump potential scan method, and CHP systems;
- ULg using a newly developed concept based on the exergy losses minimisation and energy optimisation to identify the temperature levels and compute the optimal conditions for co-

generation, CHP, ORC, steam networks and refrigeration cycles,

- UMIST using combined pinch and exergy analysis for CHP systems and heat transfer enhancement technologies..

For each type of selected technology further questions are stated and programs are applied in order to define more precisely the candidate technologies. Figure 5 shows the implemented algorithm with the steps solved to define the IEST requirements of a process.

The methods for technology candidate identification have been adapted to work with the web server framework for problem statement, calculation and reporting.

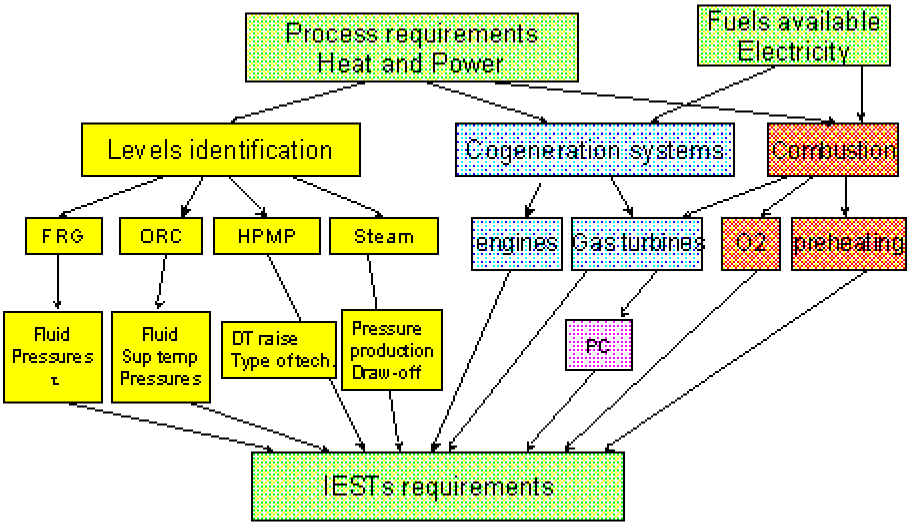

Figure 5 : Definition of technology requirement algorithm

3.4.5. Select the candidate technologies from the market

The next step of the developed methodology aims at identifying the technologies from the market to be used for each technology requirement. Two types of technologies have been distinguished: the custom made and those existing on the market with standard sizes (e.g. gas turbines or oxygen production units). For custom-made units, a sizing program is applied to determine more precisely the cost function and the performance models of the technology. For standard size units, expert system software is used to choose in a technology database the technology which can fit the requirements of the process. The goal of this step is to define a finite list of candidate technologies. For doing this, additional information is required and specific selection rules are applied by the expert system. The rules of selection developed by consortium members are stored in the rules database developed by partner ULg. For the selection rules implementation three strategies have been implemented: from simple to more complex.

Implementation 1: partner UMIST developed a JavaScript procedure to select the IEST technologies. The drawback of this implementation is that the interface with the database is limited leading to a rather complex (programming) procedure for updating the algorithm when the database is changed. When applicable though, the interest is its simplicity. Another drawback is the use of a non-standard programming language that may create problems w.r.t. browsers capabilities.

Implementation 2: partner ULg together with the corresponding technology expert partners did develop searching strategies using the search procedure of the database management system. The selection procedure proceeds in two steps: the first step (selection) eliminates all the infeasible technologies that are not able to satisfy the demand, the second step defines a distance between the requirement and what the technology can deliver. This distance is defined in such a way that it includes heuristic rules (quality or ranked list of preferences) as well as real distance between requirement and unit(s) capacity. Partner ULg has implemented this technique for the selection of compressed gas technologies, gas/diesel engines, compressors and turbines. Partner TNO has implemented a similar approach for the selection of heat pumps.

Implementation 3: partner ULg developed an advanced algorithm for the selection of the gas turbine technology. The method has been implemented using PROLOG (expert system programming language). The development made concerned the adaptation (by incorporating new rules) and improvement of an already developed method. Advanced techniques using hashing algorithms as well as more efficient solving strategies have been implemented to produce good solutions in sufficiently short calculation time. The newly developed algorithm operates 20 times faster and converges where the older does not. This development allowed running the algorithm with the complete gas turbine database.

3.4.6. Optimal insertion of the technologies

As part of their respective contributions, each of the partners did develop models to allow the optimal selection and insertion of the corresponding IEST. The goal is here to decide whether a given selected technology will be used or not in the studied system and if yes what is its optimal size. The key issue is here to determine the size considering the possible interactions with the other technologies, e.g. adapt a steam flow rate according to the selected gas turbine. This deliverable is made of three types of contributions.

1. Development of the technology models

For each selected technology or technology area, a model representing its insertion has been developed. The major characteristics of the model are the following: the model has to represent the insertion of the given technology in the process system including its interactions with the other technologies; it has to allow the calculation of the different objective functions used by the optimisation software; the parameters of the model have to be computed using the data available in the technology databases. Using its published Effect Modelling and Optimisation (EMO) concept, in collaboration with the other partners according to their respective technology expertise, ULg has developed the models for the different technology areas. Any technology model results from the analysis of the major elements to be considered when inserting a technology, using the data available in the databases together with the data required to evaluate the technology insertion.

2. Link between the technology databases and the models

Together with the partners in the different technology areas, ULg has developed an interface between the technology databases and the models of the technologies. Two types of programming techniques have been implemented and tested. The first uses the raw data available in the databases to compute model description files that will be imported as such in the insertion model. In this approach, the parameters of the model are computed directly from the parameters in the technology databases. The advantage of the approach is the easiness while the drawback is the poor interaction possibility with external parameters. The second approach uses a more sophisticated software tool that thermodynamically model the technology in order to adapt its performances to the operating conditions of the process (e.g. to compute the efficiency of a gas turbine according to the ambient temperature and to the fuel composition). The resulting programming code of a technology appears directly as HTML template pages.

3. The system modelling and optimisation

The modelling of the overall system (integrating thus the process model with sorted technology models) is automatically generated: a process superstructure represents all the interactions between the technologies and the process under study. An optimisation tool is then used to operate the selection and the optimal sizing of the technologies in the process system. The superstructure model developed by ULg operates as an interface between the individual models of the technologies and with the optimisation algorithm; e.g. the fuel consumption must account for all the technologies that may consume fuel. The overall model is modular in such a way that it allows adding and/or suppressing technologies without having to program a new overall model from scratch, or to modify the superstructure. It is easy to manage using the expert system. The concept behind the modelling is the EMO concept where each technology appears with their respective contributions to different resources balances. The so formulated mathematical problem is a Mixed Integer Linear Programming problem where the integer variables are used to select or not a given technology, while the continuous variables are used to compute the optimal level of their use, or their size in other words..

In this context, partner ULg improved its already developed Effect Modelling and Optimisation concept and its implementation in the computer tool EASY (Energy Analysis and Synthesis) that has been used as background for development. The heart of the EASY software is an optimisation formulation that allows the targeting of the technologies insertion. The system has been adapted to account for the newly developed methodology.

Optimisation for heat load scenarios

ULg has developed and implemented an optimisation strategy to account for demand (or load) variations. The mathematical formulation developed uses a MILP formulation that allows defining the technology investment to be made and to compute for each operation time range the list and the levels of usage of the technologies to be considered to satisfy the process energy requirement in an optimal way. For the development, ULg did use an existing software framework that has been adapted to handle load scenarios. The adaptation was compatible with all the existing features of the software and has been implemented in a very general manner allowing the integration of the other formulations developed for the project, e.g. use of additional variables and computing with different objective functions.

Development of different objective functions and constraints

The goal was to implement different objective functions and to incorporate constraints that allow the generation of optimal process configurations and the evaluation of the insertion of the intensified energy savings technologies. ULg has implemented new constraints and objective functions to be used in the background optimisation tool used. The different types of objective functions and constraints have been defined with partners AL and SEE. The implementation has been made in such a way that the developments are fully compatible with these made under the other tasks including the formulation used to model the different technologies and the load variation calculation. The implemented functions are the following:

- The primary energy;
- The total equivalent primary energy (primary energy + electricity primary energy equivalent based on a fuel mix definition that can be parameterised);
- The CO_2 emission (according to the fuel used);
- The total equivalent CO_2 emission (based on a conversion related to the electricity production or consumption;
- The total exergy losses (that account both exergy balance and exergy heat exchange losses);
- The operating cost (including maintenance and raw material consumption);
- The total cost including the investment based on an actualisation formula

In addition to this function definition, constraints defining the feasibility of an investment by limiting the rate of return as an inequality constraint have also been added.

All the functions are evaluated simultaneously during the optimisation evaluation, and the user chooses the preferred objective function that is used by the optimisation solver. Combined with the multiple solution generation, the adopted approach will allow comparing solutions according to different criteria.

All the generic parameters have been set default values but values specific to the user and the process environment may be introduced using the web interface. The parameters required for the definition of the cost coefficients (operation and investment costs) are computed using the specific data gathered in the technology databases.

3.4.7. Evaluate the solutions

The consortium partners have analysed different ways of exploiting the results of the optimisation method and evaluating the insertion of the IEST with an emphasis on the process retrofit. From the results of the analysis, partner ULg developed four different tools :

1) a reporting tool for presenting the results in the web browser with explanations and graphical representation. This development is the software implementation by partner ULg of the analysis made by the other partners in their respective technology area. The competitive advantage of the tool is here to transform numerical results into engineer minded reports with explanations and graphical supports.

2) a sensitivity analysis tool : that allows following the influence of different parameters on the solutions obtained. The development allows to vary the electricity price, the equivalent electricity production efficiency or the actualisation rate and to visualise the effect on the different objective functions. The interest is here to be able to identify the values (break even) that produce a change in the list of selected technologies.

3) a multiple solution generator : using the technique of the integer cut, the tool allows to generate different integer sets (i.e. technology selection sets or process configurations) and compare them with respect to the different criteria available (operating cost, profit, energy efficiency, CO_2,…).

4) a costing tool : a cost evaluation strategy has been established by the project partners for the technologies where the information was sufficient. The parameters required for the evaluation have been fitted using the data gathered in the technology databases. The implementation of the evaluation strategy has been incorporated in the reporting tools described above. For some of the technologies, a detailed cost estimation procedure has been developed and implemented by partner ULg.

At the end of the procedure, we have targeted the optimal insertion of the energy saving technology. Setting this target allows to determine the list of hot and cold streams to be used to design the heat exchanger network for which an efficient automated MINLP procedure has been developed by partner UMIST to identify the potentialities for heat transfer enhancement in the heat exchanger network. UMIST showed that although the heat exchanger network can only be considered once the list of streams is determined (i.e. when the list of IEST is determined), the heat transfer enhancement techniques may influence the overall structure of the heat exchange system and therefore an iterative approach might be useful.

3.5. Potential of application of the IEST in industrial processes

The goal of the applications was to validate the methodology and tools developed for the project. This has been made by applying the methodology to different industrial test cases with the aim of demonstrating the ability of the methodology. A second goal of the test cases was to help in the rules statement for the selection of different technologies. A third goal in the project was to critically assess the energy savings that could be obtained with the IEST in the industry.

The table below presents a summary of the results found in the different test cases by the partners. This only gives the flavour of the energy savings that could be obtained by applying IEST in the industry; it proves also the ability of the developed methodology to help in identifying appropriate and energy efficient integrated solutions.

3.5.1. Summary table of the test cases.

The numbers in the first column refer to result 4 (see here after) and to the industrial area covered (1 for chemical industry, 2 for pulp and paper, 3 for food industry, 4 for cement industry and 5 for ceramics).

4.1	AL	Chemical industry
	Project	Sulphuric Acid plant
	Expected energy savings :	-8%
	Comments :	The benefit of the integration comes from the intensification level, the use of enriched air for SO2 oxidation allows to reduce the size of the reactor (-60%), the number of equipments (by recycling) and the SO2 emissions of the process (by 72%). The use of IEST allows reducing (but not eliminating) the energy penalty related to the integrated O2 production. Although the overall energy saving is not positive the profit is positive.
4.1	ELF	Chemical industry and refining industry
	Project	Isomerisation unit
	Expected energy savings :	17.5%
	Comments :	Results correspond to the insertion of a cogeneration gas turbine used partially for post combustion (to satisfy the high temperature needs)
	Project	Crude distillation unit (standard process)
	Expected energy savings :	13%
	Comments :	Use of cogeneration with post combustion
	Project	Crude distillation unit (energy optimised scheme)
	Expected energy savings :	9%
	Comments :	Use of cogeneration with post combustion
	Project	Ammonia plant
	Expected energy savings :	13.5%
	Comments :	Use of a gas turbine to preheat air for high temperature combustion
4.2	TNO	Pulp and paper
	Project	paper production plant
	Expected energy savings :	30%
	Comments :	Integration of a gas turbine
4.2	SEE	Pulp and paper
	Project	Paper mill
	Expected energy savings :	18.5%
	Comments :	Gas turbine and steam combined heat and power production
4.3	SEE	Food industry
	Project	Dairy plant
	Expected energy savings :	20.6 %
	Comments :	Gas turbine integration
	Project	Oil-Works plant
	Expected energy savings :	24.3 %

	Comments :	Gas turbine integration
4.3	UMIST	Food industry
	Sugar plant "K"	
	Expected energy savings :	23 %
	Comments :	Increased processing capacity and energy savings with new boilers
	Project	Sugar plant "O"
	Expected energy savings :	33 %
	Comments :	Increased processing capacity 40% and energy savings with new boilers
	Project	Sunflower Oil refining plant
	Expected energy savings :	37 %
	Comments :	Benefits obtained on water usage and energy consumption. Pay back period: less than 1 year
4.4	IST	Cement industry
	Project	Cement production plant
	Expected energy savings :	20 %
	Comments :	Integration of a gas turbine and a steam combined cycle to valorise low grade energy by steam expansion
4.5	TCKI-TNO	Ceramics industry
	Project	Ceramic production line
	Expected energy savings :	Practically no savings because of the size of the system and the high temperature requirements.
	Comments :	The energy savings can only be envisaged by drastically modifying the process concepts. In these circumstances, the interest of using IEST will be raised. Only opportunity for micro gas turbines have been identified

3.5.2. Extrapolation at the European level

In order to underline the significance of the results of the EXSYS II test cases regarding the pulp and paper and the cement industrial sectors, LFME was responsible of extrapolating the results at the level of the European industry. The assumption made is that the test cases are representative of the state of the art of the European process industry of the sector. With this assumption, the energy saving could be evaluated considering a penetration factor :

European Energy savings ~= Test cases savings x penetration factor (1a)

Energy saved (EU level) = Consumed Energy (EU level) x European Energy savings (1b)

Finally, this method uses the information that is presented in parts one and two of this deliverable, and covers the *retrofitting* case only, since both the available information and the test cases refer to existing processes.

3.5.2.1. Pulp and paper industry

By applying the formula presented above to the results of the pulp and paper industrial test cases, the resulting energy saving (%) at the European level, is

P&P Energy savings = p x 22.75% (2)

where p is the penetration factor. This factor ranges between 0 and 100%. Consequently, the maximum energy savings of the European pulp and paper industry, is 22.75%. Furthermore, considering that in 1995, the total European Union energy consumption for the pulp and paper industry, was 331 000 000 MWh/y, we can calculate the amount of energy that can be saved:

Energy savings = 331×10^6 MWh/y x 0.2275 x p ~= p x 75.3×10^6 MWh/y (3)

Regarding the industrial sector of pulp and paper, which in Europe is the 7^{th} most important sector, the results are very promising: an average 22.75% (based on 1999 statistics) in energy savings at the European level. Finally, it is important to mention that, as TNO indicated in the final meeting of the project, the European pulp and paper industry is extending their business to power production as well as pulp and paper production. Hopefully, the EXSYS II tools can make this remark a reality for most contemporary plants, at minimum time and with optimal cost.

3.5.2.2. Cement industry

Using the same formula (1), the average European savings in coal for the cement industry are:

Cement Energy savings in coal (%) = 0.36 x 0.20 x p = 7.2 x p (3)

where p is again the penetration factor discussed in sections 5.1 and 5.2, ranging from 0-1 (0-100 %), and 0.36 represents the percentage of the European cement production that utilizes coal as the primary fuel. This result means that the maximum average (equivalent in coal) energy savings in the European cement industry can be 7.2%. Moreover, for an estimated 3 105 043 kW of coal that was required (1997) for the production of 224 million tons of cement in Europe, the coal saving potential is:

Coal savings = 3 105 043 kW coal x 0.2 x p = 6.21×10^5 x p kW (5)

Thus, in case where p=100%, the maximum amount of coal energy that can be saved, is 621,000 kW.

Regarding the case of the cement industry, the maximum energy savings in coal (7.2%) are also significant, especially nowadays that the European cement industry tries to be a "zero waste" industry that will utilize fuels other than fossil or liquid fuels. It is also envisaged that not only the primary energy for this industry should be derived from wastes of other industrial sectors, but the raw materials used, too. Thus, the test case examined in the EXSYS II project, showed not only significant savings in coal (used as primary fuel) by replacing it with scrap tyres, but also significant increase in power generation efficiency (by 25%) and reduction of CO_2 emissions (by 12%), among others. Consequently, IEST could play an important role for the enhancement and competitiveness of the European cement industry as well.

4. Results and conclusions

The EXSYS II project consortium has been able to develop an original method and the necessary computer tools to achieve and evaluate the optimal insertion of the Intensified Energy Saving Technologies (IEST) in the industrial processes. The major challenge that has been met in the project was to develop a software platform that incorporates the knowledge of technology and process experts in order to identify the most profitable solutions (process configurations) to be envisaged to satisfy the process energy requirements in optimal conditions. The methodology of the optimal technology insertion has been analysed, determined, implemented and validated by the project consortium.

The research consortium did identify 4 results (Result 1 to Result 4 here below), which are in fact a set of achievements available under different documents, reports, technology databases, optimisation software codes, procedures, coded rules of the expert system, ..., and -more important- knowledge. What the consortium members did name "the EXSYS methodology" is the structured solution approach that has been elaborated, implemented and validated in the project to optimally insert one or (more often) several IEST in a production process in order to improve its energy consumption.

The set of deliverables that constitute each of the 4 results have been determined on the basis of the property rights and of the exploitation intentions of the R&D Partners.

Result 1 contains the methodology and the IEST databases. The IEST insertion method has been explained in detail and can be accessed on the EXSYS web site. It is not only an intellectual result (the knowledge of the method), but a material one as wel as the IEST databases.

Result 1 is the foreground that belongs to all Consortium members.

Result 2 is the Expert System implementing the EXSYS methodology; it is available on the web server of the contract. A detailed technical description has been presented here above.

Result 2 belongs to partner ULg who did develop it.

Result 3 is made of the improvements in the optimisation software tools of the partners UMIST, TNO and ULg.

Result 3 is made of three parts based on three existing backgrounds.

Each of these partners has gained knowledge in the energy saving technology integration methods. The improvements of their optimisation methods have been integrated into their respective computer tools.

Result 4 concerns the reports of the test case studies that have been foreseen and achieved for evaluating the methodology and validating the platform tools. The benefits reside both in the technical results of the test cases (that can be exploited) and in the demonstration of the application of the methodology. The applications also demonstrate the benefits in terms of engineering work when comparing the originality of the solutions proposed and the time spent to evaluate configurations by classical methods or by the integrated method proposed.

The industrial partners who did propose the case studies own their results.

Conclusions

From the methodology point of view, the major conclusions of the finalised contract are given in the table here below; for each of these, special software solutions have been imagined and realised:

Methodology conclusions	Related software tool development
With the new developments in technology intensification, multi-disciplinarity becomes more and more important. The selection and the use of energy saving technologies require therefore expert specialists in the different energy technologies. These specialists must also be supported by specialists in technology integration since integration aims at valorising synergies between the technologies. This also means that the technologies have to be modelled according to their use by the Selection and Insertion procedures of the generic integration tool.	An expert system has been developed to drive the process engineer through the solution process of the energy saving technology insertion. The developed expert system incorporates the expertise of the technology experts by dynamically generating the list of steps to be followed to solve the problem, applying methods and search rules (as for instance the choice of the software adapted to the problem), asking for the required data at the moment when the data is needed and storing the information into a problem database.
The multi-disciplinarity concerns also the vocabulary used in the different technology fields. When studying the insertion of technologies there is therefore an important	The use of hypertext and the development of a transformation tool that includes results numbers into readable text with the use of hypertext links to explain the vocabulary

effort to be made in translating technology and process integration jargon into process vocabulary.	used and the results obtained.
The growing effort in technology development requires the need, for technology developers, of making the technologies known (their concern is also to identify and quantify the possible markets) and for the process engineers the need of knowing the available technologies. There is also a need to know what are the consequences of a technology insertion and to describe how to adapt the technologies to better answer the process needs.	Development of application database allowing the links with technology application description and typical sizes. The tools developed aim at comparing systems and at highlighting the advantages of a given technology with respect to the different objective functions. By developing a web based system the information can be up-dated on-line by the technology experts. The information is therefore directly available to all the users and synergies between technologies (technology insertions) always reflect the state of the art of all the technologies concerned.
Collecting pertinent technical data able to describe the performances of the technologies is a very difficult task even for professionals. The task is even more complex when cost estimation is concerned.	Development of on-line technology database with structured technical data accessible on a web platform allow consortium partners (experts) to share information and make it available to the others as soon as it is known. Generic information database has been incorporated in the system to be used as a substitution when more precise technology market information is not available. By this way, the developed platform offers a real potential for networking on technologies developments and their possible applications in the industry.
The information has to be ordered by level of details: from principles to precise description of the technologies. The information has to be given at the time it is needed.	The information management system developed is based on a multi-level information system powered by a web server. Links to detailed information are generated according to the results obtained. The expert system drives the user to the solution giving him access to descriptions of the methodology, the technology principles, the technical data used and the expertise rules.
The use of optimisation systems does not mean display the solution as a list of numbers.	The methods developed are using graphical representations and text formatted reports that aim in helping the engineers to transform numerical results into useful solutions.
The optimal rating of the technology integration depends on the load scenario of the process. The use of a single process load representing the process operation has to be substituted by the definition of a load scenario.	The optimisation method has been adapted to consider the process loads scenario in order to determine the optimal technology investment while proposing process configurations that will properly operate during the whole time operating range.
The fluctuation of the energy prices and the uncertainties linked to the cost estimations	Optimisation techniques that should be used are those which provide multiple results and

require a careful evaluation of the solutions proposed.	allow to analyse the sensitivities of the parameters on the solutions.
The cost of engineering studies aiming at identifying good energy saving options may jeopardise the rational use of energy efforts. For engineering companies, this results usually in the duplication of existing solutions without going into the details of the process integration. In this situation, the risk of missing good solutions just by ignorance is high and prevents the emergence of new innovative technologies.	By speeding up preliminary screening of possible solutions, the developed tool will benefit to both process engineers and engineering companies. The process engineer will have the possibility of testing solutions and comparing to other alternatives, while engineering companies will have the possibility of quickly identifying the possible options and eliminating at a very preliminary design stage the less promising ones.
The role of computer tools is to support the creativity of engineers, allowing him to evaluate multiple options based on different criteria. This applies when dealing with energy technologies. This is particularly true when integration is concerned because the adaptation of the integration conditions of a given technology can result in making the use of another beneficial. For example, the interest of the application of oxygen enrichment can be promoted by the possibility of producing more combined electricity by steam expansion.	The tools developed constitute original contributions to the energy integration techniques by incorporating the dimension of integrating energy transforming technologies. Multiple criteria (economical, environmental and thermodynamic) are generated allowing comparison of solutions with respect to different criteria. This is a step forward with respect to the classical energy integration techniques. Especially for co-generation systems. The developed tool aims at representing technologies interactions in an easy to use interactive way, highlighting the synergy opportunities for energy saving technologies integration.

Software Prototypes

The experimental web site has been used by most of the partners for the execution of the project. In will be open for use in the frame of a user consortium. The web server as described above includes technology databases, structured technology description reports and the access to the expert system and the optimisation tools EASY and ODESSY.

The optimisation development and methodologies that can be accessed through the web are also directly available in the following independent software tools :

TNO : ODESSY, the exergy based energy integration and optimisation software.

ULg : EASY, an advanced energy integration software that is integrated with the tools of the BELSIM engineering suite.

UMIST : CPEA (Combined Pinch and Exergy Analysis) software that is accessible for the members of the UMIST process integration research consortium.

5. Exploitation plans and anticipated benefits

At the end of the EXSYS II Research and Development contract, the project consortium produced four types of results as mentioned here above.

Although the full system is operational, it is still to be developed and made more robust before to envisage a commercial exploitation. Before to take such a decision, a market study should be made, then a business plan and find financial means; none of these steps has been accomplished. Therefore the Consortium has decided for an internal exploitation.

A different exploitation route will be effective for the 4 exploitable results. At the end of the contract the Partners intentions are valid for 2 years.

Result 1 : EXSYS methodology for inserting Intensified Energy Saving Technologies in industrial processes, and technology databases.

All the Consortium members have access to the methodology description and to the databases. These items can be downloaded from the EXSYS web server or exploited using it; the web server will be kept operational by ULg.

The methodology is fully original, its knowledge will increase the professional skills of the Consortium members, and it is their common achievement. The methodology is to be applied on a free basis by all the partners, but its use would be readily more efficient by using the developed Web based expert system (see result 2).

The technology databases include both technology description and technical data that are accessible on the web for visualisation, interfacing and data management. These databases represent interesting structured tools to be used as a basis for further R&D developments especially to create expertise networks in the frame of the energy saving technologies.

Result 2 : The Expert System implementing the methodology of optimal insertion of IEST is available on the web server of the contract.

ULg will make this tool available through the web server - on a free basis to the academic partners, and on an advantageous way to the industrial and semi-industrial partners so that the methodology developed can further be used in-house by all the partners. This corresponds to a new way of approaching the integration of energy technologies in the existing or new processes.

The benefit for any of the users is to have a systematic approach to be followed, accompanied by a set of knowledge supported databases. The developed tool is accessible on a web server. The intention of ULg is to offer the use of the web server in the frame of a users club. Although there is no firm commitment yet the concepts developed and the integration of the optimisation tools might be further developed in the frame of this users club. The platform offers a good opportunity for further developments to be used both for teaching and for research activities. The perspective might lead to the development of new selection rules and of the computing framework ; this club, if properly organised, might also secure the maintenance of the technical databases by creating mechanisms to insure future development.

Result 3 : Improvements in the optimisation methods of the partners UMIST, TNO and ULg.

The improvements of their optimisation methods have been integrated into their respective computer tools that will follow previously defined exploitation strategies: i.e. further research and development activities, teaching, expertise and commercialisation.

Ulg will take the necessary step to keep EASY available to be able to use the EXSYS web system.

Result 4 : Applications in test cases

The applications performed demonstrate the benefits in terms of engineering work when comparing the originality of the solutions proposed and in terms of time spent to evaluate configurations by classical methods or by the integrated method proposed. The in-house exploitation that would be made of the results of the technological application case studies is in the hands of the industrial partners who did propose the case studies.

From the test cases, we could say that energy savings are of the order of 20 % (-8% to 30% according to the cases) for the individual processes. The savings are usually related to the benefits of a proper integration of the combined production of heat and electricity. The use of compressed gas technologies allows a drastic reduction of equipment sizes (-60%), less equipment but with a penalty related to the energy consumption of the compressed gas production (this explains the -8% for one of the test cases). This effect could be compensated by the proper integration of the steam production, leading finally to profitable processes (8% reduction of the total cost) with reduced sizes and less environmental impacts (e.g. 72% of SO_2 released by a sulphuric acid plant).

The extrapolated results at the European level mainly depend on the market penetration of the IEST leading to more conservative energy saving figures of 15% (for 60 % market penetration).

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