WEB-BASED TOOLS FOR ENERGY MANAGEMENT IN LARGE COMPANIES APPLIED TO FOOD INDUSTRY

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PAR

Damien MULLER

ingénieur mécanicien diplômé EPF
de nationalité suisse et originaire de Monthey (VS)

acceptée sur proposition du jury:

Prof. A. Rufer, président du jury
Dr F. Maréchal, Prof. D. Favrat, directeurs de thèse
Prof. K. Hungerbühler, rapporteur
Prof. E. Jochem, rapporteur
Mr P. Roux, rapporteur

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FÉDÉRALE DE LAUSANNE

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Abstract

This thesis presents a methodology for energy management in large companies and its implementation through a web application and through a prototype of a simulation platform. By combining existing tools in an innovative manner and by making use of recent web technology developments, the methodology adopted provides engineers and managers with tools capable of guaranteeing an efficient and sustainable energy management. Although the methodology presented in this work is based on the experience acquired in the food industry, it can be easily applied in other industrial sectors.
The methodology is based on two fundamental approaches commonly used to analyse energy consumption in industrial contexts: the top-down approach and the bottom-up approach. The top-down approach is used in the first place to identify the factories and the specific areas within the factories in which the largest improvement potentials can be achieved. In turn, the bottom-up approach builds on the results from the top-down approach to identify and quantify the energy saving potentials.

The top-down approach is implemented through a web application in collaboration with an industrial partner. This application encompasses a modular factory model -accessible to engineers in factories through a user-friendly interface- which enables each factory to define its energy usage, allocate energy costs among the different energy consumers and compute key performance indicators. For a rational cost allocation in multi-service energy conversion units, an exergy-based methodology is presented. The efficiency of energy conversion units defined in the factory model, such as the boilerhouse or the air heaters, is assessed using thermodynamic models. The latter are simplified parametric models derived from accurate thermodynamic models developed in a general flow-sheeting and simulation software to comply with computation time and reliability requirements of the web application.
The different factory models defined in the web application can be browsed as part of the proposed top-down approach: starting from a high level overview of the factory -targeted mainly at managers- users can then focus on a specific area of the factory. Strategies are developed to guide users in identifying factories or specific areas within the factories with the largest improvement potentials. They include the use of mechanism to rate the quality of a performance indicator as well as a benchmarking module that allows to compare performance indicators across factories worldwide. In sum, the modular and adaptive aspects of the web application guarantee its long-lasting use.

In order to quantify energy saving potentials in the energy conversion units defined in a factory model, "what if?" scenarios are performed in a web-based simulation platform prototype developed in this thesis. This platform acts as a decision-support tool by providing

graphical representations of profitability and risk analysis. The platform can be accessed by human users through a web browser while other applications, such as the web application described above, may use the simulation functions through a web service.

Statistical tools that can help engineers in defining the factory model described above are also presented. They are used to correlate energy consumption with factors such as production volumes or the climate. Tests to validate the developed correlations are also described. The application of this technique in a factory shows that more than 50% of the energy consumption does not have a direct correlation with production factors and allows to identify improvement potentials.

Finally, the concept of a bottom-up approach to identify and quantify energy saving potentials in the different production processes of a factory is presented. A triple representation of the requirements of a process is introduced and applied to process integration in a concrete example. The 80/20 rule is also applied to reduce the complexity of the problem. The optimal integration of cogeneration engines and heat pumps using multi-objective optimisation is also presented.

Keywords: energy management; food industry; top-down; bottom-up; thermo-economic modeling; benchmarking; "what if?" scenarios; multi-linear regressions; degree-days; process integration; 80/20 rule; integration of utilities; cost allocation; web application; web services; multi-objective optimization.

Résumé

Cette thèse présente une méthodologie pour la gestion de l'énergie dans les grandes entreprises ainsi que son implémentation dans une application web et dans un prototype de plateforme de simulation. La méthodologie développée combine, de manière innovatrice, des techniques existantes grâce à des technologies web récentes. Elle met ainsi à disposition des ingénieurs mais aussi des managers des outils capables de garantir une gestion efficace de l'énergie à long terme. Bien que la méthodologie présentée soit basée sur l'expérience acquise dans l'industrie agro-alimentaire, elle est également applicable dans d'autres secteurs de l'industrie.
La méthodologie est basée sur deux approches fondamentales qui sont fréquemment utilisées pour l'analyse des consommations d'énergie dans l'industrie : l'approche top-down (approche descendante) et l'approche bottom-up (ascendante). L'approche top-down est utilisée dans un premier temps pour identifier les fabriques et leurs secteurs où les potentiels d'amélioration sont les plus grands. Dans un deuxième temps, l'approche bottom-up se base sur les résultats de l'approche top-down pour identifier et quantifier les potentiels d'économie d'énergie.

L'approche top-down est mise en œuvre au moyen d'une application web développée en collaboration avec un partenaire industriel. L'application comprend un modèle de fabrique accessible aux ingénieurs travaillant dans les fabriques par le biais d'une interface conviviale. Le modèle permet à chaque fabrique de définir l'usage qu'elle fait de l'énergie, d'allouer les coûts de l'énergie aux différentes unités consommatrices et de calculer des indicateurs de performance. Afin de gérer ces allocations de coût de manière rationnelle dans les unités de conversion d'énergie qui fournissent plusieurs services énergétiques, une méthodologie basée sur le concept de l'exergie est présentée. L'efficacité des unités de conversion d'énergie, comme par exemple la chaufferie, est évaluée grâce à des modèles thermodynamiques. Ces derniers, de types paramétriques simplifiés, ont été dérivés de modèles plus précis, développés à l'aide d'un logiciel de simulation. Ces modèles simplifiés permettent de répondre aux exigences de l'application web en termes de temps de calcul et de fiabilité.
Dans le cadre de l'approche top-down, une interface permet de naviguer dans les différents modèles de fabrique définis dans l'application web. En partant d'une vue d'ensemble de la fabrique, dédiée principalement aux managers, les utilisateurs peuvent par la suite se concentrer sur un secteur spécifique de la fabrique. Des stratégies sont également développées afin de guider les utilisateurs vers les fabriques ou des secteurs de fabriques où les potentiels d'amélioration sont les plus grands. Ces stratégies comprennent, d'une part, un mécanisme permettant d'évaluer la qualité d'un indicateur et, d'autre part, un module permettant l'analyse comparative des indicateurs de performances des fabriques dans le monde. Les aspects

modulaires et adaptatifs de l'application web développée garantissent sa pérennité dans un environnement en constante évolution.

Dans le but de quantifier les potentiels d'économie d'énergie dans les unités de conversion d'énergie définis dans un modèle de fabrique, des scénarios "what if ?" sont proposés dans un prototype de plateforme de simulation développé dans le cadre de ce travail. Cette dernière sert d'outil d'aide à la décision en fournissant des représentations graphiques d'analyse de rentabilité et de risque. Elle est accessible aux utilisateurs humains au travers d'un navigateur web, alors que d'autres applications web peuvent y accéder au moyen d'un service web.

Des outils statistiques pouvant venir en aide aux ingénieurs au moment de définir le modèle de fabrique sont aussi présentés. Ils sont utilisés dans le but de corréler les consommations d'énergie avec des facteurs tels que les volumes de productions ou les conditions climatiques. Des tests servant à la validation des corrélations développées sont également décrits. L'application de ces outils dans une fabrique montre que plus du 50% de la consommation énergétique de cette fabrique n'est pas directement corrélée avec les volumes de production.

Finalement, le concept d'une approche bottom-up permettant d'identifier et de quantifier des potentiels d'économie d'énergie dans les différents procédés d'une fabrique est présenté. Une triple représentation des besoins d'un procédé est introduite et appliquée à un exemple d'intégration énergétique. Le problème est simplifié sur la base de la règle du 80/20. L'intégration optimale de moteurs de cogénération ainsi que de pompes à chaleur en utilisant une approche d'optimisation multi-objectifs est également présentée.

Mots-clés : gestion de l'énergie ; industrie agro-alimentaire ; top-down ; bottom-up ; modélisation thermo-économique ; analyse comparative ; scénarios "what if ?" ; régressions multilinéaires ; degrés-jours ; intégration énergétique ; règle du 80/20 ; intégration des utilitaires ; allocation des coûts ; application web ; services web ; optimisation multi-objectif.

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Abbreviations and symbols

Abbreviations

BFD	Block flow diagram	
BOD	Biological oxygen demand	mg/l
CC	Composite curve	
CEPCI	Chemical engineering plant cost index	
CFC	Chlorofluorocarbon	
CDD	Cooling degree days	
CHP	Combined heat and power	
COD	Chemical oxygen demand	mg/l
COP	Coefficient of performance	-
CS	Carbon steel	
GCC	Grand composite curve	
GUI	Graphical user interface	
HFC	Hydrofluorocarbon	
HDD	Heating degree days	
HFO	Heavy fuel oil	
HHV	Higher heating value	kJ/kg
HVAC	Heating, ventilating, and air-conditioning	
KPI	Key performance indicator	
LENI	Laboratoire d'Energétique Industrielle	
LFO	Light fuel oil	
LHV	Lower heating value	kJ/kg
LPG	Liquefied petroleum gas	
MER	Minimum energy requirements	
MPB	Marginal payback	
MU	Monetary unit	
PB	Payback	
PUO	Process unit operation	
QMOO	Queuing multi-objective optimizer	
SOAP	Simple object access protocol	
SS	Stainless steel	
TCOP	Total cost of production	
TDS	Total dissolved solids	
VFD	Variable frequency drive	
WSDL	Web services description language	
XML	extensible markup language	

Factory model

$c_{de,i}$	Specific energy cost of distributed energy i	MU/Unit
$p_{l,i}$	Energy supplied to the energy distribution system i by the purchased energy l	Unit
$e^+_{k,i}$	Energy supplied to the energy distribution system i by the energy conversion unit k	Unit
$e^-_{k,j}$	Energy consumed by the energy conversion unit k in the energy distribution system j	Unit
$\zeta_{k,i}$	Cost allocation factor for the energy distribution system i in energy conversion unit k	-
c_l	Price of purchased energy l	MU/Unit
o_k	Overhead cost of energy conversion unit k	MU/y
C_i	Total cost of the distributed energy i	MU/y

Boiler and Air heater model

λ	Excess air coefficient	-
T_d	Dewpoint temperature	K
q_{vap}	Heat of vaporization of the steam	kJ/kg
T_a	Ambient temperature	°C
T_{stack}	Stack temperature	°C
L_{stack}	Stack losses	%
$\dot{Q}$	Heat transfer rate	W
U	Overall heat transfer coefficient	W/m^2/K
U_1	Heat transfer coefficient on shell side	W/m^2/K
U_2	Heat transfer coefficient on tube side	W/m^2/K
A	Heat transfer area	m^2
ΔT_{lm}	Log mean temperature difference	K
F	Correction factor on ΔT_{lm}	-
G	Geometric factor for radiation	-
σ	Stefan-Boltzmann Constant	W/m^2/K^4
Re	Reynolds number	-
Pr	Prandtl number	-
μ	Dynamic viscosity	kg/m/s
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
k	Thermal conductivity	W/m/K
D	Tube outer diameter	m
η_f	Fin efficiency	-
η_0	Overall efficiency of fin array	-

Compressor model

η_{Cs}	Compressor isentropic efficiency	-
η_V	Volumetric efficiency	-

τ	Compression ratio	-
$\dot{V}_{suction}$	Volume flow rate in the compressor	m^3/h
$\dot{V}_{suction\_N}$	Volume flow rate in the compressor at nominal conditions	m^3/h
$\dot{V}_{swept}$	Volume swept by the piston	m^3/h

Equipment costing

C_p	Purchased cost of equipment	MU
C_f	Final cost of equipment	MU
f_p	Pressure factor	-
f_m	Material factor	-
f_t	Type factor	-

Statistic

y_i	Measured consumption during month i	GJ/m
$\hat{y}_i$	Estimated consumption level during month i	GJ/m
a_p	Correlation coefficient of the product p	GJ/t
$v_{i,p}$	Production volume of product p during month i	t/m
h	Correlation coefficient of the degree days	GJ/°C/d
$\hat{\beta}_j$	Coefficient estimate	
$T_{i,j}$	Ambient temperature of the day j in month i	°C
T_{room}	Room temperature	°C
T_{lim}	Limit temperature for degree days calculation	°C
$T_{bal,h}$	Room temperature for heating degree days	°C
$T_{bal,c}$	Room temperature for cooling degree days	°C
k	Correlation coefficient of the base load	GJ/d
n_{month}	Number of months considered	
m	Number of independent variables in the regression	
R^2	Coefficient of determination	
α	Level of significance	
F-value(α)	Value of F statistic with a level significance α	
t-value(α)	Value of t statistic with a level significance α	
MSE	Mean square error	
SS	Sum of square	
VIF	Variance inflation factor	

Financial

i	Discount rate	%
t	Tax rate	%
d	Annual depreciation allowance	MU
n	Investment economic life	year
I	Capital investment	MU
S	Annual saving after tax	MU/y
S_t	Annual saving before tax	MU/y

Chapter 1

Introduction

In the present situation of high and volatile energy prices, introduction of emission taxes and market pressure on the prices of goods and services, the rational use of energy has emerged as a necessity for companies in recent years. In addition, social pressure to protect the environment is particularly important on large companies, which, due to their size, make a large use of resources (energy and water). As energy management has been overlooked for many years, many companies are lacking in knowledge and tools to set up an efficient energy management in their facilities. Some transnational corporations possess a large know-how spread all around the world, but still fail to share it across subsidiaries. In that context, this thesis presents the development of energy management tools designed to be applied in large companies in a web environment permitting the sharing of knowledge in the field of energy management.

1.1 Energy in industry and corporate social responsibility

The industry sector is a large energy consumer at world level. In 2003, it accounted for 31.9% of the total final consumption, which amounted to 7287 Mtoe (IEA, 2004). This share differs substantially from one country to another as illustrated in figure 1.1. Developed countries, such as the United States and Switzerland, present a large per capita consumption, but are below the world average in terms of the share of industry sector consumption in total energy consumption (24.9% in the US and 19.7% in Switzerland). In fast-growing countries, this share reaches values as high as 41.7% in China. As regards the energy sources that are used in the industry sector, figure 1.2 gives their distribution for the world and Switzerland. It highlights the low penetration rate of renewable energy sources and the high dependence of the sector on fossil fuels.

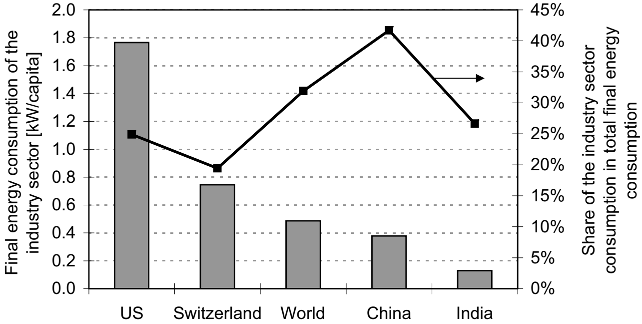
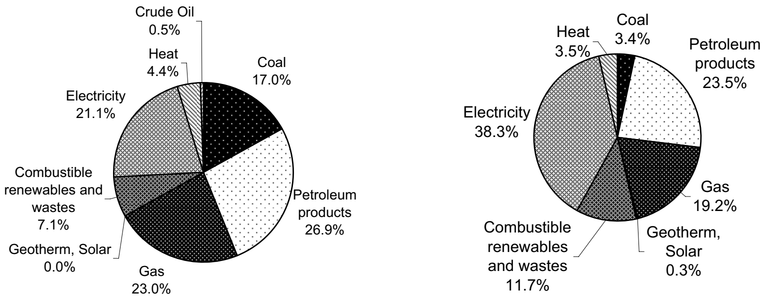


Figure 1.1: Final energy consumption of the industry sector in 2003 (IEA, 2006)



(a) World (b) Switzerland

Figure 1.2: Energy split for the industry sector in the world in 2002 (IEA, 2004) and in Switzerland in 2003 (OFEN, 2004)

The structure of the industry sector is also evolving rapidly. The consolidations observed in many industry sectors through mergers and acquisitions have given birth to transnational corporations whose energy consumption is of the same magnitude as that of a small country. For instance, in 2003, the energy consumption of the world's leading food company was 2253 ktoe (Nestec, 2005) which corresponds to 54.9% of the energy consumption of the Swiss industry sector (4107 ktoe) as illustrated in figure 1.3. This figure also highlights that the consumption of this company exceeds the industrial energy consumption of countries such as Israel, Morocco or Tunisia.

The increased importance of large corporations make them more exposed to stakeholders (Finger, 2004). Consequently, in addition to their primary goal of enhancing corporate profit,

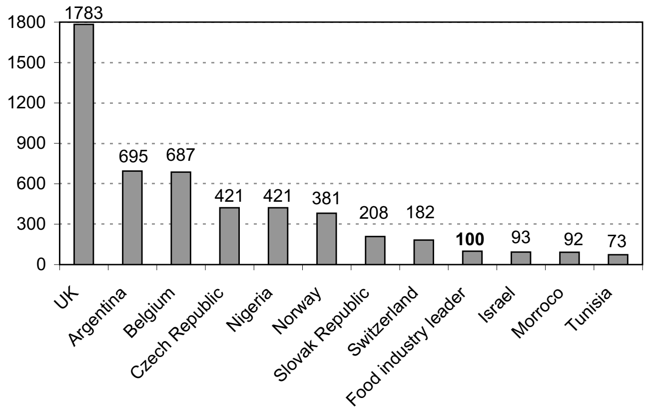


Figure 1.3: Energy consumption by the food industry leader as compared to energy consumption by industrial sector in different countries in 2003 (food industry leader=100)

companies have an increased social and environmental responsibility. Energy management and its impact inside and outside the factory concerns not only the technical department, but also other stakeholders, as shown in figure 1.4. For example, the environmental impact is part of the image of the company. In that context, an effective energy management will help to fulfill the objective of the company to conserve water and energy resources, defining the company's answers to the pressure of international non-governmental organizations (NGO), media and/or the market. The raising concerns on environmental issues also affect companies through the laws that local governments enact to protect the environment, but also through subsidies that might be available for companies promoting clean technologies for instance.

A study by SIRAN (2006) showed how the environmental reporting of large companies has evolved during the recent years. In 2006, 79 out of 100 companies of the Standard & Poor's 100 Index had special sections of their website where they published their social and environmental policies and performance, compared to 59 companies in 2005, which represents a 34 % increase. Reporting is also usually used to communicate voluntary measures to achieve a sustainable development. For example, the corporate management of General electric, one of the world largest companies, set itself the target to cut overall greenhouse gas (GHG) emissions by 2012 to 1% below their level in 2004 and to decrease the intensity of its GHG emissions (emissions in terms of its economic activity) by 30% by 2008 (The Economist, 2005). In the future, companies will be judged not only on the basis of their financial performance but also of their environmental performance. Managers are well aware of this new trend, which is taken into account in their decision-making process. A survey conducted by

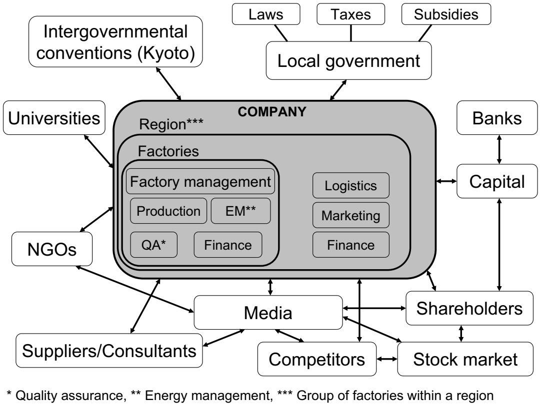


Figure 1.4: Energy management interactions with stakeholders

Harris et al. (2000) in Australian firms showed that almost 75% of their managers "agree" or "strongly agree" with the fact that environmental considerations are important in the decision-making process. Recent years have also seen the emergence of companies [1] [2] providing independent assessment of environmental performance of companies to help institutional investors and financial professionals. Trucost introduced a "carbon intensity" or "carbon footprint" indicator for a company. This measure highlights the equivalent carbon emissions per unit of turnover of the company. The first carbon footprint from Trucost concerning 44 of the largest UK investment funds was published in June 2006 (Trucost, 2006). The share of responsibility of the company in the emissions of its suppliers was also included in the calculation of the carbon footprint. It allowed to draw two interesting conclusions. Firstly, the variability was high: the worst fund has a carbon footprint more than five times larger than the best one. Secondly, and more importantly: no correlation was found between financial performances of these funds and their carbon footprint. This confirms the results of other studies that demonstrated a positive correlation between the environmental performance of a company and its shareholder value (Pye and McKane, 2000). Energy management and the resources it demands should not be perceived as a financial constraint, but as a means to increase **both** the financial and the environmental performance of a company.

[1] Trucost, www.trucost.com
[2] SiRi Company, www.siricompany.com

1.1.1 Energy in the food industry

The methodology and the tools developed in this thesis were based on the needs of the food industry. Compared to other industry sectors, the food industry has some specific characteristics that should be kept in mind when trying to put in place an energy management program. Firstly, the food industry is a non-energy intensive industry where energy is only a small part of the total cost of production. A survey among 135 Dutch companies (de Groot et al., 2001) showed that mean energy expenditure in the 19 food companies studied accounted for 3% of the sales. In the US, a similar study among 148 food companies (Adams and Milmoe, 2001) showed that energy represented between 1 to 2% in average. However, in some specific food processes, the use of energy intensive-process such as evaporation or spray-drying can lead to an energy cost representing 10% of the total cost of production (Urbaniec et al., 2000). To compare with other industry sectors, energy costs in the European Union chemical industry accounts for 8% of the sales value in 2003 (ECIC, 2005). In the refining of oil, energy represents between 50% to 70% of the operating cost (Hoez, 2004). In the steel industry, energy represents between 30% to 45% of the production cost (Larsson and Dahl, 2003). The relatively low importance of energy in the cost structure of food companies makes that energy management is not considered as a core business. Other issues, such as product quality and safety operation, have a higher level of priority in the daily business management. This explains why energy management has often been overlooked in the past and level of metering in food factories is poor when compared to other industries.

Although most of the food processes are not energy intensive, the size of the food industry in the industrial sector makes it one of its major energy consumer. For example, in 1998, the US food industry was the fifth biggest consumer (out of 20 sectors) after petroleum and coal products, chemicals, paper and primary metals and accounted for 4.4% of the energy consumption of the US industry sector (EIA, 2003). Achieving energy savings through efficient energy management programs can therefore play a significant role in the reduction of primary energy consumption. In addition, the fact that most of the saving opportunities can be replicated from one production site to the others is an other reason for developing energy management methodologies in the food industry, mainly for corporations with a large number of production sites. Finally, the relatively low temperature level of the food processes makes them good candidates for the rational conversion of energy resources by integrating combined heat and power or heat pumping solutions.

1.2 Energy management and barriers to energy efficiency

Energy management is a concept involving a wide range of tasks and goals. Its definition is likely to vary from one company to the other or even from one production facility to the other. For the sake of clarity, we will adopt as a basis for this work the definition proposed by O'Callaghan (1993):

> *Energy management is a technical and management function the remit of which is to monitor, record, analyse, critically examine, alter and control energy flows so that energy is always available and utilized with maximum efficiency*

An element that does not appear explicitly in this definition but which is of great important in an industrial context, is that all these tasks should be achieved at a minimum cost. From this definition, it appears that energy management will require considerable human resources for gathering and maintaining energy-related information (*monitor, record,[...] and control energy flows*). Indeed, these tasks are to be carried out daily so as to maintain a proper control and to gather enough information to be able to *analyse, critically examine* and *alter* energy flows in a second step. The latter will require not only skills in fields such as engineering and economics, but also decision-support tools that will be discussed later in this chapter. Due to the variety of tasks included in an energy management program, many agents will be involved at different level of responsibilities: factory technical managers, maintenance and project engineers and production and utility operators. The coordination as well as the motivation of these persons will require management skills from the factory technical manager as well as a strong commitment from the top management (Brown and Kuhel, 2001).

In many production facilities, top management commitment regarding energy management is lacking, which results in an energy consumption pattern as the one presented in figure 1.5 and referred to as "periodic initiatives". In these cases, it is only when an increase in energy costs is observed that an energy management program is set up. This course of action will often lead to short-term results, which will once again relegate energy management to a position of secondary importance. Consequently, after a short period of time, energy costs will increase again and the cycle will repeat indefinitely. To be effective and to reduce energy costs on a long-term basis (see dashed line in the figure), it is necessary to continuously perform energy audits. The energy-efficiency actions resulting from these programs will often require few or no investment and can be qualified as good-housekeeping measures. To further reduce energy costs (see dotted line in the figure), integration of new technologies and large process modifications are needed, meaning as well large investments. Obviously, the magnitude of energy savings might vary from one production site to another. The values used in this figure correspond to typical results available in literature (Turner, 2005).

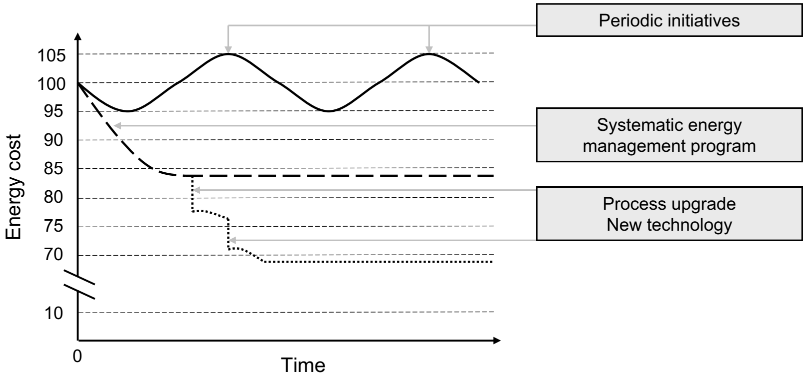


Figure 1.5: Efficiency of energy management programs

Other commonly encountered barriers to energy efficiency are the lack of resources (human and financial) and the lack of energy data due to poor levels of metering in factories (Brown and Key, 2003). Harris et al. (2000) showed that another factor preventing the diffusion of energy efficiency actions is the very conservative attitudes of firms towards risk. The value of any possible production losses due to modifications in the process are much greater than the value of the energy savings. In addition, Sandberg and Soderstrom (2003) highlighted that managers do not always have adequate information about the investment conditions due to the lack of decision-support tools.

1.2.1 Energy management programs

It is only when the structure of an energy management program has been put in place and resources made available by management that the "real" energy study can begin in a factory. It is commonly accepted in energy management books (Thumann and Mehta (2001); Turner (2005); O'Callaghan (1993); ATEE (1984) among others) that such a study (often referred to as "audits" in literature) should start with the analysis of the energy bills and the determination of where energy is distributed and used inside the factory. However, few of these sources provide tools and strategies to make the life of engineers easier with respect to these tasks. Some researchers have tackled this problem through energy modeling strategies (Bieler et al., 2003, 2004; Vogt, 2004). Two main approaches are considered in these works: top-down and bottom-up modeling approaches. Based on energy bills, the top-down approach aims at allocating the consumption among the different users in the factory by defining relationships between dependent variables, such as energy consumptions, and independent variables, such as production volumes, ambient temperature, etc. Unlike the top-down approach, which is based on the global energy consumption of the factory, the bottom-up approach aims at thermodynamically modeling the energy consumptions of the different process operations in order to recalculate the global energy consumption by summing up their different contributions. The efficiency of each method will mainly depend on the variability of the products, as shown by Bieler et al. (2003, 2004) in applications in the chemical industry. From the experience acquired by the author, the comparison of the two approaches shows that, independently of their applicability, both methods have their advantages and disadvantages, which are presented in table 1.1.

Table 1.1: Advantages and disadvantages of the top-down and the bottom-up modeling approaches

	Advantages	**Disadvantages**
Top-down modeling	• Low cost • Simple model • Easy monitoring • Easy forecasting • Flexible • Minimal maintenance	• Require statistical expertise • Require data history • No efficiency assessment • High-level modeling • No modeling of efficiency measures
Bottom-up modeling	• Based on equipment thermodynamics • Good accuracy • Clear picture of energy usage • No data history required • Efficiency assessment • Modeling of efficiency measures	• High level of metering needed • Time-consuming study • High data entry requirement • Difficulties in forecasting • High cost of use/maintenance • Based on perfect operation

Due to its characteristics, top-down modeling is better adapted for a rapid identification of the main energy drivers of a factory, which can be the basis of a more detailed study in a specific area. However, it does not provide information about the efficiency of the operations except for high level indicators such as the specific energy consumption related to a given independent variable. The bottom-up approach requires enormous efforts in terms of time, human resources, metering and model updating, though it gives a clear and precise picture of the energy usage. It is thus difficult to apply it in industries where the resources dedicated to energy management are limited.

In the methodology developed in this thesis, the priority is given to a top-down approach in a first phase which is not only limited to modeling using statistical tools but also includes information from meters and knowledge from factory staff. The bottom-up approach is used as a complement rather than as an alternative to the top-down approach, in order to analyse the main energy drivers identified in a first phase. It is applied locally and not necessarily to the whole site, as done when aiming to recompute the energy bill.

1.2.2 Energy management in large companies

If energy management programs in small and medium-sized enterprizes (SME) and in large companies strive for the same aims, implementation of the energy management best practice will take different forms in both case. SMEs are often obliged to rely on consultants or on learning networks (Jochem and Gruber, 2005) due to the scarcity of knowledge in energy management. The learning networks have demonstrated in Switzerland and Germany that important energy saving are achievable by sharing experiences among participants. However, the heterogeneous composition of the group of participants may limit the benefits of such approaches when discussing specific saving actions (Jochem and Gruber, 2004). In contrast, large companies have the opportunity to make use of their structure and resources to share and spread the in-house knowledge among the company. A typical structure of technical management in a large company and the main staff involved are presented in figure 1.6. The operational structure is composed of three levels: the top management, the regional management in charge of several factories within a region and the factory. Besides this hierarchy, a group of experts in fields such as industrial services, energy, environment or maintenance, is often available for project assessment and support. In the food industry, leading companies can have as much as several hundreds of production sites and more than 200'000 employees around the world organized in such a structure (Nestlé, 2005; Unilever, 2005).

Best energy management practices are available in literature to help the setup of efficient energy management strategies. However, energy management strategies are quite general as illustrated in the example below (Norland, 2001):

1. Commitment by top-level management
2. Clearly-defined energy-reduction goals
3. Communication of the goals throughout all levels within the company
4. Assignment of responsibility and accountability at the proper level
5. Formulation and tracking of energy use metrics
6. Identification of all potential projects on a continuous basis

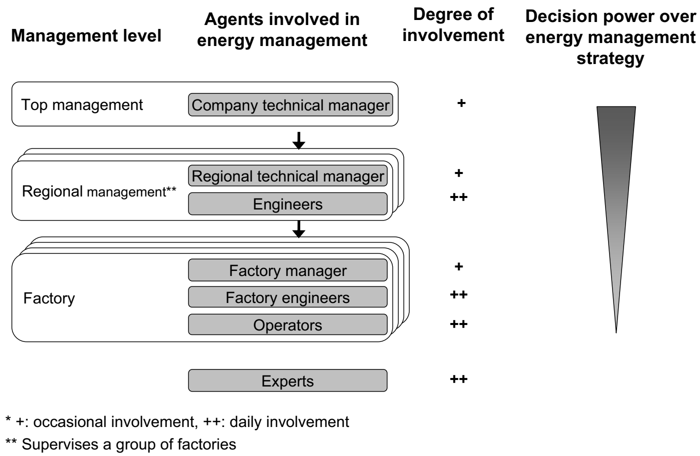


Figure 1.6: Energy management levels and related agents

7. Adoption of project investment criteria reflecting projects risks and returns
8. Provision of recognition and reward for achieving the goals

When it comes to the development of a more practical strategy, it is important to keep in mind that energy management will involve a lot of different agents, each having different responsibilities and needing specific information to efficiently play their role. A tool for energy management in such companies should take into account the expectations of the different users with whom it will interact. Managers at all levels (company technical manager, regional technical manager, factory manager) are principally interested in high-level energy and environmental KPIs of factories or of a group of factories. Based on this information, they will be able to define the main direction of energy management for the company, negotiate global purchase contracts with suppliers and set priorities for the allocation of the financial and human resources available. In addition to the previous information, engineers are also interested in sharing their experiences in implementing energy-saving measures with other engineers, benchmarking their energy performance indicators with other factories of the company, having access to documents and guidelines provided by the group of experts or the top management, etc. In that context, energy management programs can make an advantageous use of the IT structure of the company (e.g. its intranet). However, sharing this information will also signify an important effort to put in place the necessary framework. While large companies have the capacity to absorb the cost of the development of such an energy management framework among all the users worldwide, this is not the case of

SMEs. The next section proposes a summary of the main energy management software tools available on the market at the early stage of this thesis (early 2004).

1.3 Available energy management tools

The definition of energy management given in section 1.2 introduces different tasks under the concept of energy management: recording, monitoring, controlling, analysing, critically examining and altering the energy flows. In this section, we will introduce tools available in the market (in early 2004) that will help the engineer in carry out these tasks [3]. These tools have been classified in three main categories:

1. Energy monitoring tools
2. Process modeling, simulation and optimization tools
3. Process integration tools

Energy monitoring tools are used for recording, monitoring and controlling energy flows while process modeling, simulation and optimization tools and process integration tools are used to analyse and critically examine the energy flows. It has to be emphasized here that optimization tools based on modeling language for mathematical programming, such as AMPL[4] or GAMS[5], have not been considered in this survey. Indeed, such methods are often used in industry sectors that have at their disposal a large number of equipments to generate steam or electricity. This is typically the case in energy-intensive sectors or in centralized site utility systems (Hirata et al., 2005; Aguilar et al., 2005). The potential usage of these tools in a non-energy intensive industry such as the food industry was judged as limited.
In addition to these tools, governments and international organizations also provide in their websites useful decision-support documents for energy efficiency improvements. These include best practices on energy conversion unit (DOE, 2004, 2003), best available techniques (EU, 2006) and case studies of energy efficiency projects (CADDET, 2006).

1.3.1 Energy monitoring tools

By energy monitoring tools, we refer to software tools that performs real-time data acquisition of energy flows and provides some basic techniques to analyse them. These techniques

[3] Tools assisting managers in the setup of an energy management program are also available (see for example "One-2-Five® Energy" software on www.envinta.com) but are not discussed here.
[4] www.ampl.com
[5] www.gams.com

may include the possibility to make statistical analysis, such as simple or multiple regressions analysis, to track energy consumption through a targeting-monitoring interface, to benchmark the consumptions of different sites, etc. Table 1.2 presents the main monitoring softwares available in the market, based on a web survey. The entries of this table are explained hereafter:

- **Multi-site:** the software is not limited to a specific site and can integrate different production sites.
- **Multi-site benchmarking:** the software allows for benchmarking the different sites.
- **Multi-site level:** the software is designed to model the energy consumption with an increasing level of details.
- **Multi-site user:** the software is designed to be used by different users with different expectations (managers, engineers, ...).
- **Targeting-monitoring:** the software allows for targeting-monitoring of energy consumptions.
- **Real-time data acquisition:** the software is based on real-time data acquisition.
- **Compute KPIs:** the software allows for defining KPIs.
- **Simple regression analysis:** the software integrates statistical analysis tools, including simple regression analysis.
- **Multiple regression analysis:** the software integrates statistical analysis tools, including multiple regression analysis.
- **CUSUM analysis:** the software integrates statistical analysis tools, including CUSUM (Cumulative sum of deviation) analysis.
- **Bill verification:** the software proposes bill verification based on real-time data acquisition.
- **Power quality:** the software conducts power quality analyses.
- **Energy balance:** the software performs an energy balance, i.e. all energies entering a system are used in the system.
- **"What if?" on cost:** the software can simulate the effects of changes in energy costs (e.g. electricity costs in peak hours).
- **Equipment efficiency computation**. The software can compute the efficiency of some predefined equipments.

Table 1.2: Characteristics of some energy monitoring tools

	Rockwell - RSEnergyMetrix	Optima Energy Management	Energy Audit Agency - Team Sigma	STC Energy Solutions	Alliant Energy - EnergyTrax	Stark - Essentials + RT	ABB - Optimize	MPG - MPS	Itron - EEM	SMR - Utility Manager	Power measurement - ION EEM	Good Steward Software - Energy CAP Enterprise	Meniscus - IPMS	EnVINTA - ENTERPIRZE.EM	AspenTech - Aspen Utilities	ProSim - Ariane
Multi-site	✓?	✓	✓		✓	✓	✓		✓		✓	✓	✓	✓		
Multi-site benchmarking			✓		✓	✓			✓		✓		✓	✓		
Multi-level	✓						✓		✓	✓	✓	✓	✓		✓	✓
Multi-user					✓		✓		✓	✓						
Targeting-monitoring	✓	✓	✓		✓	✓		✓	✓		✓		✓	✓	✓	
Real-time data acquisition	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	
Compute KPIs	✓?	✓	✓?				✓	✓	✓?		✓	✓	✓	✓	✓	
Simple regression analysis	✓	✓	✓				✓		✓	✓		✓	✓			
Multiple regression analysis	✓	✓?					✓		✓	✓		✓				
CUSUM analysis	✓	✓	✓						✓				✓			
Bill verification		✓	✓	✓		✓	✓			✓	✓	✓		✓		
Power quality							✓				✓			✓		
Energy balance							✓		✓							✓
"What if?" on cost	✓						✓			✓	✓				✓	✓
Equipment efficiency computation								✓							✓	
Data reconciliation															✓	

✓: function available in the software, ✓? : function seems available in the software from the information on the website

1.3.1.1 Conclusion on energy monitoring tools

The tools presented in this table allow for the detection of any deviation in energy usage and for the setup of a targeting-monitoring program. In that sense, they are normally used to control the consumption of utilities (gas, electricity), but are often less appropriate for inside factory usage. For instance, only three of them are able to make a balance between the energy flow inputs and what is consumed in the factory (see "Energy balance" entry in the table). Most of them are only targeted to engineers and, in that sense, are more designed to be used locally in a factory than in large companies where managers could intervene in energy management (see "Multi-user" entry in the table). Moreover, since the majority of these tools focus only on the energy flows across the border of a factory but not inside it, they fail to provide solutions to correct the observed deviations. They find their best application in liberalized energy markets, where advanced tools for bill verification as well as for simulation of energy cost ("what if?") allow for choosing the best supplier. Some of them are specifically designed to be used for electricity monitoring since they provide power quality analysis. To summarize, these tools can not be considered as a unique solution for energy management and need to be combined to other tools, such as simulation tools, to prove useful.

1.3.2 Process modeling, simulation and optimization tools

Process modeling, simulation and optimization tools permit a better understanding of energy conversion and process units by determining their efficiency and where losses occur. Most of these tools are often to be found in the chemical industry, where they are used for process optimization and design. The following is a list of the main companies in this area and a description of their products as of early 2004.

AspenTech [6] is a spin-off from the Massachusetts Institute of Technology (MIT) founded in 1981. Nowadays, the company provides solutions for process companies in the following domains: engineering, plant operation/supply chain and operations management. Its solutions focus on oil & gas, petroleum, chemicals and pharmaceuticals, but they are general enough to be used in a wide range of industries. AspenTech provides various tools related to energy that are included in an engineering suite called Aspen Engineering Suite (AES). One of them is the Utilities™ software, which was already introduced in table 1.2 concerning energy monitoring tools. Other energy-related modules in AES are:

[6] www.aspentech.com

- Simulation and optimisation: both steady-state and dynamic for oil & gas, petroleum, chemicals, pharmaceuticals (Aspen Plus® , HYSYS® , Aspen Dynamics® , HYSYS Dynamics™)
- Thermo-economic models for equipments (Aspen Aerotran™, APLE™, etc)
- Thermophysical property data (Aspen Properties™)
- Energy integration through pinch analysis (HX-NET® and Aspen Pinch®)
- Data reconciliation (Aspen Advisor™), which is also integrated in the Aspen Utilities™ module.
- Design and simulation of heat transfer equipment(Aspen HTFS+®)
- Process integration through pinch analysis (HX-NET® and Aspen Pinch®). See 1.3.2 for more details.

SimSci-Esscor [7] is an operating unit of Invensys Systems that provides various software tools related to process simulation, optimization and monitoring:

- ARPM and DATACON are software for on-line performance monitoring. Based on simulation models, both software perform real-time data reconciliation to provide the user with accurate process performance indicators. The first software is more dedicated to refiners and petrochemical companies
- DYNSYM is a dynamic process simulation software that includes various process and electrical unit operations.
- PRO/II is a process simulation program performing rigorous particularly adapted for chemical, petrochemical, oil & gas, pharmaceuticals and engineering companies. It offers a Graphical user interface (GUI) called PROVISION. PRO/II can easily be interfaced with Aspen HTFS+ (see above), HTRI and Linnhoff March's SuperTarget (see below)
- ROMeo is a software similar to ARPM and DATACON but it has the advantage of including optimization capabilities. It is aimed at refining, petrochemical, and chemical industries.
- HEXTRAN is a software for heat transfer simulation, which is described in 1.3.2.

ProSim [8] is a spin-off of Institut National Polytechnique de Toulouse founded in 1989. Apart from its energy management software Ariane described in table 1.2, the company offers the following energy-related software tools:

[7] www.simsci-esscor.com
[8] www.prosim.net

- ProSimPlus is a steady-state Simulation & optimization software aimed at chemical, petrochemical, oil & gas and engineering companies. A thermodynamic database is used as the base for mass and energy balances around operation units defined by models. ProSimPlus also allows for sensibility analysis and equipment design.
- Simulis® Thermodynamics, ProPhy Plus, DIPPR L03+ are software tools for the calculation of thermophysical properties.

Process Systems Enterprise Limited (PSE) [9] was established in 1997 as a spin-off from Imperial College in London. Their main product is gPROMS®, an advanced equation-based software for the process industries. It allows for dynamic or steady-state simulation, optimization or parameter estimation. These characteristics make gPROMS a powerful tool for both design and operations. Moreover, the software has an open interface enabling easy links with other software such as FLUENT, Aspen Plus, Hysys, Matlab, Simulink, various automation systems and physical properties packages.

Belsim [10] is a spin-off from the University of Liège that was founded in 1986. The company launched Vali (Belsim, 2003), which is a data validation software based on a Sequential Quadratic Programming - Interior Point (SQP-IP) solver. The software was developed for the following markets: power & utilities, oil & gas, chemical, engineering & construction and polymers. Vali is based on mass and energy balances performed using a thermodynamic model database. It can be used for process performance monitoring, process performance optimization, plant steady-state simulation and sensibility analysis. Vali can be used on-line or off-line and can be integrated in various control systems.

Others providers of process simulation software are available in table 1.3.

1.3.2.1 Conclusion on Process modeling, simulation and optimization tools

Process modeling, simulation and optimization tools play a decisive role in energy management. They provide a sound basis for assessing the efficiency of process units as well as energy conversion units through the computation of thermophysical properties and mass/energy balances. When coupled with energy monitoring tools (see section 1.3.1), they permit to obtain reliable performance indicators through data validation. They allow to set energy consumption targets at the level of the unit operations and to set priorities by identifying the units with the highest losses. In addition, simulation and optimization features provide a reliable decision supports for energy saving actions. However, and contrary to energy monitoring

[9] www.psenterprise.com
[10] www.belsim.com

Table 1.3: Process simulation tools

Company	Software	Comment
Bryan Research[a]	ProMax	
Epcon International[b]	System 7	
Intelligen[c]	SuperPro Designer and EnviroPro Designer	for WWTP and water purification
GSE systems[d]	SimSuite Pro	
Chemstations[e]	CHEMCAD	steady-state and dynamic simulation
Deerhaven Technical[f]	PD-PLUS	No Graphical User Interface (GUI)
Virtual Materials Group[g]	VMGSim	steady-state simulation for oil & gas, refining and petrochemical industries
WimSim[h]	Design II	
Aurel Systems[i]	CADSIM Plus	steady-state and dynamic simulation

[a]www.bre.com, [b]www.epcon.com, [c]www.intelligen.com, [d]www.gses.com, [e]www.chemstations.net, [f]www.deerhaventech.com, [g]www.vmgsim.com, [h]www.winsim.com, [i]www.aurelsystems.com

tools, these tools require a strong knowledge in thermodynamic and modeling to be exploited at the fullest. This is also the reason why most of the companies presented in this section also provide consulting services. In addition, although they offer very user-friendly and intuitive interfaces, the familiarization with the use of such tools may take some time and be frustrating at first. Consequently, these tools need to be used on a regular basis which is also justified due to their high cost. In large companies, they will often be used by experts in energy and processes (see section 1.2.2).

1.3.3 Process integration tools

Process integration tools focus on possible heat recovery by heat exchange in the system, offering a holistic vision of the process and the energy conversion systems. While some companies provide commercial solutions, research institutes are also very active in the development of process integration tools. One of the leading companies in the area is Linnhoff March [11], founded in 1984 by Professor Bodo Linnhoff - inventor of the pinch method (Linnhoff and Flower, 1994) - and the March Consulting Group. The company provides an energy and a water integration software based on the pinch technology as well as utility modeling software:

- SuperTarget® and PinchExpress. Based on energy pinch analysis, these tools allow to set the best economic performance target for heat recovery through the computation of the minimum energy requirement (MER). The input data can be extracted from simulation software such as PRO/II, Aspen Plus. Going one step further than PinchExpress, SuperTarget allows for designing an optimal network of heat exchangers and

[11] www.linnhoffmarch.com

identifying cogeneration opportunities (total site analysis).

- WaterTarget Suite is a software aiming at minimizing water usage in the industry. It is composed of two software tools. WaterTracker produces reconciled balances of water and contaminant using models of standard equipments. The results can be exported to the second software of the suite called WaterPinch. The latter uses pinch analysis to identify water re-use, recycling, re-generation and effluent treatment opportunities. WaterPinch also enables contaminant sensitivity analysis
- ProSteam® is a Microsoft® Excel add-in for modeling steam utility systems.

AspenTech (see section 1.3.2) software portfolio also includes process integration software:

- HX-NET® and Aspen Pinch® are software that allow for heat exchanger network targeting, design and optimization. Aspen pinch can also be used for total site analysis and includes heat and power models for furnace, gas turbines, steam turbines and refrigeration systems.
- Aspen Water is a software for water management based on pinch technology. It includes a database of standard operations, data reconciliation of water chemistry, identification of investment options and contaminant sensitivity analysis.

SimSci-Esscor (see section 1.3.2) proposes a software for heat exchanger networks called HEXTRAN. It can be used for heat exchanger design operational analysis and performance monitoring and for network synthesis and optimization through pinch analysis. National Engineering Laboratory (NEL) [12] is a pinch-based software for heat exchanger network design and retrofit.

Besides these commercial solutions, various research institutes have developed their own software in the field of process integration. The centre for process integration of the University of Manchester developed the process integration software SPRINT[13], which has been used in various applications (Plesu et al., 2005; Al-Riyami et al., 2001). The Laboratory for Analysis and Synthesis of Chemical Systems at the University of Liège largely contributed to the EXSYS II project by providing EASY software for the computation of process integration problems (Kalitventzeff and Maréchal, 2000). The development of this software is still in progress at the Laboratory for Industrial Energy Systems (LENI) at the Ecole Polytechnique Fédérale de Lausanne (EPFL). This group also developed the integration software pinchLENI in the framework of the thesis of Staine (1994). Other groups active in process

[12] www.nel.uk
[13] www.ceas.manchester.ac.uk/research/researchcentres/centreforprocessintegration/softwaredevelopment/

integration include the Heat and Power Technology group at Chalmers University of Technology and the Department of Energy and Process Engineering at the Norwegian University of Science and Technology

1.3.3.1 Conclusion on process integration tools

Solving a process integration problem requires as a basis a good knowledge of the process as well as the availability of sufficient data on energy flows. In addition, it requires some thermodynamic knowledge to define the heat and temperature profile of hot and cold streams as well as the approach temperatures that will be used in the heat exchangers. Consequently, the prerequisites to use such tools are high. Once the streams have been introduced in the tools, the definition of the minimum energy requirements as well as the targeted energy consumptions through the integration of utilities are straightforward. The energy saving potentially achievable by heat recovery is a very valuable information to determine efficiency gaps. In that sense, its representation on a graph such as the one of figure 1.5 can give a very interesting result. However, the difficulty to implement these potential savings in real world applications and in particular in food industry is a real drawback of process integration, which is not reduced by using computer tools. This will be discussed in more detail in Chapter 5. Finally, process integration tools focus only on thermal and water flows; thus, the scope of the application of such tools is limited to a part of the total energy consumption.

1.4 Synthesis and objectives of the methodology

1.4.1 Synthesis

This chapter has highlighted the importance for large companies of increasing the energy efficiency in their production sites in order to reduce production costs but also to minimize the impact of their activities on the environment. To be efficient, energy management will require a common strategy to coordinate the different agents involved in such a program (managers, engineers, energy experts, production operators and utility operators) and to create the necessary conditions to share and exploit the in-house knowledge in energy. Besides top management commitment, the success and the sustainability of an energy management program will also rely on tools and methods and, particularly, on computer-aided tools. A survey of the commercial solutions available in the market showed that none of them can be considered as sufficient on its own to fulfill the objectives for energy management in large companies. Most of them are aimed at engineers and fail to integrate users such as managers. Consequently, the objective of this work is to develop a comprehensive methodology and a framework of IT tools addressed to all the agents involved in energy management that will guarantee an efficient and sustainable energy management. As this work has been developed in close collaboration with a partner from the food industry, the development of the methodology has taken into account the specificity of this sector. This includes the relatively low importance of energy costs in the total production costs resulting in limited human and financial resources, the importance of hygienic factors as well as the resistance of the production management when it comes to process modification.

This work has lead to the development of a web application in collaboration with an industrial partner as well as a prototype of a web-based simulation platform. The developed web application relies on a modular factory model (**Chapter 2**) that is used, among other tasks, to describe energy usage in factories worldwide. The factory model makes use of thermodynamic models (**Chapter 3**) to compute in background the efficiency as well as performance indicators of energy conversion units. The factory models defined by engineers in the factories worldwide can then be accessed and benchmarked in the web application (**Chapter 6**). In future versions of the application, "what if?" scenarios will be made available to user to evaluate and quantify the improvement potentials. In that context, a prototype of such a simulation platform based on thermo-economic models has been developed for demonstration purpose (**Chapters 6** and **7**).
Besides the implementation of these tools, the developed methodology also presents a top-down modeling approach (**Chapter 4**) aimed at helping engineer in defining the factory models in the web application as well as the concept of a bottom-up approach used to identify energy saving opportunities in the processes (**Chapter 5**).

1.4.2 Chapter 2: the factory model

This chapter presents the strategy put in place to model energy flows in a production facility in a standardized way. The aim of this modular model is to give an insight of the main energy drivers in the facility. Based on a graphical user interface, the factory system's inputs (energy and raw materials) and outputs (finished goods and wastes) are defined in a first step. In a second step, the factory system is decomposed in sub-systems, regrouped in three categories: energy conversion, energy consumption and waste treatment. These sub-systems (e.g. boilerhouse, chocolate production line, wastewater treatment plant) can exchange purchased and converted energies among them using energy distribution systems. Based on the data entered, performance and financial indicators of the system and the sub-systems are computed. A methodology is then introduced to allocate the energy costs as well as the overhead costs of energy conversion units among the energy consumers. A strategy to allocate cost in multi-service units based on exergy is also discussed. Finally, "browsable" factory representations resulting from the model are presented.

1.4.3 Chapter 3: thermo-economic models of energy conversion units

Chapter 3 introduces the thermodynamic models of energy conversion technologies that have been developed to assess the present performance of equipments but also to simulate potential changes in operation. The simulation software used to develop these models is briefly presented as well as the way to interact with it in batch mode. The thermodynamic models that are presented in this chapter are: boilerhouse, air heaters, complex refrigeration cycles, air compressor and cogeneration units. A special emphasis is put on the boilerhouse model, for which a simplified parametric model has been developed to meet the requirements of the web application developed. Finally, a thermo-economic model of a boiler economizer to be used for simulation purposes is described in detail.

1.4.4 Chapter 4: statistical methods as a support to the top-down approach

This chapter presents statistical tools that are used to correlate energy consumptions with independent variables, such as production volumes or ambient temperature. Given the low level of metering usually encountered in food factories, such tools will support the definition of the factory model introduced in Chapter 2. The concept of degree days is then introduced to model the effect of ambient temperature on heating and cooling requirements of a facility. In order to validate the developed models, a set of tests is performed on the model itself but also on each independent variable present in the model. A test to detect correlations between independent variables (multicollinearity) is also introduced. For the sake of demonstration, these concepts are then applied in a food factory in Switzerland. Models based on monthly data are developed and validated for purchased energies such as the fuel or electricity consumption, and for converted energies inside the factory. These models have showed that the share of energy consumptions not correlated to production volumes is high. This stresses the need for changing operation practices during process stand-by periods.

1.4.5 Chapter 5: bottom-up approach

Chapter 5 introduces the bottom-up approach, which is used to identify energy saving potentials in the process. Contrarily to the top-down approach that considers the energy bills as a starting point of the energy analysis, the bottom-up is based on the definition of the process requirements. In this chapter, we introduce three representations of the process requirements that are interchangeable: the thermodynamic representation, the technological representation and the utility representation. The thermodynamic representation is used to define the energy requirements of the product (e.g. heating chocolate from 20°C to 30°C). The technology used to fulfill this needs is referred to as the technological representation (e.g. a hot water loop). Finally, the utility representation accounts for the utility that is consumed in the unit. The definition of these requirements will allow to identify inefficiencies in a unit, but also to consider heat integration. However, gathering the data required to perform such an analysis for an entire site means a lot of resources, which is often not acceptable in the food industry. To overcome this difficulty, the 80/20 principle is introduced and demonstrated in an example. Based on this simplification, a process integration analysis is performed on the three representations and allows to quantify the energy savings achievable by considering each representation separately. Finally, the integration of heat pumps and reciprocating engines using multi-objective optimization is considered as an alternative to the boiler used presently.

1.4.6 Chapter 6: a global application for energy management

In Chapter 6, we introduce the web dimension of this work by integrating the factory models described in Chapter 2 in a web-based and company-wide energy management application. Gathering all the energy-related information in a centralized database allows the users worldwide (managers and engineers) to browse other factory models and to establish priorities in the allocation of resources for energy management. To make navigation easier, a color code inspired from traffic-light is used to give an information regarding the quality of a performance indicator (good - fair - bad). This rating mechanism is based on the know-how of the energy experts. The interface used to benchmark factories is also presented. Due to the size and the diversity of production facilities in the food industry, filters that can be applied to benchmarking results are introduced.

While the bottom-up approach allows to identify energy saving in the process, potential improvements in energy conversion units will be identified using standardized "what if?" scenarios. The simulations developed for the boilerhouse are presented as well as the underlying thermodynamic models. "What if?" scenarios have been implemented in a web-based simulation platform prototype, developed in this work. The platform also implements a graphical assessment of the profitability and of the risk linked to the investment required. Finally, a module allowing to generate PDF reports of simulation is presented.

1.4.7 Chapter 7: IT implementation

This chapter describes the IT implementation of the web-based simulation platform that is introduced in Chapter 6. The web application implemented by the industrial partner of this project and that is partly presented in Chapter 2 and 6 will not be discussed in this work. The importance of user-friendliness in the development of computer-aided tools is also commented. Emerging technologies, such as Ajax, that have been adopted to address user-friendliness issues are presented. Finally, the possibility for the web application to interact with the simulation models developed using web services is described.

Chapter 2

The factory model

In the web application developed, the energy-related data of factories worldwide are gathered, treated and presented using a specific factory model for each factory. The factory model is, consequently, the core element of the application on which the tools and methods to be presented in the following chapters ("what if?" scenarios, benchmarking, etc) will rely. In that context, the factory model should:

- Provide the engineers in factories with a user-friendly interface to collect all energy-related data in a standardized manner.
- Detect a maximum of errors during the data entry process through tests.
- Perform mass/energy balances [1] and validate the consistency of the entered data.
- Structure and store the data in such a way that they are easily accessible to other tools and methods.
- Compute key performance indicators and assess the efficiency of energy conversion units through thermodynamic models.
- Provide a way to allocate the energy costs among the different energy consumers in a factory.
- Provide "screen shots" on the energy flows and the performance of the factories through an interface. These representations will be classified in different levels corresponding to the expectations of the different users of the application (engineers and managers).
- Act as a decision support tool to prioritize the allocation of the energy management resources in the factory

[1] We will see later in this chapter that some energy flows are described using mass units (e.g. HFO flows are expressed in tons/year) while other are described using energy units (e.g. electricity is expressed in kWh/year)

This chapter focuses on the description of the factory model implemented in the web application. The underlying thermodynamic models used to compute efficiencies of energy conversion units will be presented in Chapter 3.

2.1 The factory system and its sub-systems

The factory model developed in this work is based on the systemic representation of the sub-systems and the mass and energy flows in a factory illustrated in figure 2.1. The system boundary includes not only the processes that transform raw materials into final products and by-products, but also the energy conversion units and their distribution networks, production support units, waste collection and waste treatment units. Horizontal flows concern transformation of raw materials into products or by-products through a set of process unit operations (PUO). The unit operations are made possible by the use of support of production and energy conversion units. Energy distributions systems are used as the interface between the energy conversion units and the PUOs. Since the transformation of raw materials into products is imperfect, some of the flows will leave the system as waste streams, which will have to be processed before being released to the environment. For a maximum system efficiency, horizontal flows have to be maximized while minimizing the vertical flows which include energy usage and waste generation. Figure 2.1 also clearly reflects the first principle of thermodynamics, expressed in the well known "more in-more out" rule of process integration (Linnhoff and Flower, 1994): the resources that do not leave the system as product, by-product or useful energy will leave the system as waste or emission. Maximizing the horizontal flows and minimizing the vertical ones (resources) means therefore minimizing the environmental impact.

2.2 Top-down representation and levels

We have seen in Chapter 1 that energy management in large companies involves different users at different levels of the company's hierarchy (see figure 1.6). Managers at all levels (factory, regional and top management) are not energy specialists but still have the responsibility to give directions on energy management as well as to set objectives based on high level key performance indicators of factories. Engineers, however, have to find solutions to achieve these objectives and will consequently focus much more on analyzing and optimizing the factory sub-systems. In order to cope with the needs of both types of users, the factory model

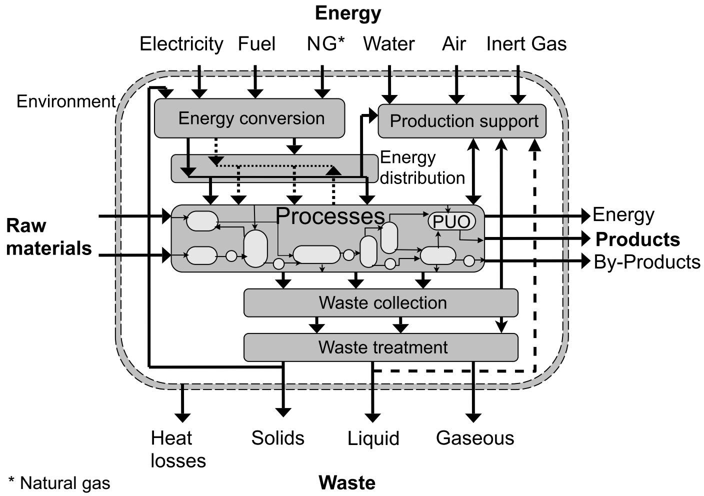
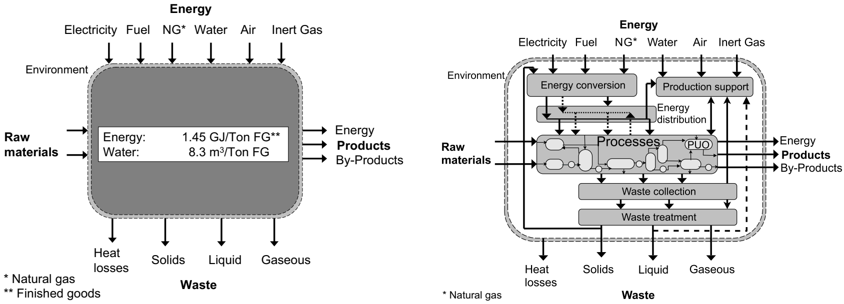


Figure 2.1: Typical production setup

developed introduces different levels of details. A top-down approach is thus considered for the modeling of factories. It starts with a high level overview of the factory, which concerns all users (level 1), before focusing on its sub-systems in a second step (level 2), which is more aimed at engineers. The level 1 focuses consequently on the flows that cross the system border: the energy purchased, the waste generated as well as the factory products. The level 2 is concerned with the different sub-systems of a factory. These sub-systems are grouped in three categories: **energy conversion units** (including sub-systems such as boilerhouse or refrigeration units), **energy consumers** (production lines, administrative buildings) and **waste treatment units**. These two levels are illustrated in figure 2.2(a) and 2.2(b).

As illustrated in figure 2.2(a), key performance indicators will be associated to each level. The definition of relevant key performance indicators is necessary to have a rapid and reliable assessment of the current state of the system. These indicators have to be defined in a standardized manner so that they can be applied consistently in all the factories of the company. This will also guarantee reliable results when benchmarking factories in the web application (see Chapter 6). Decisions in energy management do not only depend on the performance of a given unit but also on its annual energy cost compared to the total energy cost of a factory. A unit that is performing badly but represents only a small percentage of the energy costs will be considered of secondary importance compared to a unit that performs fairly but accounts for a much larger share of the energy costs. Strategies to rate the quality of an indicator will be discussed in Chapter 6.



(a) Level 1 (b) Level 2

Figure 2.2: Levels considered in the factory model

The two levels, consequently, provide both energy-related and financial KPIs. Level 1 representation, targeted mainly at managers, includes indicators such as the energy cost as a percentage of the total cost of production (TCOP) or the energy usage per ton of finished goods. Level 2 indicators define the cost of the utilities (e.g. CHF per ton of produced steam) or energy indicators such as the efficiency of the boilerhouse.

Though interesting, the definition of a factory model able to describe all the energy and material flows as illustrated in figure 2.2(b) is not realistic in an industrial context. Developing an interface in the web application that would allow engineers to define such a model would be too time-consuming. From the perspective of the user, collecting all the required information would be an impossible task. The structure of the factory model that has been implemented in the web application concentrates, therefore, on the vertical flows (energy and wastes) and excludes the horizontal flows described by the product recipes. The general structure of the factory model is presented in figure 2.3. The three categories of sub-systems previously defined exchange energy among them using **energy distribution systems**. The factory model also describes the context and environment within which the factory operates. Characterization of the factory environment includes financial figures such as total cost of production and its split (variable cost, fix cost, depreciation, etc), the local currency, currency conversion factors with respect to the central currency (CHF in our case), tax rate on profit, information on the factory location and the local climate. The contact information of the engineer responsible for the model is also to be provided. Describing the environment of a factory is essential to take into account the specificity of each factory. This will guarantee a more accurate assessment of the performance and a better basis to compare factories among each others. The main objective of the developed web application is not to monitor the energy flows in a factory but to identify energy saving potentials and provide decision-support tools for their implementation. Consequently, the definition of the factory model is based on yearly data.

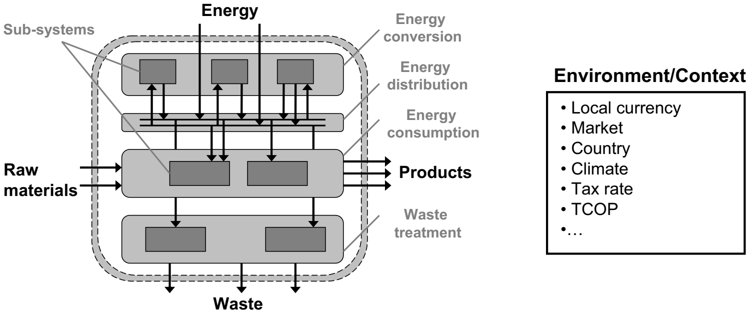


Figure 2.3: General structure of the factory model

2.2.1 Level 1: high level overview

As mentioned earlier, level 1 focuses on the material flows through the factory border: energy resources (hereinafter **purchased energies**), waste and emissions generated and finished goods produced. It has to be mentioned here that information on raw materials will not be considered as a key element in the factory model. Optionally, the user can provide data for information purposes. However, accurate data on the production volumes are necessary to define relevant and valid key performance indicators such as energy usage per ton of finished good. It has to be mentioned here that most of the data collected for the level 1 are also needed for environmental reporting making synergies possible. In the future, the possibility to use the developed web application for environmental reporting could save time and money both in the factories needing to supply the information and in the head office of the company.

2.2.1.1 Purchased energies

The purchased energies considered in the factory model are of different types: fuel, electricity, utilities supplied by a third party (e.g. steam, compressed air) and water. The latter is also considered as an energy resource since it is tightly linked with the energy usage (Zhelev and Zheleva, 2002). Indeed, the person in charge of energy management in a factory will often be accountable for water management. Each type of purchased energies is defined using standardized names and units, which are presented in the upper part of table 2.1. Since the developed web application is to be used worldwide, most of them are either SI base units or SI derived units. The required information to define each purchased energy includes financial information, such as the annual cost, the quantities consumed but also energy-related information, such as the lower heating value. Information required specifically for each type of purchased energy is provided in the lower part of table 2.1. The information will be used as a basis to compute performance indicators but also as a support for the identification of energy saving opportunities. For instance, the sulphur content of liquid fuels is required to evaluate the possibility of corrosion in heat recovery units for boilers or air heaters.

The definition of the factory model has to be as user-friendly and intuitive as possible so that the time and effort invested by engineers in collecting data can rapidly show useful results. In that context, default values for the characteristics of typical purchased energies are provided to the user in case they are not available from the energy suppliers. These default values are presented in table 2.2. Some of them have been directly extracted from literature (Favrat, 2001; Basu et al., 2000; ATEE, 1984; Silva et al., 1998; Vandagriff, 2001) while others such as the lower heating value of coffee ground have been derived from computations that can be found in appendix A. For instance, the lower heating value of coffee grounds is by default provided to the user when he defines their humidity using data of figure A.2. Optionally, the user can override this value. CO_2 emissions in table 2.2 are based on LHV as recommended by the Intergovernmental Panel on Climate Change guidelines (IPCC, 1997). The equivalent CO_2 emissions of other greenhouse gases product of the combustion (N_2O) or unoxidized (CH_4 with Natural gas) included in the Kyoto protocol (UNFCCC, 1997) can be neglected when computing combustion emissions even if their equivalent emissions are high (1 tonne CH_4 = 21 tonnes CO_2 and 1 tonne N_2O = 310 tonnes CO_2).

Guaranteeing that the information provided by the user is consistent and valid is essential. Indeed, detecting errors at the earliest stage possible will avoid spending time afterwards in trying to find the reasons why a computed indicator is invalid. Indeed, problem prevention is preferred to problem resolution. In the developed interface of the factory model, this takes the form of tests performed on the values entered by the user. For instance, some data should be between given lower and higher bounds (e.g. lower heating value (LHV) of LFO has to be in the range 41,400 - 44,200 kJ/kg) while some others have to be positive or null (e.g. annual quantity of a given purchased energy).

2.2.1.2 Wastes and emissions

As waste management is not the main purpose of the developed factory model, description of the waste flows leaving the system will be limited to the three following categories: waste

Table 2.1: Definition of purchased energies in the factory model

	Fuels and biofuels		**Electricity**		**Utilities from third parties**		**Water**	
Purchased energies	LFO	[liter]	Electricity	[kWh]	Steam	[Tons]	Water	[m^3]
	Diesel	[liter]			Hot water	[m^3]		
	HFO	[Tons]			Compressed air	[Nm^3]		
	Natural Gas	[Nm^3]			Cold	[kWh]		
	LPG	[kg]						
	Coal	[Tons]						
	Wood	[Tons]						
	Coffee ground	[Tons]						
Information required	Quantity	[Units/y]	Quantity	[Units/y]	Quantity	[Units/y]	Quantity	[Units/y]
	Cost	[MU/y]*	Cost	[MU/y]	Cost	[MU/y]	Cost	[MU/y]
	CO_2 tax	[MU/y]	CO_2 tax	[MU/y]	CO_2 tax	[MU/y]		
	LHV	[kJ/kg]	Supply tension	[V]	Pressure [d,f]	[barg]		
	CO_2 emissions	[kg/GJ]			Temperature [d]	[°C]		
	Sulphur content [a]	[%]			Condensate return [d]	[m^3]		
	Moisture content [b]	[%]			Condensate return temp. [d]	[°C]		
	Wood type [c]				Supply temperature [e]	[°C]		
					Return temperature [e]	[°C]		

* MU: monetary units; [a] for LFO, Diesel and HFO; [b] for coal, wood and coffee ground; [c] for wood; [d] for steam
[e] for hot water and cold; [f] for compressed air

Table 2.2: Typical purchased energies in industry

	LHV **kJ/kg**	**HHV** **kJ/kg**	**CO_2 emissions** **kg/GJ (LHV)**
Natural Gas	49000	54300	56.1
HFO	40100	42200	78
LFO	42900	45600	73.8
Diesel	42900	45600	73.8
LPG (propane)	46100	49800	64.7
LPG (butane)	45600	49200	66.3
Hard coal	30000	30900	85
Brown coal	9500	9800	91.5
Wood	18000	19400	0
Coffee ground (dry)	23000	24400	0
			kg/MWh
Electricity			*

* depends on the local generation mix. Swiss electricity: 110;
UCTE (continental Europe) electricity: 450 (ECOINVENT, 2003).

water, solid wastes and CO_2 emissions. With respect to energy management, waste water has two main interests. Firstly, its temperature is a good indicator of the amount of heat that has to be extracted from the factory and allows to consider potential heat recovery before the discharge. Secondly, the biological oxygen demand (BOD) and chemical oxygen demand(COD) allow for the quantification of potential biogas production through anaerobic digestion (Kleerebezem and Macarie, 2003). The biogas produced could then be used as a substitute to fossil fuel for boilers or air heaters. This could be typically the base of a "what if?" scenario. However, and as it would be discussed later in this work, "what if?" scenarios have been limited to energy conversion units in a first step. Similarly, solid wastes also have the potential to be recycled and used as a fuel. This is typically the case in the coffee industry, which generates large amounts of coffee ground. The data needed for the definition of the waste water and solid wastes streams are given in Table 2.3.

Table 2.3: Definition of waste streams in the factory model

Waste water		**Solid wastes**	
Treated waste water discharged	[m^3]	Amount disposed	[Tons]
Untreated waste water discharged	[m^3]	Annual disposal cost	[MU]
Annual discharge cost	[MU]		
Average BOD load at discharge	[mg/l]		
Average COD load at discharge	[mg/l]		
Average Temperature at discharge	[°C]		

* MU: monetary units.

Regarding gas emissions, the only gas considered here is CO_2. This choice is based on two reasons. Firstly, CO_2 emissions and the potential CO_2 taxes have a significant importance when evaluating the profitability of energy efficiency measure. Secondly, as mentioned in Chapter 1, the carbon intensity of a company is becoming an important indicator of the impact of the company on the environment, indicator that is used by various stakeholders (NGOs, investors, etc). In the model, the CO_2 emissions are obtained by multiplying the amount of energy used by its CO_2 emission factor ([kg/GJ] see table 2.1).

2.2.2 Level 2: focusing on the factory sub-systems

Going one step further than level 1, level 2 focuses on the sub-system inside a factory. As shown in figure 2.3, the sub-systems considered are classified into three main groups: the energy conversion units that transforms purchased energies into useful energies such as steam, the energy consumers (mainly production units) and waste treatment units. Each of these groups might include several sub-systems. For instance, most of the food factories will often have at least a steam boilerhouse, a refrigeration unit and a compressed air unit as energy conversion units. The different sub-systems considered have access to energy resources through energy distribution systems, which are discussed in the next section.

2.2.2.1 Energy distribution systems

In the developed factory model, the energy distribution systems will serve as a means to distribute the different energies (hereinafter **distributed energies**) available in the factory among the different sub-systems. Each distributed energy has its corresponding energy distribution system. A distributed energy can be a purchased energy that is used in the factory without being converted such as natural gas or the result of a conversion of other energies (e.g. steam resulting from the conversion of fuel and water). Alternatively, a distributed energy can be a mix of these two cases. For instance, electricity purchased from the grid and electricity produced inside the factory by a cogeneration unit can both supply the electricity distribution system. When creating an energy distribution system, the user has to specify the type of energy, which has to be one of the energies available in table 2.1 (e.g. LFO, steam, cold, etc). Automatically, the created energy distribution system will be assigned the default physical unit associated to this energy type (see table 2.1). This definition of the energy distribution process provides a great flexibility to model the factory under study. The user may for example define distinct chilled water distribution systems according to their temperature level or distinct steam distribution systems according to their pressure levels. When the model defined by the user will have to be validated, balances on energy distribution systems will guarantee that all the distributed energies are used. In addition, the determination of the specific cost of each distributed energy will allow to allocate the cost among the different sub-systems. Such issues will be covered in section 2.3.

2.2.2.2 Energy conversion units

Energy conversion units are used to transform distributed energies by interacting with the energy distribution systems. For example, a steam boilerhouse might consume LFO, natural gas, electricity and water to produce steam. Thus, an energy conversion unit consumes energy in different energy distribution systems, transforms them and supplies the resulting energies to other energy distribution systems. This has been implemented in the developed factory model by using a table called "Consumption & Distribution" with two entries for each energy distribution system as illustrated in figure 2.4 for a steam boilerhouse. The first entry (named "consumption") corresponds to the distributed energy consumed by the energy conversion unit being modeled while the second entry (named "distribution") enables to define the energy distribution systems that are supplied by the energy conversion unit. An additional column (named "÷") allows for defining cost allocation factors in the case of multi-service units. In the example considered here, since steam is the only output of the unit, all the costs of the unit will be allocated to this distributed energy, resulting in a 100% allocation factor. Cost allocation factors will be further reviewed in section 2.3.

Consumption & Distribution:

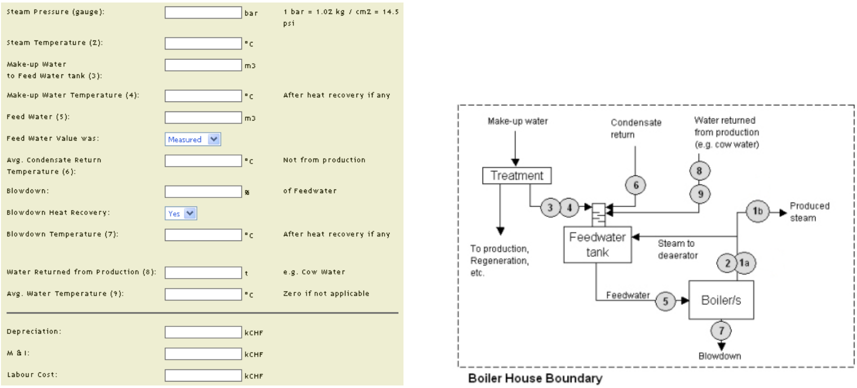
Distribution System:	consumption	distribution	Unit	÷	
Electricity	152000	0	kWh	0	Edit
Potable water	56090	0	m3	0	Edit
LFO	16600	0	l	0	Edit
Natural Gas	5720289	0	Nm3	0	Edit
Steam	0	78376	t	100	Edit
Compressed air	0	0	Nm3	0	Edit
Chilled water	0	0		0	Edit

Figure 2.4: "Consumption & distribution" table for a steam boilerhouse

A wide range of standard energy conversion units are considered in the factory model: boilers for steam generation, boilers for hot water generation, air heaters for spray drying process, refrigeration units, air compressors, cogeneration engines, gas turbines. It has to be noticed here that emergent energy conversion technologies such as fuel cells, wind turbines, geothermal plants have also been studied (Witschi, 2005) but have not been included in the model due to their low level of penetration at the time of the development of the web application.

Indeed, the objective of the factory model is not to be able to cover all the production sites of the company but the most typical one. In that context, the developed models for these technologies could be exploited in future versions of the application in "what if?" scenarios.

Beside the "Consumption & Distribution" table, each conversion unit is modeled using a standardized form, as the one shown in figure 2.5(a) for the steam generation. This form contains technical information of the unit but also financial information regarding depreciation, maintenance and labor cost. These overhead costs will be taken into account later when allocating the costs of the unit to the energies it produces. Technical information is used to compute key performance indicators of the unit through thermodynamic models (see Chapter 3). Most of the fields in the form are referred to with a number in brackets, which corresponds to a stream in a simplified scheme of the boilerhouse provided in the form (see figure 2.5(b)).



(a) (b)

Figure 2.5: "Input form" for a boilerhouse with the related simplified scheme

2.2.2.3 Energy consumers

Energy consumers are the second category of sub-systems considered in the factory model. They are split into two groups: production units and infrastructure. The latter is used to model the consumption of administrative buildings, canteen, etc. The consumption of such unit is affected by factors such as the climate but not by production volumes. The distinction is being made from production units in order to have a more precise idea of the energy consumption split and a more accurate energy cost allocation. This will be particularly helpful when the factory models will be used to benchmark factories worldwide (see Chapter

6). Thus, factories operating in severe climate with large administrative surfaces and low building quality will not be penalized when analysing energy consumption of production units. In the same context, production units or lines are defined by the type of finished goods that they produce. Energy usage per ton of finished good can vary significantly among processes. For instance, milk powder processing is much more energy intensive than chocolate processing. In the factory model, 23 product types are considered. Introduction of the type of production in the model allows for the application of filters when it comes to benchmark factories (see Chapter 6). Each production unit is also defined by the amount of finished goods produced annually. This value is then used to compute indicators such as the energy intensity of a product (energy usage per ton of finished good). Similarly to energy conversion units, energy consumption of production units as well as infrastructure are defined using a "Consumption & Distribution" table which contains all the energy distribution systems that are defined in the factory model (see figure 2.6). However, the possibility for a production unit to supply energy to an energy distribution system is not considered in the model as shown in figure 2.6, where the distribution column is missing. Two main reasons explain this choice. Firstly, this configuration is not very frequent in the food industry except maybe for processes implying evaporation. For these particular cases, the model for the steam boilerhouse has been designed to handle this case as shown in figure 2.5 where two fields ("Water returned from production" and "Avg. water temperature") allow to take into account the condensate (e.g. cow water for milk) returned to the boilerhouse. As this energy flow does not go through the energy distribution systems, its associated cost is null. Secondly, the primary objective of the factory model is to have a better insight of the energy conversion and usage. If "energy consumers" such as a production unit had to be treated with the possibility of producing distributed energies, supplementary data available mainly from production and purchase departments would have been required to determine the actual cost of these produced energies.

Consumption & Distribution:

Distribution System:	consumption	Unit	
Electricity	8473710	kWh	Edit
Potable water	376301	m3	Edit
LFO	0	l	Edit
Natural Gas	0	Nm3	Edit
Steam	66376	t	Edit
Compressed air	6300000	Nm3	Edit
Chilled water	8339520	kWh	Edit

Figure 2.6: "Consumption" table for a production line

2.2.2.4 Waste treatment units

The third category of sub-systems considered in the factory model are the waste treatment units. Three standardized units are available in the current version of the model: waste water treatment units, air treatment units and incineration units. Similarly to energy consumers, these units are able to consume energy from the energy distribution systems but are not authorized to supply them. Some processes release however a large amount of waste which can be recycled and used as fuel. This is typically the case of soluble coffee production where approximately 0.91 kg of coffee ground (waste) is generated per kg of soluble coffee produced (Silva et al., 1998). These biomass residues have an energy content that can cover up to 75% of the thermal energy of a typical process of soluble coffee. The benefits of recycling these wastes are the avoidance of the waste disposal cost as well as a reduced CO_2 emissions rate, since in most cases these residues will substitute fossil fuels. The recycling of coffee ground is modeled by defining them as a purchased energy (see table 2.1). The user can then set the price and the energy content of the coffee ground just as he does with other conventional purchased energies. Appendix A.2 describes briefly the treatment process of the coffee grounds and presents curves of the lower and higher heating values as a function of the humidity of the coffee grounds.

2.2.2.5 Model validation

Once all the energy flows among the different sub-systems have been defined, the model is validated by performing a balance on each energy distribution system. To be valid, a model should present a null balance on each energy distribution system (i. e. all the energy supplied to an energy distribution system should be consumed). If the balance is not null, the residuals for each energy distribution system are provided to the user so that he can modify the model to make it valid. The validation process also makes sure that the cost allocation factors (column "÷" of the "Consumption & Distribution") in multi-service energy conversion units sum to 100. Validity of a model is a necessary condition to proceed to the allocation of energy costs.

2.3 Allocation of energy costs

Cost allocation aims at distributing the costs of purchased energies as well as the costs of operation and maintenance of the energy conversion units (overhead costs) among the different energy consumers (energy consumers and waste treatment units). It plays a key role in the energy management methodology implemented in the web application. Firstly, it determines the actual cost of distributed energies, such as a ton of steam. Based on the specific costs of the distributed energies, it allows for the identification of the main energy-related cost drivers in the factory and consequently for setting priorities for more detailed studies. Thirdly, it provides reliable information to assess the profitability of energy saving actions. Two specific costs are computed for each distributed energy: the variable cost, which only includes energy costs, and the total cost, which includes both the energy costs and the overhead costs.

Cost allocation in the factory model is based on the scheme presented in figure 2.7 which is derived from figure 2.3. This figure shows how the different sub-systems interact with the energy distribution systems: the energy conversion units can consume or deliver distributed energy to the energy distribution systems while the energy consumers and the waste treatment units can only consume distributed energies. The path of cost allocation will follow the natural path of energy flows in the system: the purchased energies entering the system are converted before being distributed and used in the process unit operations or in waste treatment units. The first step of the allocation concentrates therefore on the energy conversion units and on the determination of the cost of the distributed energies: steam, hot water, glycol water, compressed air, etc. If there is no conversion needed to generate a distributed energy (for example the natural gas distribution system), its cost is directly obtained from the purchased cost. In the case of energy distribution systems supplied by an energy conversion unit, the computation of the cost will take into account the different distributed energies consumed by the unit. If the total cost is to be obtained, the overhead costs of the unit are also taken into account. The fact that an energy conversion unit may use a distributed energy that could, in turn, use the output of the energy conversion unit makes loops possible. Such a case is illustrated in figure 2.7 between the energy conversion units 1 and n_u. This situation could take place, for instance, when generating electricity with an engine. The engine will require water for its cooling. The treatment of water necessitates electricity thus making a loop between the engine and the water treatment unit. Loops do not permit to sequentially compute the specific cost of distributed energies. The costs must be computed simultaneously by solving a linear system of equations. A supplementary difficulty comes from the fact that one conversion unit may have several outputs. For example, a refrigeration cycle can produce cold for different networks at different levels of temperature.

This is illustrated in figure 2.7 where energy conversion unit 1 has two outputs referred to as $e^+_{1,1}$ and $e^+_{1,2}$.

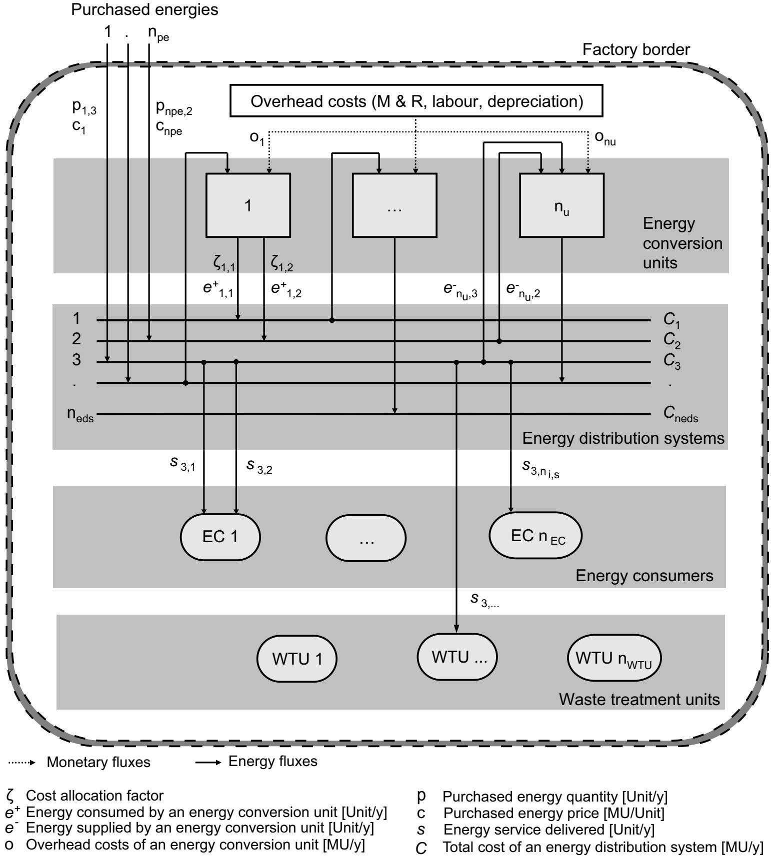


Figure 2.7: Allocation of energy costs in the factory model

Mathematically, the linear system of equations to be solved to determine the specific cost of distributed energies can be written as:

$$A\vec{x} = \vec{b} \tag{2.1}$$

The matrix A has a size $n_{eds} \times n_{eds}$ where n_{eds} is the number of energy distribution systems in the factory. $\vec{x}$ of size n_{eds} is the vector containing the specific cost of the distributed energies.

$$\vec{x} = \begin{bmatrix} c_{de,1} \\ c_{de,2} \\ \vdots \\ c_{de,n_{eds}} \end{bmatrix} \tag{2.2}$$

The diagonal elements of matrix A correspond to the total amount of energy that is distributed in each distribution system. It is constituted of two parts: purchased energies bought outside the factory and converted energy produced inside the factory by energy conversion units. Mathematically, this is expressed as:

$$a_{ii} = \sum_{l=1}^{n_{pe}} p_{l,i} + \sum_{k=1}^{n_u} e^{+}_{k,i} \quad \text{for} \quad i = 1, ..., n_{eds} \tag{2.3}$$

where n_{pe} is the number of purchased energies, $p_{l,i}$ is the energy supplied to the energy distribution system i by the purchased energy l, n_u is the number of energy conversion units and $e^{+}_{k,i}$ is the energy supplied to the energy distribution system i by the energy conversion unit k. The value(s) of $e^{+}_{k,i}$ is (are) directly extracted for each energy conversion unit from the "distribution" column of their "Consumption & distribution" table (see figure 2.4).

The non-diagonal elements of A correspond to the energy consumed by the energy conversion units to produce the distributed energies. Mathematically, we have:

$$a_{ij} = -\sum_{k=1}^{n_u} (e^{-}_{k,j} \cdot \delta_{k,i} \cdot \zeta_{k,i}) \quad \text{for} \quad i = 1, ..., n_{eds}; \quad j = 1, ..., n_{eds}; \quad i \neq j \tag{2.4}$$

where $\delta_{k,i}$ is defined as

$$\delta_{k,i} = \begin{cases} 1 & \text{if} \quad e^{+}_{k,i} \neq 0; \\ 0 & \text{else.} \end{cases} \tag{2.5}$$

where $e^{-}_{k,j}$ is the energy consumed by the energy conversion unit k in the energy distribution system j, $\zeta_{k,i}$ is a coefficient used to allocate part of the total cost of the energy conversion unit k to the output in the distribution system i. Once again, the values of $e^{-}_{k,j}$ and $\zeta_{k,i}$ are directly taken from the "Consumption & distribution" table of the corresponding energy conversion unit (column "consumption" and "÷" [2]). The term $\delta_{k,i}$ is used to determine if the conversion unit k supply some energy to the distribution system i. The $\zeta_{k,i}$ coefficients are

[2] The values of the "÷" column are provided in the user as a percentage and are thus divided by 100 to be used in cost allocation

a figure between 0 and 1 and sum to 1 for a given energy conversion unit. Mathematically, we have:

$$0 \leqslant \zeta_{k,i} \leqslant 1 \quad \text{for} \quad k = 1, ..., n_u; \quad i = 1, ..., n_{eds} \tag{2.6}$$

$$\sum_{i=1}^{n_{eds}} \zeta_{k,i} = 1 \quad \text{for} \quad k = 1, ..., n_u \tag{2.7}$$

The vector $\vec{b}$ of size n_{eds} is obtained by

$$b_i = \sum_{l=1}^{n_{pe}} p_{l,i} \cdot c_l + \sum_{k=1}^{n_u} (o_k \cdot \delta_{k,i} \cdot \zeta_{k,i}) \qquad \text{for} \quad i = 1, ..., n_{eds} \tag{2.8}$$

where c_l is the cost per unit of purchased energy l, and o_k is the overhead cost (labour, maintenance, depreciation) for energy conversion unit k. The second term is used only if the total cost of each distributed energy is targeted.

The specific costs for each distributed energy are then obtained by computing the inverse of matrix A:

$$\vec{x} = A^{-1}\vec{b} \tag{2.9}$$

The cost allocation as implemented transfers all the input costs (cost of purchased energies and overhead costs of energy conversion units) to the energy distributed in the factory. It means that the energy conversion units are not allocated any cost on themselves. The allocation to the energy consumers and waste treatment units is then simply computed as:

$$C_m^{EC} = \sum_{i=1}^{n_{eds}} c_{i,m}^{EC} c_{de,i} \quad \text{for} \quad m = 1, ..., n_{EC} \tag{2.10}$$

$$C_n^{WTU} = \sum_{i=1}^{n_{eds}} c_{i,n}^{WTU} c_{de,i} \quad \text{for} \quad n = 1, ..., n_{WTU} \tag{2.11}$$

where C_m^{EC} is the total energy cost of the energy consumer m and $c_{i,m}^{EC}$ is the quantity of distributed energy i consumed in the energy consumer m. Similarly, C_n^{WTU} is the total energy cost of the waste treatment unit n and $c_{i,n}^{WTU}$ is the quantity of distributed energy i consumed in the waste treatment unit n [3]. The property of the cost allocation is that the

[3] it has to be noticed here that these notations are not represented in figure 2.7

overall energy bill can be reproduced while defining the cost of the energy distributed to the process units. Based on this information, the major energy drivers in the process can be identified.

2.3.1 From distributed energies to energy services

While the cost allocation to the energy consumers and waste treatment units as implemented through equations (2.10) and (2.11) has the advantage of simplicity, it has the main disadvantage of considering average specific costs ($c_{de,i}$) for the distributed energies. If this assumption is realistic for cases such as electricity, it can diverge significantly from the "true" cost of the distributed energy in other cases such as steam. Indeed, steam usage with and without condensate return should not be allocated the same specific cost. Producing steam from condensate will be much cheaper than from water, which has to be first demineralized and preheated up to the temperature of the feedwater tank. The concept of **energy services** is introduced to handle such situations. Contrary to the cost allocation implemented through equations (2.10) and (2.11), an energy consumer or waste treatment unit can be supplied by different energy services from the same energy distribution network as illustrated in figure 2.7. In this figure, the energy consumer 1 (EC 1 in the figure) uses two different energy services referred to as $s_{3,1}$ and $s_{3,2}$ from the energy distribution network 3. The cost of the energy service s can be derived from the average cost of the distributed energy $c_{de,i}$ by weighting the different services using the cost allocation factor $\tilde{\zeta}_{i,s}$. The only constraint on this factor is that the total cost of each distributed energy has to be maintained, that is, the equation (2.12) must remain valid.

$$a_{ii} c_{de,i} = C_i = \sum_{s=1}^{n_{i,s}} c_{i,s} s_{i,s} = \sum_{s=1}^{n_{i,s}} \tilde{\zeta}_{i,s} c_{de,i} s_{i,s} \tag{2.12}$$

where :

$n_{i,s}$	is the total number of energy services produced by the distributed energy i
C_i	is the total cost of the distributed energy i
$c_{i,s} = \tilde{\zeta}_{i,s} s_{i,s}$	is the specific cost of the energy service s produced from the distributed energy i
$s_{i,s}$	is the energy service s produced from the distributed energy i
$\tilde{\zeta}_{i,s}$	is the cost allocation factor of the energy service s produced by the distributed services i.

It has to be mentioned that the concept of energy services introduced in this section has not been implemented in the current version of the factory model.

2.3.2 Multi-service energy conversion units

Multi-service energy conversion units are frequently found in the food industry. These units are typically refrigeration units with cold production at different level of temperatures, cogeneration units such as gas turbines or reciprocating engines that can simultaneously produce electricity and steam or hot water. Intuitively, even if the energies delivered have the same units (GJ), their quality often differ. Indeed, removing one gigajoule at -50°C requires much more energy than at -10°C. Similarly, one gigajoule of electricity is much more useful than one gigajoule of heat. The cost allocation can, consequently, not be based on the different amounts of energy delivered. The "quality" of the energy produced has to be taken into account when allocating the cost of the energy that has been introduced into the unit (determination of the cost allocation factors in the "÷" column of the "Consumption & Distribution" tables). As a consequence, exergy, which characterizes the quality of an energy flux, is the only rational basis for allocating costs in multi-service energy systems as stated in Bejan et al. (1996) and Borel and Favrat (2005).

Many authors have proposed exergy-based methods for cost allocation in multi-service energy systems. These methods belong to the field named thermoeconomics or exergoeconomics. In 1990, four researchers (C. Frangopoulos (Frangopoulos, 1994), G. Tsatsaronis (Tsatsaronis and Pisa, 1994), A. Valero (Valero et al., 1994) and M. von Spakovsky (von Spakovsky, 1994)) proposed to compare their methodologies by applying it to a predefined gas turbine problem called CGAM problem (Valero et al., 1994). Although the four methodologies differ significantly, they all address the problem by dividing the system into subsystems and by considering one single product for each of those subsystems. Cerqueira and Nebra (1999) showed that the methods proposed by Frangopoulos, Valero and Lozano present equal results if there is a consistent definition of the physical units and their products and if externalities are treated equally. Several new methodologies have been presented in the recent years (Bejan et al., 1996; Erlach et al., 2001).
These advanced methods are not only used for cost allocation but also for system optimization since they go in detail and divide the system into sub-systems. Therefore, they are difficult to implement in a generic application that should manage a wide range of multi-service energy systems. Although not implemented in the current version of the factory model, exergy-based cost allocation should be implemented in the future by considering the energy conversion unit as a black-box: the cost of the input energies (e^-) and the overheads

(o) have to be distributed among the output energies (e^+). In order to compute the total quantity of exergy delivered by the energy conversion unit, the exergy content of each output energy is computed. For thermal streams, the exergy content ($\dot{E}$) of a stream delivering a heat load ($\dot{Q}$) from T_{in} to T_{out} is computed by equation (2.13) when the specific heat of the stream is assumed to be constant.

$$\dot{E} = \dot{Q}(1 - \frac{T_a}{T_{lm}}) \tag{2.13}$$

T_a is the ambient temperature (expressed in K) and T_{lm} is the logarithmic mean of temperatures computed by $T_{lm} = \frac{T_{in}-T_{out}}{ln(\frac{T_{in}}{T_{out}})}$. In the case where the heat is delivered at a constant temperature T, the following equation is used to determine $\dot{E}$:

$$\dot{E} = \dot{Q}(1 - \frac{T_a}{T}) \tag{2.14}$$

As regards mechanical streams, the exergy content ($\dot{E}$) of a stream is equivalent to its energy content ($\dot{W}$):

$$\dot{E} = \dot{W} \tag{2.15}$$

The total exergy ($\dot{E}_{tot}$) delivered by an energy conversion unit in the different energy distribution systems is obtained by summing up the individual contributions of each stream:

$$\dot{E}_{tot} = \sum_i \dot{E}_i \tag{2.16}$$

Finally, the cost allocation factor ζ_i assigned to each stream is computed as follows:

$$\zeta_i = \frac{\dot{E}_i}{\dot{E}_{tot}} \tag{2.17}$$

This formulation guarantees than the condition expressed in equation (2.7) remains valid. To illustrate the concept presented, it will be applied to a refrigeration unit and a cogeneration engine.

2.3.2.1 Example of a refrigeration unit

A large number of technologies can be considered for industrial refrigeration: vapor-compression refrigeration systems, absorption refrigeration systems, air refrigeration systems, etc (see Dincer (2003) for more details on these technologies). However, vapor-compression systems are largely dominating the market in industry. In the food industry, many processes require cold at different level of temperatures, which are provided by a single vapor-compression unit. Typical configurations for these units include NH_3 multistage cycles or NH_3/CO_2 cascade cycles. Beyond the configuration used, exergy-based cost allocation relies on the amounts of cold delivered and the corresponding temperature at which they are delivered. Let us consider, for instance, a refrigeration unit delivering the same amount of cooling load ($\dot{Q}_i$ =200 kW) at 3 different temperature levels (-17°C -47°C and -52°C). Considering the black-box approach, the objective is to split the cost of the incoming electricity among the 3 services provided ($i = 3$). Assuming that the ambient temperature T_a is 25°C, the services provided occur below the ambient temperature. Consequently, the services do not consist in delivering heat but in "accepting" heat from the cold source. In such cases, equation (2.14) becomes:

$$\dot{E} = \dot{Q}(\frac{T_a}{T} - 1) \tag{2.18}$$

The exergy content of each stream i ($\dot{E}_i$) computed from this equation and the resulting ζ_i obtained from equation (2.17) are presented in table 2.4. These values are to be compared with the ζ_i that would have been obtained using a purely energy-based approach. In that case, each service supplied would have been allocated one third of the total cost since they are equivalent in terms of the cooling load supplied.

Table 2.4: Cost allocation in a refrigeration unit (T_a=25°C)

Network i	**Temperature** **°C**	$\dot{Q}_i$ **kW**	$\dot{E}_i$ **kW**	ζ_i **-**
1	-17	200	32.8	0.197
2	-47	200	63.7	0.383
3	-52	200	69.7	0.419
Total		600	166.2	1

One unit that could fulfill these three services is the NH_3/CO_2 cascade unit whose model is presented in figure 3.9. This detailed thermodynamic model takes into account the isentropic efficiency of the compressors (this model will be described in more detail in Chapter 3). The electricity consumptions (e_i^+) associated to each service that have been computed by the model are given in table 2.5 [4]. It can be observed that the ζ_i computed from the modeled electricity consumptions - obtained by dividing the electricity consumption of each stage by the total electricity consumption - are very close to the one computed in table 2.4. Comparing both tables allows as well for the computation of the second-law efficiency of the modeled

[4] the electricity required by the compressor of the upper stage of the cycle (NH_3) has been split into three contributions proportionally to the cooling load required at the condenser of each CO_2 loop

cycle. Indeed, the total exergy content of the streams of table 2.4 represents the work needed to extract that heat from the three cold temperatures to the ambient temperature using reversible cycles. By dividing this theoretical minimum work by the one modeled, we conclude that the second-law efficiency of the unit modeled in figure 3.9 is approximately 56%. A detailed analysis of the repartition of the exergy losses of this cycle is available in appendix B.

Table 2.5: Cost allocation in a NH_3/CO_2 refrigeration unit based on a thermodynamic model (T_a=25°C)

Network i	**Temperature** **°C**	$\dot{Q}_i$ **kW**	e_i^+ **kW**	ζ_i **-**
1	-17	200	59.3	0.200
2	-47	200	112.4	0.379
3	-52	200	125.0	0.421
Total		600	296.7	1

By extension, this demonstration of cost allocation can also be applied to units that provide both refrigeration and heating services. This would be the case for example if the NH_3/CO_2 cascade unit would release the heat available at the condenser of the upper stage in a low temperature heating network. The heat delivered at a temperature of 35°C could now be considered as a heating service. Assuming reversible cycles are used, the heat available at the condenser ($\dot{Q}_4$) is obtained by achieving energy balance on the system:

$$\dot{Q}_4 = \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 + \dot{E}_{tot} = 766.2 \quad [\text{kW}] \tag{2.19}$$

Using equation (2.14) to determine the exergy content of this new service, the new ζ_i that would be obtained are presented in table 2.6. According to this cost allocation, removing 1 kWh of heat at -52°C is nearly 11 times more expensive that supplying the same kWh of heat at 35°C.

Table 2.6: Cost allocation in a polygeneration unit (T_a=25°C)

Network i	**Temperature** **°C**	$\dot{Q}_i$ **kW**	$\dot{E}_i$ **kW**	ζ_i **-**
1	-17	200	32.8	0.171
2	-47	200	63.7	0.333
3	-52	200	69.7	0.365
4	35	766.2	24.9	0.130
Total			191.1	1

2.3.2.2 Example of a cogeneration engine

Combined heat and power (CHP) setups will also deliver different types of energy services. Typical CHP units include reciprocating engines and gas turbines. However, in the food industry, given the limited heat and power demand in most of the factories, reciprocating engines are better adapted than gas turbines. In addition, as many food processes occur at limited temperature levels, the heat of the cooling water from the engine that is available at around 90°C can be used for heating purposes in the process. The three forms of energy delivered by a cogeneration engine are:

- mechanical energy from the shaft $\dot{W}$;
- heat of the hot flue gases at the exhaust of the engine to be cooled up to the chimney temperature in a recovery boiler : $\dot{Q}_g$ and
- heat of the cooling water of the engine $\dot{Q}_w$.

Unlike the refrigeration unit, a cogeneration unit does not only supply heat at different temperatures but also mechanical work. While for mechanical work the exergy content is equivalent to the energy content, determination of the exergy content of thermal streams is calculated by equation (2.13). Based on the exergy content of the three output streams, the ζ_i can be easily determined as shown in table 2.7 for a 1.2 MW_{el} engine [5]. It can be noticed in this table that even if the mechanical work accounts for less than 50% of the useful energy produced by the unit, it is allocated more than 70% of the input cost of the unit. As regards cooling water, although this stream represents nearly 30% of the useful energy, it is allocated only 8% of the total cost due to its low exergy content.

Table 2.7: Cost allocation in a 1.2 MW_{el} cogeneration engine (T_a=25°C)

Stream	T_{in} **°C**	T_{out} **°C**	η **-**	**Energy kW**	$\dot{E}$ **kW**	ζ_i **-**
Mechanical	-	-	0.37	1200	1200	0.711
Flue gases	500	120	0.23	746	350	0.208
Hot water	90	80	0.25	811	137	0.081
Total	-	-	0.85	2757	1687	1

[5] Typical values have been assumed for the share of the different services (η).

2.4 Model browsing

If the first objective of the factory model is to collect and store energy-related data in a standardized way, the second objective is to provide the user with an interface permitting to "browse" the factory model and to have a quick access to key information. This is done through screen shots of the model, which will permit to understand how the energy is used in the factory, to determine the environmental and energy performance of the factory, to identify which are the most energy and cost intensive units in the factory, to determine the efficiency of energy conversion units, etc. In accordance with the top-down philosophy presented in section 2.2, the browsing of the model will be divided in a factory overview (level 1 representation) and in more detailed views of the factory sub-systems (level 2 representations).

2.4.1 Level 1: factory overview

The level 1 overview is mainly aimed at managers. Consequently, it displays the different purchased energies entering the system with their associated annual bills as well as the emissions generated and the production volumes. The key performance indicators (KPIs) displayed in this level concern energy and water usage together with waste water generation and CO_2 emissions as illustrated in figure G.1. This level 1 representation has been taken from an early version of the developed application.

2.4.2 Level 2: factory sub-systems

Figure G.2 presents a level 2 representation of the energy conversion units. The three energy conversion units are classified according to their annual cost. The latter is split for each unit in four contributions: energy cost, depreciation cost, maintenance cost and operation cost. It has to be noticed here that while going deeper in the factory using the navigation bar the energy and waste flows through the factory border are still displayed as a frame. This allows to permanently relate the information of sub-systems with that of the global system. The user interested in better understanding the high annual cost of the "Steam Generation" unit can focus on that unit by simply clicking on it. The resulting representation is given in figure G.3. A pop-up window provides detailed information on the selected unit. It includes the level of energy consumption of the unit and the related costs as well as the distributed energy produced (steam in this case) and performance indicators. The common indicators for all the energy conversion units are the variable and total energy costs - for the total cost operation, maintenance and depreciation costs are added -, the variable and total specific energy cost and the variable and total cost of the distributed energy produced in the unit computed according to section 2.3. Efficiency indicators computed according to thermodynamic models presented in Chapter 3 are also provided. The colors associated with these performance indicators are used to rate them. This rating will be discussed in detail in Chapter 6.

2.5 Conclusion

In this chapter, we introduce a modular model of a production facility as well as the IT interface used to interact with it. The model fulfills different aims. Firstly, it provides, through a user-friendly interface, a means for engineers in factories to gather all the relevant energy-related data in a standardized manner. Secondly, based on the data entered by the user, it allows for allocating the cost of the energies purchased as well as the overheads costs among the different energy consumers. In this context, an exergy-based method is proposed to rationally allocate the costs in multi-service energy conversion units. Thirdly, it computes several standardized key performance indicators as well as efficiencies of energy conversion units, based on thermodynamic models that will be presented in the next chapter. The structure of the model was designed in such a manner as to be browsed in a top-down fashion using an IT interface. Indeed, the models of factories worldwide will be made available to the different users involved in energy management through the developed web application. This will be discussed in Chapter 6. A first level (level 1), targeted mainly at managers, gives a high-level overview of the factory with financial and environmental indicators. In the second level (level 2), targeted at engineers, the factory system is divided in sub-systems grouped in three categories: energy conversion units (e.g. a boilerhouse), energy consumers (e.g. a production line) and waste treatment units (e.g. a waste water treatment plant). The model has been thought as a decision-support tool for the allocation of the resources available for energy management at management level and for the identification of specific areas within the factory with important improvement potentials.

Although the proposed factory model fulfills the aims defined in the original specifications, a potential of improvement still exists. This is particularly the case of the modeling of waste streams in a factory. Indeed, the current model allocates the cost of the purchased energies as well as the overhead costs to the energy consumers, but fails, for example, to do the same for the costs related to the discharge of waste water. In addition, the behavior of waste treatment units has not been modeled. Models of these units would permit to have a better insight of their efficiency and could also be used to evaluate the possibility to recycle waste by, for instance, producing biogas. Another improvement potential lies in the possibility of coupling or making synergies with existing tools in the company. For example, we have mentioned in this chapter that the developed factory model could be used for environmental reporting, thus decreasing the amount of information that engineers in factories have to provide to the head offices. One of the objectives of the model is also to decrease to the minimum the input needed from the user. In that context, we can imagine in the future the possibility to extract all the financial data required by the model automatically from business solutions such as SAP[6]. Finally, the proposed model focuses in the description of the flows of distributed energies within the factories. By doing so, it allows for the identification the main energy drivers in a factory but does not lead to energy savings in the process. A description of the usage made of the converted energies in the process could be integrated in the model and would thus help to identify energy efficiency gaps as it will be shown in Chapter 5. Although such a description implies a much larger effort as regards data collection and model building, it could be useful to consider this option in the future.

This last point also highlights another difficulty that engineers face in factories: the lack of data on energy consumption inside a factory and, more particularly, in the process. Availability of data is a key issue for feeding the model. In that context, punctual measurement might be needed as a complement to existing data. Chapter 4 will provide statistic tools to help the engineer in identifying the main factors affecting energy consumption in the factory, which will allow to set priorities as regards the specific measurements to be made. It has however to be mentioned here that the perfect factory model is not achievable and that it would not make sense due to the effort required to achieve such a model. Engineers in factories should consequently always keep in mind the 80/20 principle while modeling their factories. This principle states that 80% of the energy consumption results from only 20% of the units of a factory. The relevance of this principle in food industry will be demonstrated in Chapter 5.

[6]www.sap.com

Chapter 3

Thermo-economic models of energy conversion units

In the methodology proposed in this thesis, thermo-economic models are used to assess the efficiency of energy conversion units in the factory model (see Chapter 2) as well as to perform "what if?" scenarios (see Chapter 6). Thermodynamic modeling is needed to compute the efficiency as well as the performance achievable through simulations, while economic modeling of equipments enables to compute the profitability by determining the investment required. Thermodynamic models are usually developed with the help of process simulation tools that permit the computation of thermophysical properties, liquid/vapor equilibrium and of mass/energy balances. Economic modeling will imply the development of correlation linking the cost of an equipment with the size of the equipment. Usually, the effect of changing economic conditions (inflation) is also modeled to be able to adapt equipment costs.

Food processes are very diverse and involve many different process unit operations (drying, melting, extraction, evaporation, pasteurization, cooling, freezing, freeze-drying, cleaning, fermentation, etc). However, the number of energy conversion units that supply these process unit operations with useful energy is often limited. They include for example boilers for the generation of steam or hot water, air compressors, refrigeration cycle for air-conditioning or for production of chilled water, air heaters for drying processes, etc. Developments of generic models of energy conversion technologies offers consequently a good "rate of return" compared to process units due to their high applicability in production sites. In addition, models of such units are usually easier to develop than process technologies since they involve common substances with well known properties and behaviors. The choice to model this type of unit over process units is even strengthen by the fact that most of production managers are very reluctant to modify established processes. Although not treated in this work, the modeling of cross-cutting process unit operations could, however, be considered in the future.

3.1 Belsim-Vali

Among the different modeling and simulation tools available in the market (see section 1.3.2), the software Vali from the company Belsim S.A. has been chosen in this project. This software has been used successfully in various applications at LENI ranging from pulp and paper (Brown et al., 2005) to biomass conversion (Gassner and Maréchal, 2005) and fuel cell systems (Marechal et al., 2005). In this section, we will describe briefly the use of the software to develop models. For more details about the software, readers are referred to Belsim website[1] or to Vali User's guide (Belsim, 2003).

A Vali model is composed of different units such as heat exchanger, mixer, reactors which are linked together by streams. This streams can be material streams, thermal streams or mechanical streams. Material streams are defined by their composition i.e. the compounds that they contain and by thermodynamic methods that allows to compute their properties. Vali also allows for the definition of external equations that can be used for example for the definition of performance indicators or control parameters. Measurements of the process (thermodynamic state, composition, control parameters) and their precision can be set by the user. When solving the model, the redundancy in the model is used to reconciliate the measurements. That means that unmeasured values are computed and the precision of reconciled value is quantified. If there is no redundancy in the problem, the software behave like a classical simulation software.

3.1.1 Running a Vali model

A Vali model (file extension `.bls`) can be easily created and run via the Graphical User Interface (GUI) provided with Vali. Example of a boiler house model as seen in the GUI can be found in figure 3.2. One interesting feature of Vali in the framework of this thesis is the fact that a model created in the GUI can afterwards be run in batch mode without opening the GUI. Thus, once the model of a given unit as been developed in the GUI, it can be stored in a database of models in the web application and be used in batch mode to compute efficiency indicators in the factory model. Running Vali in batch mode requires the definition of three files: the vali information file (`.vif`), the measurement file (`.mea`) and a text file

[1] www.belsim.com

containing the value of the measurements (see figure 3.1). The `.vif` file is used to define which model (`.bls` file) and measurement file have to be used and what are the options of the run (for example, `-bat` in figure 3.1 indicates the batch mode). The measurement file serves to define the text file containing the value of the measurements (`measurement_in.txt` in the figure), the output file in which the results will be written (`data_out.txt` in the figure) and which results have to be written and the desired units.

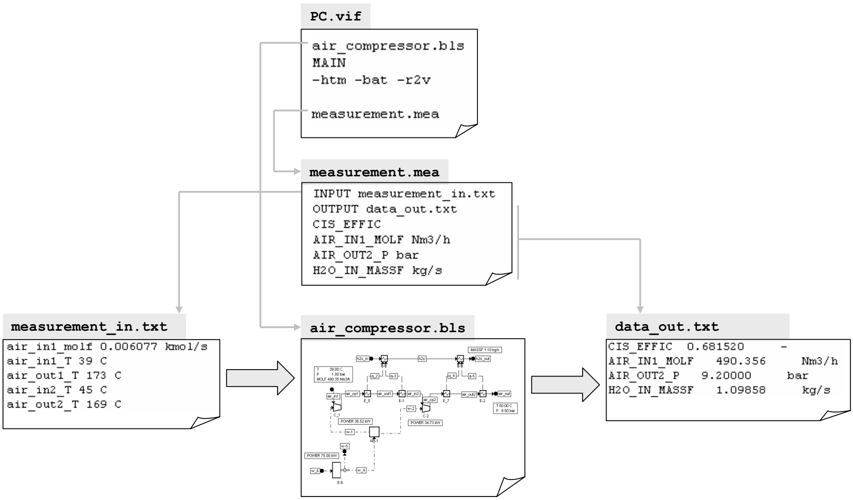


Figure 3.1: Running a Vali model in batch mode using a measurement file

3.2 Boilerhouse

As boilers are the largest energy users in the food industry (Adams and Milmoe, 2001), they have naturally been chosen as the first unit to be modeled in this work. In the US industry, steam generation accounts for 37% of the fossil fuel consumption (EIA, 1997). As illustrated in table 3.1, boilers in food industry are usually small compared to other industrial sectors (Einstein et al., 2001). This table shows that in the US food industry 61% of the boilers have a power inferior to 29MW.

In the factory model, the steam generation not only include the boilers but the whole boilerhouse system as illustrated in figure 2.5(b). The corresponding model developed in Vali is presented in figure 3.2. The different units of the models are: a fire-tube boiler, a storage

Table 3.1: Size of boilers in the US industry

	3-14.7 MW	**14.7-29 MW**	**29-73 MW**	**> 73 MW**	**Total [MW]**
Chemicals	25.7%	15.7%	28.8%	29.8%	145'437
Food	35.9%	25.1%	25.5%	13.5%	76'011
Paper	10.1%	10.9%	24.9%	54.1%	107'924
Refining	15.7%	13.5%	22.9%	47.6%	61'325
Primary metals	28.2%	12.3%	21.9%	37.6%	55'354

tank for the steam condensates as well as the makeup water, a deaerator and a feedwater pump. It has to be noticed that the treatment of raw water to produce makeup water is not considered. Although most of the boilerhouses in the food industry have several boilers, the developed model considers a single unit that is used to compute the overall efficiency of all the boilers including stand-by boilers.

3.2.1 Combustion

The boiler itself is modeled using a reactor for the burner and three heat exchangers. The burner has as inputs a fuel stream and an air stream to oxidize the fuel and as outputs a material stream for the fumes resulting from the combustion and a thermal streams that account for radiation losses [2]. As radiation losses represent usually only a small percentage of the energy content of the fuel, they have a very limited influence on the temperature at the outlet of the burner. The composition of the streams entering and going out of the burner are presented in table 3.2. As shown, in this table two main categories of fuel were considered: liquid fuel (referred to as "Fuel" in the table) and gaseous fuel (referred to as "Natural gas"). Each category of fuel has its corresponding boilerhouse model (for instance the model represented in figure 3.2 is the "Natural gas" boilerhouse model). The model for oil-fired boilers is able to handle both LFO and HFO which can be described by their content in hydrogen H , carbon C, oxygen O and sulphur S. Similarly the model for natural gas can also be used to model a LPG-fired boilerhouse since all the compounds of either propane or butane gas are included in the natural gas. The "energy content" of the fuel can be defined in the model either by the composition or directly by specifying its LHV or HHV. The possibility to have multi-fuel burners (e.g. oil and gas) is discarded due to the difficulty of convergence for models with such units. Coal is not considered in the model since it is used only in a minority of steam boilers in the food industry. Even when the consumption of coal is expected to increase for electricity production, the tendency is to get rid of it for

[2]in reality, radiation losses occurs on the radiative and convective heat transfer section of the boiler. However, for practical reasons, radiation losses were assigned to the burner

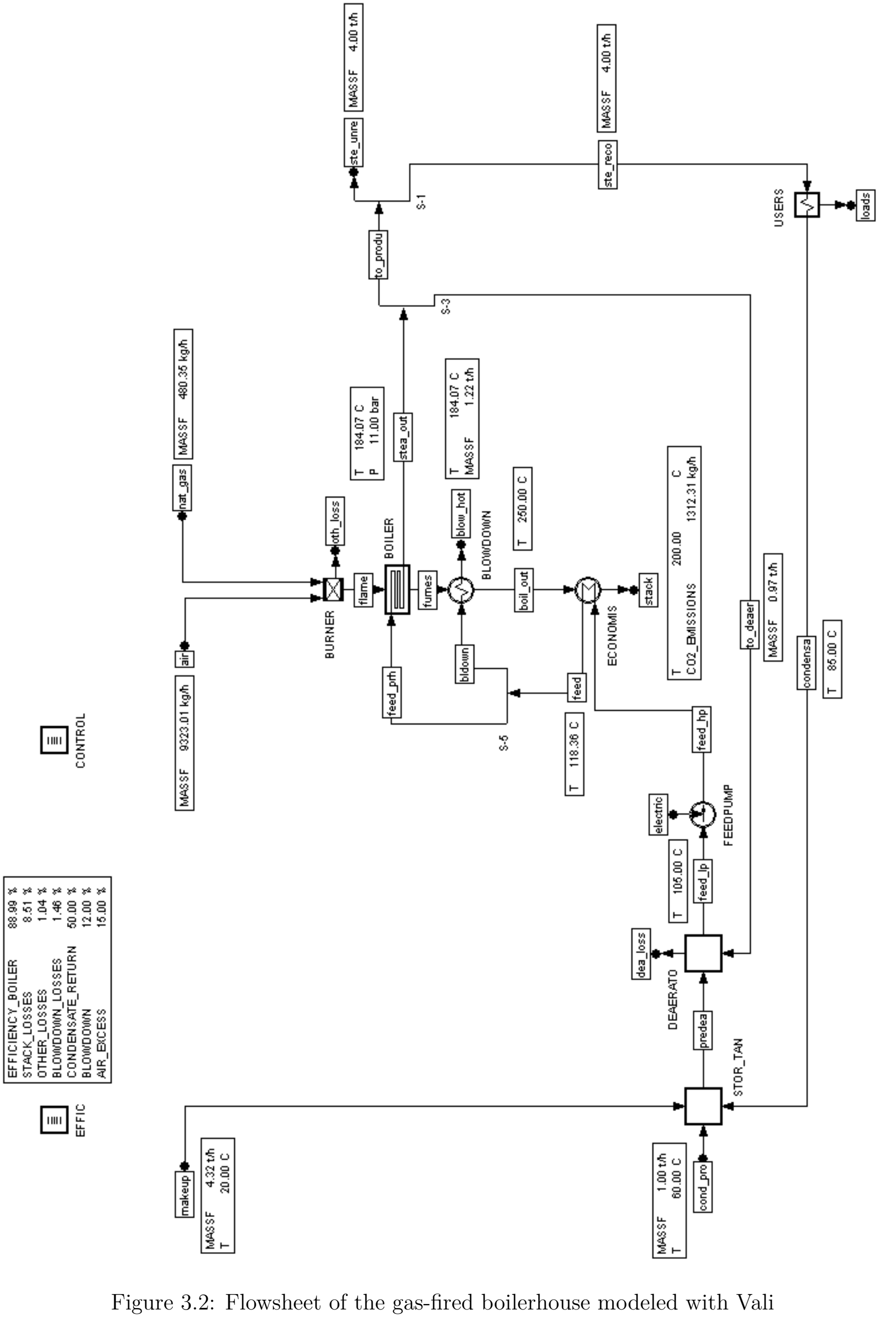


Figure 3.2: Flowsheet of the gas-fired boilerhouse modeled with Vali

steam generation in industry.

Table 3.2: Composition of streams involved in the combustion

Fuel	**Natural gas**		**Air**	**Fumes**
C	CH_4	H_2	N_2	CO_2
H	C_2H_6	O_2	O_2	H_2O
S	C_3H_8	N_2		N_2
O_2	C_4H_{10}	CO_2		O_2
	C_5H_{12}	H_2S		SO_2
	C_6H_{14}			SO_3

Composition of the fumes in table 3.2 also emphasizes that formation of NO_x as well as incomplete combustion (formation of CO) are not considered in the different boilerhouse models. NO_x are ignored due to the difficulty to model their formation mechanism (see Li et al. (2004) for more details on NO_x modeling and the related literature). This simplification is acceptable since NO_x formation has not a high impact on the efficiency of the boiler. Incomplete combustion is not included in the models since in most of the modern boilers it is negligible.

3.2.1.1 Air excess

Air excess (λ) is an important parameter of the combustion. It is defined as the mass of air actually needed for the combustion divided by the mass of air needed for a stoichiometric combustion:

$$\lambda = \frac{M_{air}}{M_{air,sto}} \tag{3.1}$$

Air excess influences the temperature at the outlet of the burner and, consequently, the stack losses. The latter are defined as the residual heat available in the flue gas at the boiler stack. They are usually expressed as a percentage of the energy content of the fuel burnt. Typical values of air excess are given in table 3.3 for different fuels and furnace types. Neglecting the nitrogen content of the fuel (this can be easily assumed for natural gas and LPG), the entire nitrogen in the flue gas comes from the combustion air. Under this assumption, the excess air coefficient can be written as

$$\lambda \approx \frac{1}{1 - \frac{79 O_2}{21 N_2}} = \frac{1}{1 - 3.76 \frac{O_2}{N_2}} \tag{3.2}$$

where N_2 and O_2 are respectively the nitrogen and the oxygen content in the flue gases expressed in %. Alternatively, the air excess may also be determined from the CO_2 content in the flue gas. In this case, the air excess will depend of the fuel that is used. Equivalences between air excess, O_2 content and CO_2 content in flue gases for LFO, HFO, LPG and natural gas are available in figure A.1 (see appendix A).

Table 3.3: Typical values of excess air coefficient λ (Basu et al., 2000).

	Oil fired and gas fired furnace		Circulating fluidized bed with coal
	Negative pressure in furnace	Slightly positive pressure in furnace	
λ	1.08-1.10	1.05-1.07	1.2

3.2.1.2 SO_3 formation and dew point

Dew point is a critical parameter when designing heat recovery systems in boilers since condensation in the equipment obliges to consider a stainless steel equipment which results more expensive than common carbon steel (cost of heat recovery units are studied in more detail in section 3.2.6). Theoretical dew point in the fumes can be determined using the partial pressure of water. However, in practice, dew point will also be influenced by the concentration of SO_3 in the fumes. As the sulphur contained in the fuel can be transformed into SO_2 or SO_3 (see table 3.2), an additional equation is introduced to remove this degree of freedom (Lee and Shih, 1985):

$$SO_3 = -27.712 + 4.331S + 29.863\frac{1}{O_2} - 3.707\frac{S}{O_2} + 54.396log(O_2) \tag{3.3}$$

where SO_3 is the concentration (in ppm), S is the sulfur content of the fuel (% mass) and O_2 is the molar fraction of oxygen in the flue gases(%). This correlation is valid in the range $1 \leq O_2 \leq 4$ and $0.5 \leq S \leq 5$.

Based on the SO_3, the dew point T_d (expressed in K) can then be computed from a correlation from Pierce (1977):

$$\frac{1000}{T_d} = 2.0690 - 0.0391log(P_{H_2O}) - 0.1689log(P_{SO_3}) + 0.0329log(P_{H_2O})log(P_{SO_3}) \tag{3.4}$$

P_{H_2O} and P_{SO_3} are the partial pressure in the flue gases expressed in $\frac{kN}{m^2}$. The SO_3 molar fraction as well as the dew point obtained for a heavy fuel oil (H: 11.3%, C: 84.6%, O: 0.13%, S: 3.7% and Water: 0.4%) are presented in figure 3.3. This figure also presents the theoretical dew point that would have been obtained without taking into account the presence the SO_3 in the fumes. The increase observed in the dew point ranges from 82°C at low air excess to 102°C at higher air excess.

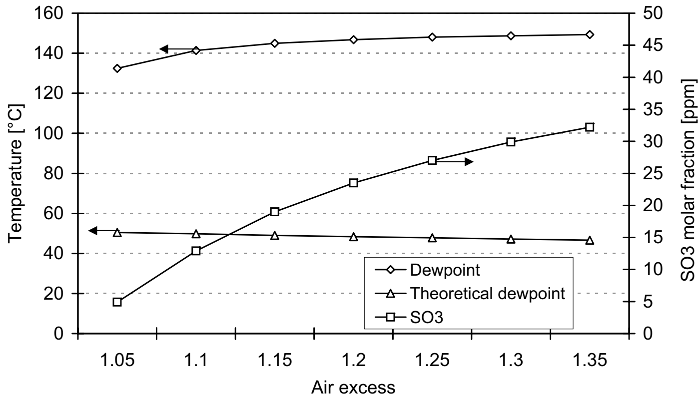


Figure 3.3: Dew point and SO_3 molar fraction for HFO

3.2.2 Heat transfer in the boiler and the economizer

As heat exchanger model in Vali can only handle two material streams at outlet (fumes and steam for the boiler), the heat transfer section of the boiler is split into two heat exchangers in order to model the steam produced and the blowdown water withdrawn from the boiler. As illustrated in figure 3.2, the heating of the water lost in the blowdown to the saturation temperature is modeled in a separate unit. The heat load of this unit divided by the energy content of the fuel determines the blowdown losses (expressed in %). The steam produced in the second unit is assumed to be saturated (vapor fraction = 1). In order to take into account effects of part load operation, an advanced model (available in appendix C) has been developed for the heat transfer in the boiler. However it has not been included in the generic models described here.

As illustrated in figure 3.2, an economizer is used to preheat the feedwater with the flue gas exiting the boiler. Modeling of the heat transfer in the economizer is also particularly important especially when the possibility to add such a unit in an existing boiler is to be simulated (see section 6.3.3). Indeed, the global heat transfer coefficient in the economizer determines the required surface to achieve a given heat recovery. As the cost of the economizer is a function of its heat transfer surface, the heat transfer coefficient has to be well characterized in order to have a reliable estimation of the cost of the unit.

3.2.3 Condensate return and deaeration

The steam produced by the boiler is split into two streams in the model (see figure 3.2). A small fraction of the steam is used to preheat the mix of condensate return and make-up water in the deaerator while the remaining steam is used in the different production processes. The steam used in the production facilities is further split into two streams. The first one accounts for the steam not returned to the boilerhouse while the second one accounts for recovered steam. The latter is mixed with make-up water as well as other condensates from production (e.g. cow water) in a storage tank. From this storage tank, the water is sent to the deaerator which is modeled using a black-box with a steam injection to heat up the incoming water. According to sources in literature (DOE, 2004; Fath and Hashem, 1988), the steam lost through the vent is taken as 10% of the injected steam. At the outlet of the deaerator, the feedwater goes through the feeding pump whose outlet pressure is set at 10 bars above the steam pressure at the outlet of the boiler.

3.2.4 Performance indicators for the boilerhouse

The critical indicators and control parameters of the boiler house are presented in table 3.4. The overall boiler efficiency is completed by an analysis of the losses which are split into three categories: losses at the stack of the boiler, blowdown losses and other losses (radiation, stand-by). The condensate return rate is obtained by dividing the amount of steam condensate returned to the boilerhouse by the total amount of steam sent to production. Improving the condensate return rate of a steam system decreases the make-up water needed which results in a reduced consumption of fuel and make-up water as well as a reduced water treatment cost. In addition, since steam condensate are high quality water, the quality of the feedwater is improved and the blowdown rate is decreased. The blowdown is necessary to reduce levels of suspended and total dissolved solids (TDS) in the boiler. The blowdown rate is defined as the ratio of blowdown water removed from the boiler during a period to the feedwater injected in the boiler during the same period. The optimum blowdown rate depends on the boiler type, the operating pressure, the quality of make-up water and of water treatment. Blowdown rate can range from less than 1% to 20% depending on the quality of the feedwater (Harrell, 2003). However, in most of the case, blowdown rate is a value between 4% to 8%. Decreasing the blowdown rate will reduce the consumption of energy, water and chemicals while maintaining a low levels of deposits in the boiler.

Table 3.4: Critical variable of the boilerhouse

Indicator	**Unit**
Overall efficiency of boilers	%
Stack losses	%
Blowdown losses	%
Other losses	%
Condensate return rate	%
Blowdown rate	%
Air excess λ	-

3.2.5 Simplified boilerhouse model

As explained earlier, thermodynamic models are used in the web application to assess the efficiency of existing equipment described in the factory model and to simulate new operating conditions in "what-if?" scenarios (see Chapter 6). For instance, data supplied by the user through interface such as the one presented in figure 2.5 are used to compute, using the boilerhouse model, the indicators that will be later displayed in a factory representation such as the one of figure G.3. Although the development of accurate models of boilerhouses allows for a better understanding of the phenomenon occurring in these intallations, these models are, in most of the cases, too complex to be used in the web application. As illustrated in figure G.3, the performance indicators computed in the factory model do not require such detailed models. Even when the use of these Vali models is adapted for batch computation, the experience acquired with this software has highlighted, however, three main limitations. Firstly, the overall calculation time is high due mainly to the time required to launch Vali. For the sake of user-friendliness, computation time should be as short as possible in the developed application. Secondly, communications between the web application and Vali would make the overall system more complex and, consequently, increase the level of maintenance and reduce its stability and reliability. Thirdly, Vali models needs good initial values to converge thus necessitating a pre-computation treatment (choice of the initialization in function of the values sent by the web application). All these reasons have lead to the development of a simplified parametric model of a boilerhouse coded using traditional programming language. This simplified model relies on the experience acquired when modeling the boilerhouse with Vali. The flow-sheet of the model is shown in figure 3.4. This scheme is identical to the one available in figure 2.5(b) except for the reference of the different points that have been simplified here. Compared to the Vali model presented in figure 3.2, the simplified model considers the boiler as one unit including optional equipment such as the economizer. The collection of steam condensate as well as the deaeration process are represented in one single unit called "Feedwater tank". In addition, the deaeration losses through the vent in this unit have been neglected. The variables associated with the model are presented in table 3.5. They corresponds to the fields of the input form available in figure 2.5 [3].

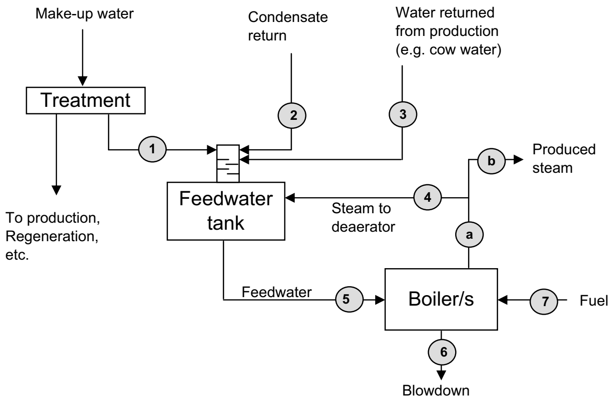


Figure 3.4: Scheme of the simplified boilerhouse model

Table 3.5: Variables of the simplified boilerhouse model

	Unit	**Variable name**	**Nr in Fig. 3.4**
Steam a	Tons/year	$\dot{m}_a$	a
Steam b	Tons/year	$\dot{m}_b$	b
Steam to deaerator	Tons/year	$\dot{m}_4$	4
Steam T	°C	$T_{st,a}$	a
Steam P	barg	$P_{st,a}$	a
Makeup	m^3/year	$\dot{m}_1$	1
Makeup T	°C	T_1	1
Feedwater	m^3/year	$\dot{m}_5$	5
Feedwater T	°C	T_5	5
Condensate	m^3/year	$\dot{m}_2$	2
Condensate T	°C	T_2	2
Blowdown	m^3/year	$\dot{m}_6$	6
Water from production	m^3/year	$\dot{m}_3$	3
Water from production T	°C	T_3	3
Fuel	Nm^3/year	$\dot{m}_7$	7
Fuel LHV	kJ/Nm^3	LHV_f	7
Condensate return rate	-	cr	
Blowdown rate	-	br	
Overall efficiency of boilers	-	η	

[3] As mentioned earlier the number used to identify the fields in the form do not correspond to those of figure 3.4

3.2.5.1 Thermodynamic model

The thermodynamic model is based on energy and mass balances over the different units of the system as well as on the definition of the performance indicators (η, cr, br). The resulting set of 7 linear equations is:

$$\begin{cases} \dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 - \dot{m}_5 = 0 \\ \dot{m}_1(h_5 - h_1) + \dot{m}_2(h_5 - h_2) + \dot{m}_3(h_5 - h_3) + \dot{m}_4(h_5 - h_4) = 0 \\ \dot{m}_a + \dot{m}_6 - \dot{m}_5 = 0 \\ \dot{m}_a - \dot{m}_b - \dot{m}_4 = 0 \\ \dot{m}_a(h_4 - h_5) - \dot{m}_7 LHV_f \eta = 0 \\ \dot{m}_2 - \dot{m}_b cr = 0 \\ \dot{m}_6 - \dot{m}_5 br = 0 \end{cases} \tag{3.5}$$

Based on the data supplied by the user (see figure 2.5), solving the system for the unknowns $\dot{m}_2$, $\dot{m}_4$, $\dot{m}_6$, η, $\dot{m}_b$, cr, br allows for the assessment of the present state of the system. Indicators such as the overall efficiency of boilers η, the blowdown rate br and the condensate return rate cr are then available to be displayed in the factory model (see figure G.3).
The computation of the properties of the different points of the models is briefly discussed below. The determination of the enthalpy of liquid water at point 1, 2, 3 and 5 is computed according to (Belsim, 2003):

$$h_L(T) = a \cdot T + b \cdot T^2 + c \cdot T^3 + d \cdot T^4 \quad [\text{kJ/kg}] \tag{3.6}$$

with

$$\begin{aligned} a &= 2.82 \\ b &= 0.0059 \\ c &= -0.00001167 \\ d &= 0.000000009 \end{aligned}$$

The saturation temperature of the steam (needed to determine h_4) is computed from the following equation (ATEE, 1984):

$$T_{st,a} = 100 \cdot \left(\frac{P_{st,a} + 1}{0.965}\right)^{\frac{1}{4}} \quad [^\circ\text{C}] \tag{3.7}$$

Based on the saturation temperature, the heat of vaporization of the steam (q_{vap}) is determined using Watson equation (Vidal, 1997):

$$q_{vap} = 3048.75 \cdot (1 - \frac{T_{st,a} + 273}{647.3})^{0.3343} \quad [\text{kJ/kg}] \tag{3.8}$$

The exponent in this equation has been optimized to fit accurately the heat of vaporization for steam pressure ranging from 1 to 30 bars. Finally, we have:

$$h_4 = h_L(T_{st,a}) - h_5 + q_{vap} \quad [\text{kJ/kg}] \tag{3.9}$$

One of the simulation included in the "what if?" scenarios for the boilerhouse concerns the addition of an economizer (see section 6.3.2). This simulation requires the computation of the stack losses L_{stack} of the boilers. The equation used for that purpose (OFEFP, 2005) has as input variables the stack temperature T_{stack}, the ambient temperature T_a (both expressed in °C) and the content of oxygen in the fume O_2 (% vol.):

$$L_{stack} = (T_{stack} - T_a) \cdot [\frac{A}{21 - O_2} + B] \tag{3.10}$$

A and B are parameters that depends on the fuel type. A parameter identification based on the Vali models of the boilerhouse has been used to estimate the values of these parameters for LFO, HFO, NG and LPG (butane and propane). The composition of the fuels have been taken from table A.1 and A.2. 30 points have been generated for each fuel ($O_2 = 0, 1, 2, 3, 4, 5$ and $T_{stack} = 350, 300, 250, 200, 150$) and T_a was set to 25°C. The results of the parameter identification are presented in table 3.6.

Table 3.6: Parameters to be used in equation (3.10) according to the fuel type

	A	**B**
LFO	0.708	0.0072
HFO	0.72	0.0066
NG	0.668	0.0099
LPG (Butane)	0.672	0.0081
LPG (Propane)	0.670	0.0084

3.2.5.2 Comparison with Vali model

The simplified boilerhouse model aims at reducing the computing time while guaranteeing an acceptable accuracy of the results. In order to validate it, it has been compared to the Vali model for the simulation of an economizer on a natural gas boiler [4]. Starting from a present stack temperature of 250°C, five simulations (temperature of fumes after the economizer of 225, 200, 175, 150, 125°C) have been performed with each model. The results obtained for the fuel saving and the estimated heat transfer surface required are reported in figure 3.5. This figure highlights the good behavior of the simplified model. The error for the prediction of the fuel saving ranges from 0.47% to 1.74% while it is between 0.7% and 1.92% for the heat transfer surface required. The average computer time required for the simulation was approximately 6 times smaller for the simplified model (0.7 second versus 4.1 seconds for the Vali model).

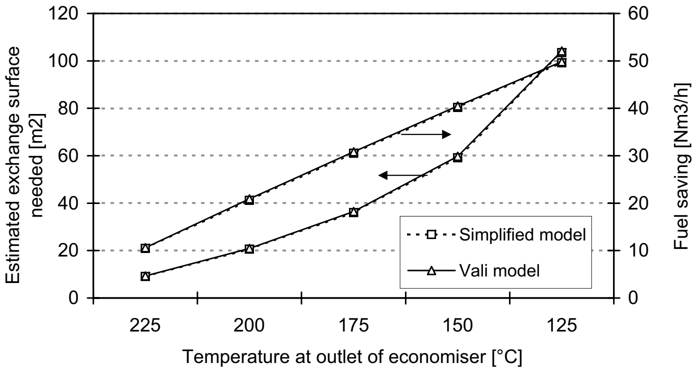


Figure 3.5: Comparison of the results of the Vali model and the simplified model

3.2.6 Equipment costing

Equipment costing aims at determining the cost of an equipment based on different parameters: the type of equipment (heat exchanger, pump, reactor, etc), its size, its construction material (carbon steel, stainless steel, etc) and the pressure at which it will operate. Turton (1998) and Chauvel et al. (2001) propose correlations for estimating the purchase cost for various equipments. In this work, the correlations from the second reference are used since they are more recent (mid-2000 compared to 1996 for Turton). These correlations are based on correction factors according to the type (f_t), the material of construction (f_m) and the operating pressure (f_p) applied on a base cost C_p to determine the final cost C_f of an

[4]Although not presented in this chapter, the simplified model for this "what if?" scenario (see section 6.3.3.1) is more complex than the model presented in the previous section and has been, consequently, judged more relevant to compare the simplified model with the Vali model

equipment:

$$C_f = C_p \cdot f_t \cdot f_m \cdot f_p \tag{3.11}$$

The price are given in Euro and includes assembly. The C_p and the correction factors for different types of equipment are available in Chauvel et al. (2001). The base cost C_p is expressed in function of a capacity parameter that depend of the type of equipment. For instance, the capacity parameter for heat exchangers is the heat transfer area A.

As costs evolves with time due to inflation, records of price information have to be updated using, for instance, the following formula:

$$C_2 = C_1(\frac{I_2}{I_1}) \tag{3.12}$$

where C_1 and C_2 are respectively the known purchased cost at base time and the updated purchased cost. I_1 and I_2 are the cost index at base time and when the updated cost is desired. The Chemical Engineering Plant Cost Index (CEPCI) available monthly in *Chemical Engineering* is used as a cost index (Vatavuk, 2002). This index is a composite of four sub-indexes (equipment, construction labor, buildings and engineering & supervision). The variation of the index as well as the equipment and engineering & supervision sub-indexes for the period 1970-2005 is available in figure 3.6.

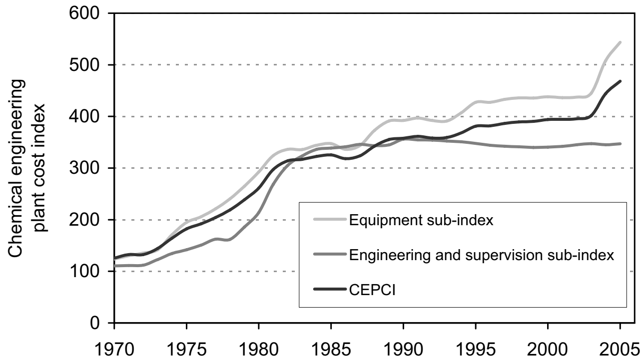


Figure 3.6: Evolution of the CEPCI for the period 1970-2005

3.2.6.1 Application to the estimation of the cost of an economizer

One of the frequent retrofit in a boilerhouse that implies a relatively important investment is the addition of an economizer in the boiler fumes in order to preheat the feedwater.

Estimation of the cost of such a unit is taken as an example to illustrate the steps adopted for estimating the final cost of equipments.

Based on the figure proposed in Chauvel for heat exchanger, a linear fit of the base cost C_p in function of the capacity parameter A is realized on the relevant range for the application. In this case, the range considered for the heat transfer area is from 10 to 140 [m^2]. 140 is chosen as an upper bound since it corresponds more or less to the surface required for a stainless steel economizer (U=56.8 [W/m^2/K]) on a 25 [t/h] boiler to cool down fumes from 250°C to 150°C with feedwater at 105°C. The resulting equation for C_p is:

$$C_p = 5770 + 123 \cdot A \quad [2000€] \tag{3.13}$$

Taking into account the inflation (CEPCI 2000 = 394.1, CEPCI May 2006 = 495.6) and the correction factors of table 3.7, the final costs for carbon steel (CS) and stainless steel (SS) economizers are:

$$\begin{aligned} C_f(CS) &= 7766 + 166 \cdot A \quad [2006€] \\ C_f(SS) &= 14737 + 314 \cdot A \quad [2006€] \end{aligned} \tag{3.14}$$

Table 3.7: Correction factors for heat exchangers (Chauvel et al., 2001)

	Carbon Steel	**Stainless Steel**
f_t	1	1
f_m	1	1.9
f_p	1.07	1.07

The obtained costs have been compared with the prices of carbon steel and stainless steel economizers available on the website of a supplier of economizers (*Boilerroom equipment, Inc* [5]). The characteristics of the economizers (called *heatsponge*) used for the comparison are available in table 3.8.

Table 3.8: Data of *heatsponge* economizers

Tube diameter [m]	D	0.019
Fin height above tube [m]	H	0.0127
Fin thickness [m]	t	0.001
Distance between fins [m]	F	0.005

Based on the equations available in appendix C.2 and assuming that $U_1 = 100$ [W/m^2/K] and k are respectively 60 and 15 [W/m/K] for Carbon Steel (CS) and Stainless Steel (SS),

[5] www.heatsponge.com/economizer.shtml

the fin efficiency η_f, the overall surface efficiency η_0 as well as the global heat transfer U can be computed for CS and SS economizers (see table 3.9). Knowing U, the approximate heat transfer surface can be computed for both materials for different size of economizers (7, 14, 21, 28, 35 tubes). These surfaces as well as the price for these different economizers available on the website of *Boilerroom equipment* (may 2006) are reported in table 3.10.

Table 3.9: Characteristics of *heatsponge* economizers

	k	η_f	η_0	U
	[W/m/K]	**-**	**-**	**[W/m^2/K]**
Carbon Steel	60	0.8	0.816	81.6
Type 304 Stainless Steel	15	0.53	0.568	56.8

Table 3.10: Costs of different *heatsponge* economizers

Identifier	**Material**	**Nr of tubes**	**Estimated area [m^2]**	**Cost [US$]**
HS-7-BASE-5-CS	CS	7	27	15641
HS-14-BASE-5-CS	CS	14	54	26666
HS-21-BASE-5-CS	CS	21	81	37691
HS-28-BASE-5-CS	CS	28	108	48716
HS-35-BASE-5-CS	CS	35	135	59741
HS-7-BASE-5-SS	SS	7	27	16866
HS-14-BASE-5-SS	SS	14	54	29116
HS-21-BASE-5-SS	SS	21	81	41366
HS-28-BASE-5-SS	SS	28	108	53616
HS-35-BASE-5-SS	SS	35	135	65866

A comparison of the costs of economizers with the costs obtained with equations (3.14) is presented in figure 3.7. The estimated costs have been converted to US dollars using the following exchange rate: 1 € = 1.28 US$. This figure shows that the estimated costs tend to underestimate the cost of CS economizers and to overestimate those of SS economizers. However, the trends from correlations and data from the market are similar, which validate the use of such correlations for a first estimation of equipment costs.

3.3 Air heaters

Together with steam and hot water boilers, air heaters are the main consumers of fossil fuels in the food processes covered in this work. Air heaters are used to supply air at high temperature (typically between 300-400°C) for spray drying processes. Spray drying is used for example in milk powder or instant coffee processing. In these processes, the product is atomized into fine droplets in the drying chamber where it get in contact with the hot air. The moisture content will be typically reduced from 50-55% to 3-3.5% in the case of milk

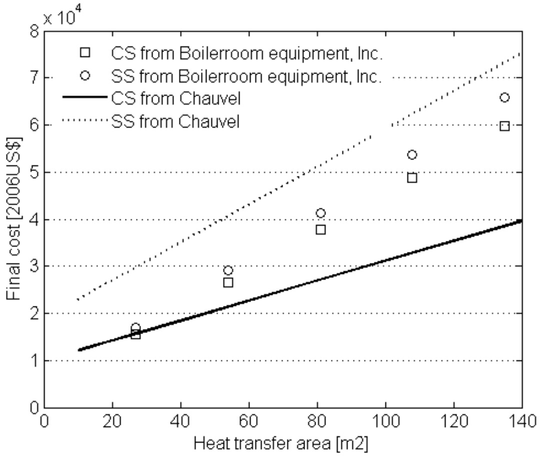


Figure 3.7: Costs of economizers obtained for different materials of construction

powder and 75-85% to 3-3.5% in the case of instant coffee. The air heater model that has been developed is presented in figure 3.8.

When compared with the model of the boilerhouse (figure 3.2), it appears that both models present similarities especially for the combustion. Indeed, the burner is modeled identically as in the boilerhouse model (see section 3.2.1). The main difference lies in the operating conditions: the excess air in air heaters is approximately 1.3 at nominal load to protect the combustion chamber from overheating. At partial load, the excess air is even higher to ensure a complete combustion. The heat exchangers (heater and economizer) are also modeled with the same units as in the boilerhouse but have different characteristics due to the type of heat exchange (air-fumes for the air heater, water/steam-fumes for the steam boiler). Another important difference regarding heat exchange is the temperature allowable at the exit of the economizer. Since the incoming cold stream is at ambient temperature air, the exit temperature of the fumes in a counter-current design can be set much lower than for a steam boiler where the inlet temperature of water (usually 105°C) is a limiting factor. Thus, if considering a non-condensing economizer in a gas-fired air heater, outlet of the fumes can be as low as 80°C for an air heater while 150°C is a minimum value for a steam boiler. The critical variables of the air heater are presented in table 3.11. The losses are divided into two contributions: stack losses and other losses (radiation and stand-by). It has to be emphasized here that over a long period the stand-by losses can be significantly higher here than for a boiler. Indeed, the preheating of the air heater as well as the ducts to the spray-drying towers can necessitates typically 30 minutes making sometimes the coordination

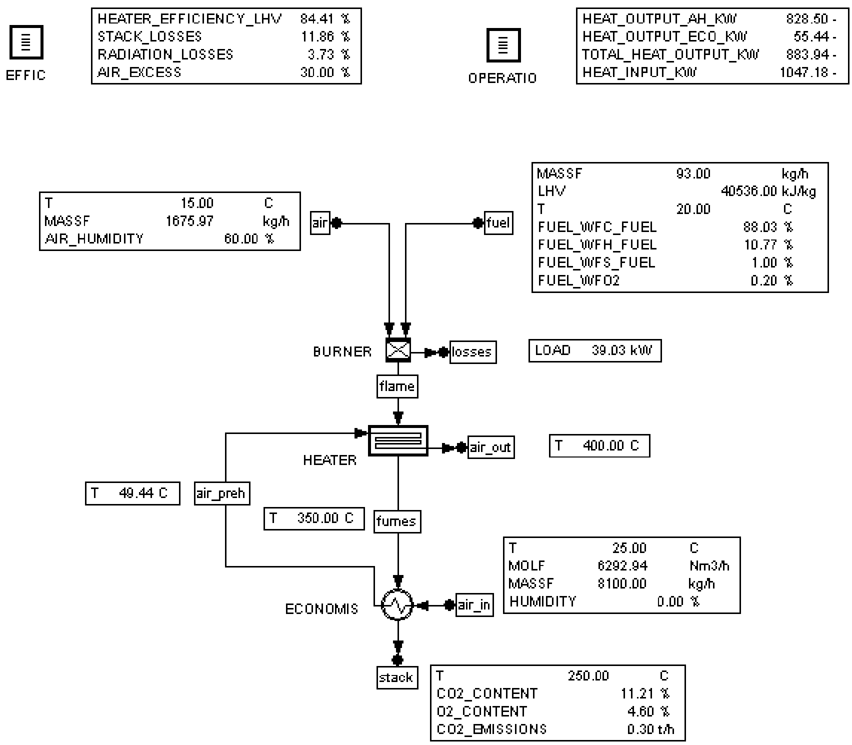


Figure 3.8: Flowsheet of the air heater model

between production operators (responsible for the spray-drying towers) and utility operators (responsible for the air heaters) difficult. It is not uncommon to have preheated air heaters waiting long minutes for the production to start.

Table 3.11: Critical variable of the air heater

Indicator	**Unit**
Overall efficiency of boilers	%
Stack losses	%
Other losses	%
Air excess λ	-

3.4 Refrigeration

Refrigeration is omnipresent in the food industry. It is used in the process (freeze-dried coffee, frozen food, ice-cream, etc), to maintain the cold chain of the product throughout its production and distribution but also for HVAC in the facilities. The wide range of applications results in a wide range of configurations for the refrigeration units that provide cold services. In this work, three main configurations have been modeled: a single-stage NH_3 unit, which is used in nearly all factories that do not need cold in negative temperatures, a multistage NH_3 unit and a NH_3/CO_2 cascade unit for low temperature application (down to -50°C). It has to be highlighted that these three types of cycle are all vapor compression systems. Absorption systems have been discarded at first to focus on existing systems in the food industry. However, installations based on absorption should be considered in the future since they present many advantages (high reliability, low repair and maintenance cost, oil-free technology, possibility to reach low temperature) and are especially relevant in the context of cogeneration and rationale use of energy resources.

The models developed also focus on natural, ecologically safe refrigerants - NH_3 (R717) and CO_2 (R744) - which are the fluids most commonly found in industry nowadays. The current dominance of these refrigerants is explained by the restrictions on CFCs due to their ozone depletion potential and more recently on HFCs due their global warming potential. CO_2 is an "old" refrigerant that has been used in the refrigeration units before the emergence of the CFCs in the 30s. It was then abandoned for different reasons. Nowadays, it is more and more used as a substitute to HFCs and CFCs due to its environmental friendliness. CO_2 has the advantage to be the only non-flammable and non-toxic fluid that can also operate in a vapor compression cycle below 0°C. However, its use in cycle that reject heat at ambient temperature represents a challenge since its critical temperature is 31.1°C (Kim et al., 2004). In the NH_3/CO_2 unit modeled, the CO_2 is used in the lower stage and stays consequently in subcritical conditions.

3.4.1 Modeled cycles

This section focuses on the description of the NH_3/CO_2 cascade unit. The reader is referred to Timms (2005) for details regarding the modeling of the multi-stage NH_3 unit. The modeling of the single-stage NH_3 unit is similar to the upper stage of NH_3/CO_2 cascade unit described in this section. The modeled NH_3/CO_2 cascade unit is represented in figure 3.9 It consists in a high-stage NH_3 cycle with an economizer and a lower stage using CO_2 and providing cold at three different levels of temperature (here -52°C , -47°C and -17°C). The intermediate pressure of the NH_3 cycle (economizer) is set at the geometric mean of the evaporation and condensing pressure as suggested in Perry et al. (1997). The distribution of cold by the CO_2 is achieved using recirculating systems which guarantees saturated vapor at compressor inlet and an increased heat transfer in the evaporator.

The first stage of the modeling has been the choice of thermodynamic model for the computation of liquid and vapor enthalpy of NH_3 and CO_2. This has been done by comparing the results obtained with different models available in Vali with values from tables (Stewart et al., 1986). The results have shown that the best models to compute the liquid and vapor enthalpy of NH_3 are respectively LIDEAL2 and Lee-Kesler, while for CO_2 the best model for both the liquid and vapor enthalpy is Lee-Kesler model.

3.4.2 Compressor models

The availability of accurate models for compressors is crucial for the global quality of the model since these equipments determine not only the mechanical work required at the shaft but also part of the thermal energy that will have to be withdrawn from the system. The detailed models of these equipments presented here have been developed using data from Sabroe [6] that can be found in Timms (2005).

In a real compressor, the working fluid is cooled down during its compression resulting in a non-adiabatic transformation. However, the unit that models compressors in Vali handles only adiabatic compression. As a consequence, the compressor has been modeled in two steps. First, the fluid is compressed in an adiabatic compressor up to the pressure at the outlet of the "real" compressor being modeled. Then, in a second step, the fluid is cooled down without pressure drop in order to reach the final state corresponding to the outlet temperature of the "real" compressor. These two steps are illustrated in figure 3.10.

The aim of the compressor model is to determine the isentropic efficiency of the adiabatic compressor and the heat to be removed expressed as a fraction of the work required at the shaft. The isentropic efficiency of an adiabatic compressor can be written as:

$$\eta_{Cs} = \frac{h_{IVs} - h_I}{h_{IV} - h_I} \tag{3.15}$$

where h_I is the enthalpy of the fluid at the compressor inlet, h_{IV} is its enthalpy at the compressor outlet and h_{IVs} is the enthalpy after an isentropic compression from h_I up to

[6] www.sabroe.com

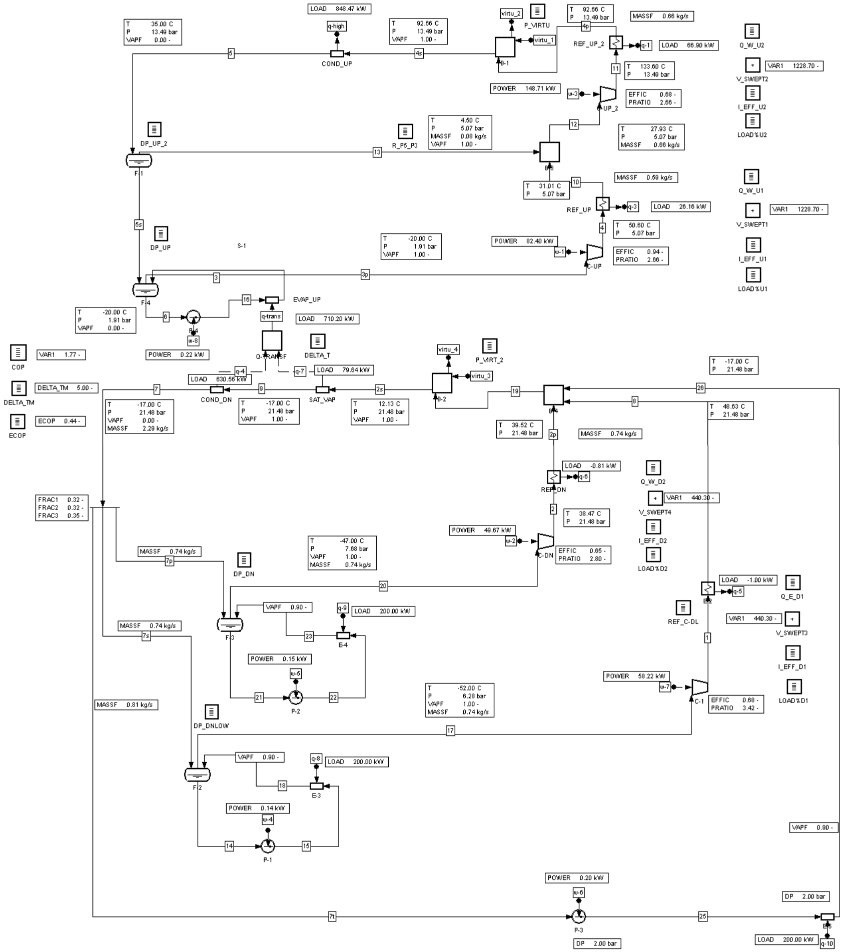


Figure 3.9: Flowsheet of NH_3/CO_2 cascade unit modeled with Vali

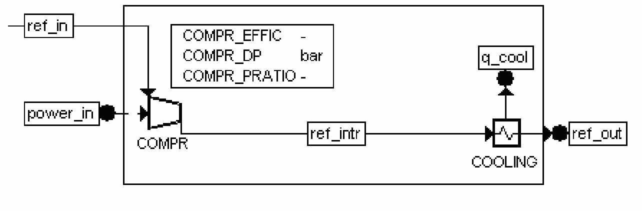


Figure 3.10: Compressor model developed in Vali considering an adiabatic compression and a separate cooling

the pressure at the outlet of the compressor. The denominator of this expression is the mechanical work required at the shaft. To keep the compressor model as general as possible, it has been based on dimensionless parameters such as the compression ratio $\tau = P_{IV}/P_I$ and the load of the compressor. The latter is defined as:

$$Load = \frac{\dot{V}_{suction}}{\dot{V}_{suction\_N}} \tag{3.16}$$

where $\dot{V}_{suction}$ [m^3/h] is the actual volume flow rate in the compressor, $\dot{V}_{suction\_N}$ is the volume flow rate at nominal conditions. $\dot{V}_{suction}$ can be computed from the massflow of refrigerant in the compressor $\dot{m}$ and its volume v_I [m^3/kg] at the inlet of the compressor:

$$\dot{V}_{suction} = \dot{m} \cdot v_I \cdot 3600 \tag{3.17}$$

Finally, from $\dot{V}_{suction}$ and the volume swept by the piston $\dot{V}_{swept}$ (available from the supplier) it is possible to compute the volumetric efficiency of the compressor η_V:

$$\eta_V = \frac{\dot{V}_{suction}}{\dot{V}_{swept}} \tag{3.18}$$

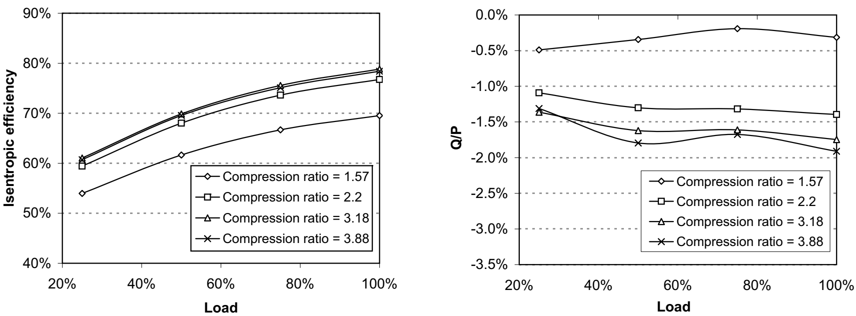
The data available from Sabroe for a given inlet state (P_I and T_I), outlet state (P_{IV}) and load are: the outlet temperature (T_{IV}) and the mechanical power required at the shaft. Based on these data, the isentropic efficiency as well as the cooling required can be obtained using the Vali model available in figure 3.10. The characteristics obtained for the compressor are subsequently fitted and the resulting correlations are programmed in Vali refrigeration models. For the NH_3/CO_2 cascade unit presented in figure 3.9, two compressors have been modeled using this strategy: a CO_2 reciprocating compressor for the lower stage of the cascade unit and a NH_3 screw compressor for its upper stage.

3.4.2.1 CO_2 reciprocating compressor

The model for the reciprocating compressor is based on data of the HPC 108S compressor from Sabroe. Its main characteristics are presented in table 3.12. Four different loads have been considered (100%, 75%, 50% and 25%) as well as four inlet state at saturation conditions (T_I of -25°C, -35°C, -45°C and -50°C). The isentropic efficiency and the cooling load as a fraction of the input mechanical work obtained with Vali are presented in figures 3.11(a) and 3.11(b). It can be observed that the isentropic efficiency decreases at part load operation and that this compressor is not efficient for small compression ratios. As regards the cooling of the compressor, figure 3.11(b) highlights that instead of cooling there is an heating effect on the compressed fluid. This is due to the fact that the compression occurs below the ambient temperature.

Table 3.12: Characteristics of compressor HPC 108S from Sabroe

Number of cylinders	8
Bore x stroke [mm]	100 x 80
Max. rpm	1500
$\dot{V}_{swept}$ @ 1500 rpm $[m^3/h]$	452
Cooling capacity (R744 -50°C/-10°C) [kW]	465
Cooling capacity (R744 -40°C/-5°C) [kW]	689



(a) Isentropic efficiency

(b) Cooling Power

Figure 3.11: Isentropic efficiency and cooling as fraction of input power for compressor HPC 108S

Based on these curves, a set of 5 correlations has been developed to estimate these two characteristics of the compressor based on the compression ratio τ, the massflow of refrigerant in the compressor $\dot{m}$, the volume v_I and $\dot{V}_{suction\_N}$. The developed correlations for the HPC 108S compressor are available in table 3.13. These correlations are programmed sequentially in Vali as illustrated in figure 3.12. Since the isentropic efficiency varies in function of both the compression ratio and the load, a first correlation is used to compute a reference curve of the isentropic efficiency in function of the load (see entry $\bar{\eta}_{Cs} = f(Load)$ in table 3.13) that is corrected in a second step by the dependence to the compression ratio ($\Delta\eta_{Cs} = f(\tau)$). As shown in equations (3.16), (3.17) and (3.18), the load is dependent of the volumetric efficiency. Timms (2005) showed, however, that the volumetric efficiency can be considered as independent of the load and thus can be expressed only in function of the compression ratio ($\eta_V = f(\tau)$). Similarly to the isentropic efficiency, the cooling needed is first expressed in function of the compression ratio ($(Q\bar{/}P) = f(\tau)$) and then corrected in a second step in function of the load ($\Delta(Q/P) = f(Load)$).

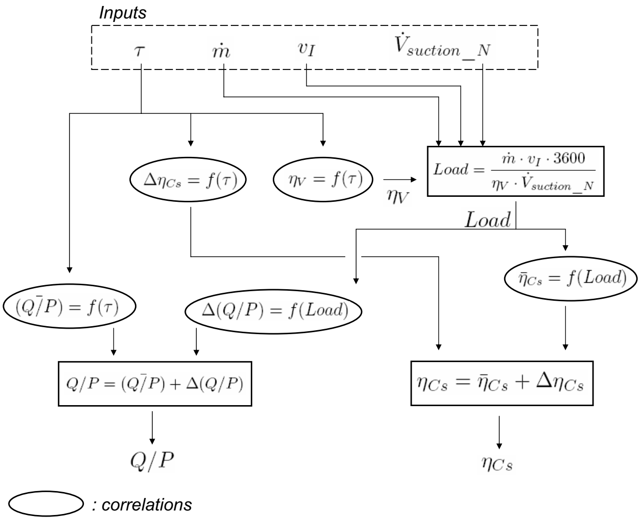


Figure 3.12: Sequence of use of correlations implemented in the Vali model of a compressor

Table 3.13: Correlations developed for the HPC 108S compressor

$\eta_V = f(\tau)$ *	$\eta_V = -0.0588 \cdot \tau + 1.0387$
$\bar{\eta}_{Cs} = f(Load)$ **	$\bar{\eta}_{Cs} = -2 \cdot 10^{-5} \cdot Load^2 + 0.0049 \cdot Load + 0.4779$
$\Delta\eta_{Cs} = f(\tau)$ *	$\Delta\eta_{Cs} = 0.018 \cdot \tau^3 - 0.1834 \cdot \tau^2 + 0.6119 \cdot \tau - 0.6419$
$\Delta(Q/P) = f(Load)$ **	$\Delta(Q/P) = 3 \cdot 10^{-5} \cdot Load^2 - 0.0075 \cdot Load + 0.3172$
$(Q\bar{/}P) = f(\tau)$ *	$(Q\bar{/}P) = -0.0027 \cdot \tau^3 + 0.0259 \cdot \tau^2 - 0.0839 \cdot \tau + 0.0748$

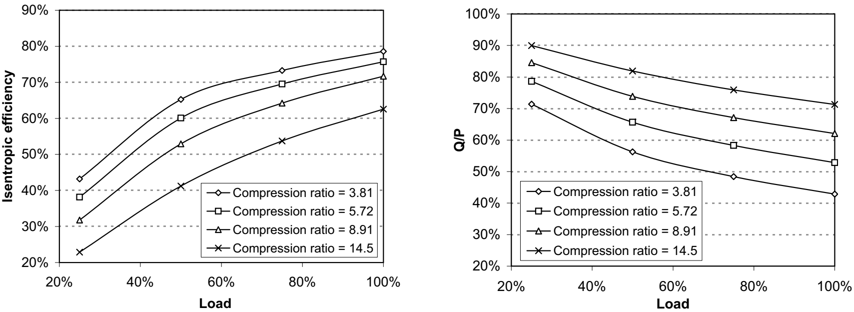
*validity: $1.57 < \tau < 3.88$, ** validity: $25\% < Load < 100\%$

3.4.2.2 NH_3 screw compressor

A similar approach has been used to model the NH_3 screw compressor. The model has been based on data from the SAB 202 SM compressor whose main characteristics are presented in table 3.14. As shown in the table, this compressor can be used both as a high stage compressor or in the lower stage as a booster. The results presented here have been obtained for a high stage usage. The curves obtained for the isentropic efficiency (see figure 3.13(a)) show that the decrease at part load is more important here than for the reciprocating compressor. As the compressor operates at ambient temperature, the cooling needed is positive in this case and depends on both the load and the compression ratio as shown in figure 3.13(b). Using the same methodology as for the reciprocating compressor, the set of correlations developed to approximate these curves are available in table 3.15.

Table 3.14: Characteristics of compressor SAB 202 SM from Sabroe

$\dot{V}_{swept}$ @ 2960 rpm $[m^3/h]$	1207
$\dot{V}_{swept}$ @ 3550 rpm $[m^3/h]$	1448
Cooling capacity (R717 High stage -10°C/+35°C) [kW]	793
Cooling capacity (R717 Booster -40°C/-10°C) [kW]	238



(a) Isentropic efficiency (b) Cooling Power

Figure 3.13: Isentropic efficiency and cooling as fraction of input power for compressor SAB 202 SM

Table 3.15: Correlations developed for the SAB 202 SM compressor

$\eta_V = f(\tau)$ *	$\eta_V = -0.0064 \cdot \tau + 0.9113$
$\bar{\eta}_{Cs} = f(Load)$ **	$\bar{\eta}_{Cs} = 8 \cdot 10^{-7} \cdot Load^3 + 0.0002 \cdot Load^2 + 0.02 \cdot Load - 0.0467$
$\Delta\eta_{Cs} = f(\tau)$ *	$\Delta\eta_{Cs} = -0.0002 \cdot \tau^2 - 0.0108 \cdot \tau + 0.1074$
$\Delta(Q/P) = f(Load)$ **	$\Delta(Q/P) = 2 \cdot 10^{-5} \cdot Load^2 - 0.0058 \cdot Load + 0.2556$
$\bar{(Q/P)} = f(\tau)$ *	$\bar{(Q/P)} = 0.0003 \cdot \tau^3 - 0.0098 \cdot \tau^2 + 0.1213 \cdot \tau + 0.2116$

*validity: $3.81 < \tau < 14.5$, ** validity: $25\% < Load < 100\%$

3.5 Air compressors

Compressed air is together with chilled water and steam one of the utility that is present in nearly each production site in the food industry. It is used for applications as diverse as process control, product conveying, bottling, sealing applications, etc. The level of pressure required in the food industry is typically between 3 to 10 barg. As compressed air might be in some case in contact with the product or even directly used as a raw material, its quality is of primary importance in food industry. Given these specifications, the two types of air compressor that are commonly used are reciprocating compressors and screw compressors. Reciprocating compressors are preferred for small capacity and if the variation of the load operation is important. The model developed in this work (see figure 3.14) concerns a water-cooled two-stage screw compressor. After a first stage of compression, the air passes through an intercooler to be cooled down before entering the second stage of compression. Finally, it is cooled down in an aftercooler. As explained in the refrigeration model, the compressor unit in Vali can only handle adiabatic compression. Consequently, the same modeling method has been adopted here: a stage of compression is modeled through an adiabatic compression followed by a cooling of the compressed air to reach the temperature observed at the outlet of the "real" compressor. This explains why there are additional cooling units before the intercooler and the aftercooler in figure 3.14. An important assumption on which this model relies is the equality between the cooling power of the two compressors (heat flux "q_2" and "q_4"). This assumption is necessary to determine how the input mechanical power is distributed between the two compression stages and, consequently, what is the isentropic efficiency of each stage. In the perspective of benchmarking air compressors of different types, a one-stage equivalent model is also included in this model (see bottom-right corner of the figure). The conditions at the inlet and outlet of this simplified model are identical to the ones of the two-stage model. This allows to compute a global isentropic efficiency for the compressor. Another performance indicator computed by the model is the specific consumption of the compressor expressed in Wh/Nm^3.

3.6 Cogeneration

Cogeneration systems that have been considered in this work are "topping cycles" (Kreith and West, 1997). They use the heat released by the fuel at high temperature to produce electricity. The rejected heat is, then, used to produce useful thermal energy such as steam or hot water. "Topping cycles" include various configurations: back-pressure steam turbine between steam headers, gas turbine with heat recovery, reciprocating engines with heat

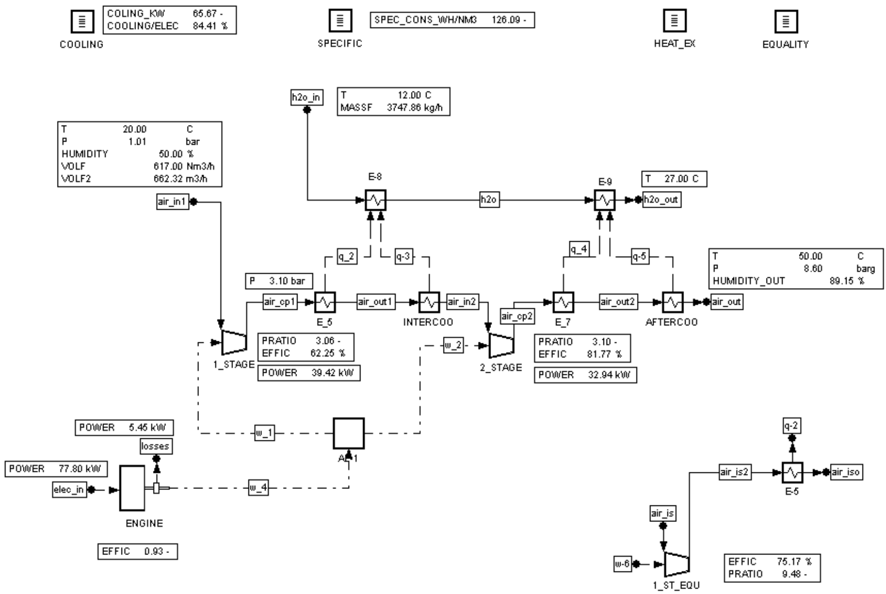


Figure 3.14: Flowsheet of the two-stage air compressor modeled with Vali

recovery. Some advanced concept of CHP plant for food industry are also available in literature. For example, Korobitsyn (2002) showed that the combination of a gas turbine with an air bottoming cycle is a high-efficiency solution that provide clean hot air for drying process. However, in this work, models of cogeneration systems have only been used to assess the possibility to integrate such equipments in low temperature processes in the context of the bottom-up approach (see Chapter 5). In the context of food industry, the reciprocating engine appears as the most relevant technology for CHP as the heat from both the fumes and the cooling of the engine can be potentially used in low temperature processes. In the application discussed in Chapter 5, a diesel engine has been considered. It has been modeled using the equations from Baillifard (2002) that are based on a review of equipments available in the market. These equations are presented in table 3.16.

3.7 Conclusion

The thermo-economic models of energy conversion units presented in this chapter play an important role in the developed methodology. Based on the data supplied by users in a

Table 3.16: Diesel engine model

	Unit	Equation
Mechanical efficiency	[-]	$\eta_{mec} = 0.0131 \cdot ln(P_{mec}) + 0.3452$
Cooling	[-]	$\eta_{cool} = 0.2875 \cdot P_{mec}^{-0.0139}$
Fumes	[-]	$\eta_{fumes} = 0.5433 \cdot P_{mec}^{-0.1026}$
Investment (P_{mec}>1000 kW)	[CHF]	$C_i = 1687 \cdot P_{mec}^{0.9009}$
Investment (P_{mec}<1000 kW)	[CHF]	$C_i = -0.391(\frac{3}{4}P_{mec})^2 + 850.89\frac{3}{4}P_{mec} + 306016$
Maintenance	[cts/kWh]	$C_m = 5.98 \cdot P_{mec}^{-0.2058}$

factory model, they will serve in the first place to assess the efficiency of the units and identify the main improvement potentials. In a second step, the thermo-economic models are used to evaluate these potentials by simulating modifications in operating conditions or the impact the improvement of an indicator may have. The use of these models in so called "what if?" scenarios will be reviewed in detail in Chapter 6. A large part of this chapter is dedicated to the description of the boilerhouse model. This energy conversion unit is used to show the modeling strategy adopted. As the developed models should be applicable in as many cases as possible, an important time needs to be spent at first in defining a standard model. The experience of the group of energy experts in energy in the company is very valuable in this process. Based on the selected configuration, a detailed thermodynamic model is developed with a process modeling tool. Even when such tools allow for a rapid definition of an accurate model, they often present limitations when run in the background of an application, as calculation engines. These limitations mainly include a high CPU time to perform calculations, problems of convergence and problems of communication with the main application. Development of a simplified parametric model allows to overcome these problems while guaranteeing a satisfying accurate results.

In the current version of the developed web application (see Chapter 6), implementation of these simplified models has been limited to the boilerhouse. However, detailed models of units such as air heaters, air compressors or refrigeration cycles are developed using a process modeling tool and could be implemented in the application in the form of simplified models. These tasks will not require an important effort as regards the first two technologies mentioned above. With respect to refrigeration cycles, the large amount of configuration possible as well as the different working fluids that might be considered make such implementation much more complex. In addition to energy conversion units, the modeling of cross-cutting technologies used in the process, such as vacuum production, could be envisaged to help engineers find energy savings in the process itself.

In this chapter, we focus on well-established energy conversion technologies that are commonly found in the food industry. These were considered as a priority when defining the scope of this work. It has to be mentioned, however, that models of emerging technologies have also been considered in this project (Witschi, 2005). The modeled technologies include "CO_2-free" systems, such as solar heating, photovoltaic systems, wind turbines, geothermal systems and biomass conversion systems. Models of efficient CHP units such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), have also been developed. In the future, assessment of the potential use of these technologies could be integrated in the application through "what if?" scenarios.

Chapter 4

Statistical methods as a support to the top-down approach

In the top-down approach, we try to allocate the energy costs among the different production units. For that purpose, we introduced in Chapter 2 a modular factory model. When data is available, the production units are well instrumented and the processes are well documented, the definition of such a model is relatively easy. However, in the food industry, the lack of information on the process as well as on the side production processes like cleaning, packaging or waste treatment make the definition of such a model much more complex. Before launching a large-scale measurement campaign to obtain lacking pieces of information, it might be worthwhile to exploit the information already available to identify which are the products that affect the more the energy bill and limit measurements to the units linked with the production of those products. As energy bills (purchased energies) and production records are always available, data-driven models such as multi-linear regression models can be used to define relationships between dependent variables (i. e. energy consumptions) and independent variables. Experience shows that linear models are accurate enough to explain energy consumptions in most of the cases (Vogt, 2004). Beside production data, other variables that might have a significant impact on the consumption of purchased energies such as outside temperature can be added to the model. Results of the regression show which variable has the biggest influence on energy consumption allowing to focus energy measurements on that line of product. This top-down modeling strategy is not only applicable to purchased energies but also to distributed energies inside the factory provided that measurements for that energies are available.

4.1 Multi-linear regression models

Multi-linear regression models are based on a "black-box" approach to link an observed variable with independent variables that might have an influence on the observed variable. Contrarily to physical models, black-box models do not require a preliminary knowledge of the system being modeled since they only focus on its inputs and outputs. The only requirement is the availability of reliable data record that should cover the same periods for dependent and independent variables. This method is consequently particularly appropriate when starting the analysis of a system such as a factory. The identification of the model parameters give a first indication of the main energy drivers for the modeled dependent variable. If no knowledge of the system is required, a preliminary knowledge of the system might be an advantage when defining the independent variables to be included in the model. However, we will see later in this chapter that selection algorithms exist to determine which are the significant independent variables among a given starting set of such variables. As a consequence, it might be better to ignore one's intuition in a first step and use a large set of independent variables whose significance will be validated in a second step.

To illustrate the use of multi-linear regression models, we will consider the example of figure 4.1. This figure is based on the typical representation of a factory available in figure 2.1. The objective of the method is to find a relationship between a dependent variable y (the fuel purchased in the figure) and the different independent variables: the products (x_1 to x_o), the by-products (x_{o+1} to x_{p-2}) and the outside climatic conditions (x_{p-1}). As shown in the figure, the heat losses to the environment, that will determine the heating requirements, are a function of the outside temperature T. A general linear model can then be written as illustrated in the figure. As the model does not explain accurately the observed consumption y, a term ϵ accounting for the error of the model is introduced in the equation. By using statistical methods, it is possible to determine the values of β_0 to β_{p-1} that minimize the square of the error of the model.

The multi-linear regression model is based on n similar equations. Each equation being based on a set of observations available for the dependent and independent variables (y, x_1 to x_{p-1}). These observations will be typically monthly or weekly records. Mathematically, the multiple linear formulation for n observations and for $p-1$ independent variables is given by equation (4.1).

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + ... + \beta_{p-1} x_{ip-1} + \epsilon_i \quad i = 1, 2, ..., n \tag{4.1}$$

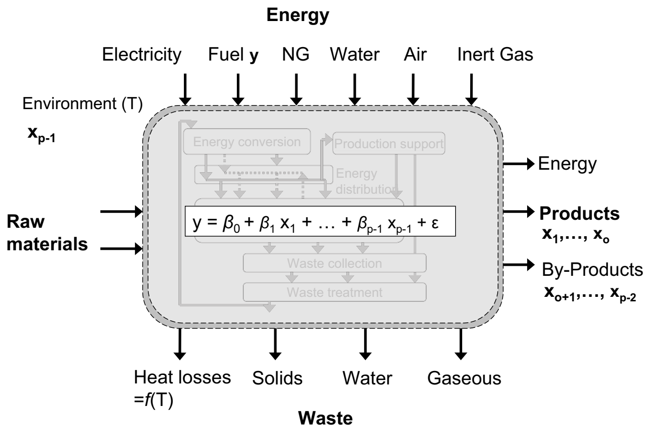


Figure 4.1: Multi-linear black-box model

In matricial form, equation (4.1) becomes

$$\mathbf{Y} = \mathbf{X}\beta + \epsilon \tag{4.2}$$

where $\mathbf{Y}$ is a $(n\times1)$ vector of observations, $\mathbf{X}$ is a $(n\times p)$ matrix containing all the independent variables observed including the constant (represented by a column of 1), β is a $(p\times1)$ vector of parameters and ϵ is a $(n\times1)$ vector of errors.

The vector that minimizes the sum of the square of the errors when substituted to β in equation (4.2) is the least square estimate of β and is referred to as $\mathbf{b}$. It is computed as follows:

$$\mathbf{b} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} \tag{4.3}$$

The estimated values $\hat{\mathbf{Y}}$ of the dependent variable $\mathbf{Y}$ are then obtained by:

$$\hat{\mathbf{Y}} = \mathbf{X}\mathbf{b} \tag{4.4}$$

The coefficient of determination R^2 is a popular indicator of the quality of a regression. It represents the fraction of variability in $\mathbf{y}$ that can be explained by the variability in $\mathbf{X}$. It is computed from the total sum of square SS_T and the explained sum of squares SS_E:

$$R^2 = \frac{SS_E}{SS_T} = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \tag{4.5}$$

where

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{4.6}$$

R^2 is always a figure between 0 and 1. A perfect fit of the data by the model ($\hat{y}_i = y_i \; \forall i$) results in a R^2 of 1. However, a high R^2 does not guarantee that the regression is statistically significant. This is especially true when the number of observations n is small. In the extreme case, a model with $n-1$ independent variables perfectly fits n observations ($R^2 = 1$). It means that the coefficient of determination can be improved by adding independent variables which will not necessarily means that the quality of the model has improved. Consequently, the coefficient of determination of a regression gives a first indication of the quality of the model but is insufficient to validate its significance.

4.1.1 Significance of the model

In order to validate the developed correlation, we should take into account the degrees of freedom of the regression ($p-1$) and of the residuals ($n-p$). This is achieved using the Fischer (F) statistic defined as:

$$F = \frac{(n-p)R^2}{(p-1)(1-R^2)} \tag{4.7}$$

If the F value is higher than the value of the Fisher distribution statistic ($F(p-1, n-p, 1-\alpha)$) at a given level of significance α, the regression can be considered as statistically significant and the null hypothesis (H_0) in the test below can be rejected.

$$H_0\text{: } \beta_j = 0 \quad \text{against} \quad H_1\text{: not all } \beta_j = 0 \qquad j = 1, ..., p-1$$

4.1.2 Significance of the independent variables

We have seen above that adding independent variables to a model will improve the R^2 of the regression without necessarily improving the quality of the model. Indeed, the impact of significant variables might be diluted by the presence of variables that are insignificant and consequently not desired. This might also create confusion in our comprehension of the system being modeled. Consequently, the regression has to include only significant independent variables in order to have good predictive capabilities. This is done by testing the validity of each of the coefficients of the model against the null hypothesis that expresses no dependence:

$$H_0 : \beta_j = 0 \quad \text{against} \quad H_1 : \beta_j \neq 0 \quad \text{for } j = 0, ..., p$$

The t statistic is used to accept or reject the null hypothesis (H_0). It is defined as

$$t = \frac{\hat{\beta}_j}{\sqrt{c_{jj} \cdot MSE}} \tag{4.8}$$

where $\hat{\beta}_j$ is the coefficient estimate and the denominator is the estimated standard error of that estimate. MSE is the error mean square and is computed according to the following formula:

$$MSE = \frac{\sum_{i=1}^{n} (\epsilon_i)^2}{n - p - 1} \tag{4.9}$$

c_{jj} is the jth diagonal element of matrix $\mathbf{C} = (\mathbf{X'X})^{\mathbf{-1}}$. If t exceeds the value of the Student distribution statistic ($t(n-p, 1-\alpha)$) with a level of confidence α the null hypothesis can be rejected and the tested coefficient is "statistically significant". If it is not the case, the corresponding independent variable has to be removed from the model.

4.1.3 Test for multicollinearity

If the number of independent variables in the model is large, the risk of having correlations among them (meaning they might be measuring similar phenomena) increases. This case is referred to as multicollinearity. This is not desired since it will lead to a badly conditioned matrix $\mathbf{X'X}$ in equation (4.3). This will affect the quality of the estimates of the model. In the extreme case where one independent variable is linearly dependent on the other columns, $\mathbf{X'X}$ is singular resulting in an infinite number of solutions for $\mathbf{b}$. Multicollinearity can be detected by computing Variance inflation factors (VIF). The VIF_j are computed according to the following formula:

$$VIF_j = \frac{1}{1 - R_j^2} \tag{4.10}$$

where R_j is the coefficient of determination of the regression of the independent variable j with all the other independent variables.

There is no theoretical value above which multicollinearity will seriously affect the quality of the regression. However, most of the authors (Freund and Wilson, 1998; Haan, 2002) used a threshold value between 5 and 10 to accept or reject the model due to multicollinearity.

4.2 Typical independent variables

Selection of the set of independent variables to be included in the model is based on the experience and the judgement of the plant engineer or on typical independent variables that will be introduced in the next sections. It principally depends on the dependent variable being modeled. We will see later in this chapter that, for example, heating requirements for a facility will not be considered as an independent variable in a model for electricity consumption if no electrical heating is implemented in the factory. It has to be emphasized here that no independent variables should be discarded at first since statistical tests will be performed in a second step to validate their presence in the model. The range of independent variables that might be considered for the modeling of energy consumption is very wide. For instance, Al-Ghanim (2003) showed that energy consumption can be correlated with maintenance aspects such as failure rate in addition to production factors. Other authors such as Vogt (2004) include independent variables such as the number of production days or the total hours worked. In this work, the independent variables that have been considered apart from production volumes are linked to the influence of the climate.

4.2.1 Degree days

In the food industry, the climate has an important impact on the energy bill. Outside temperature affects consumption for heating and cooling of buildings, cooling loads of cold stores as well as the efficiency of equipments such as chillers, cooling towers and the temperature of "raw materials" such as water or air. Furthermore, humidity will influence, for example, the requirements of drying units, the load of environment control units or the frequency of defrosting in cold stores. The influence of weather is therefore particularly relevant in the food industry since most of the raw materials and products have to be maintained in a controlled atmosphere both in terms of temperature and humidity. When it comes to quantify the heating and/or cooling requirements of premises the temperature difference between the outside temperature and the room temperature may be used as an independent variable. This measure of the severity of a climate is referred to as degree day [°C · day].

4.2.1.1 Heating degree-days: definitions in different countries

Heating requirements will be characterized through heating degree days, which are usually defined by equation (4.11). It assumes a linear dependence with the temperature difference between the balance point temperature $T_{bal,h}$ and the mean outside temperature T_{mean}.

$$HDD(T_{mean}) = max[0,\ T_{bal,h} - T_{mean}] \tag{4.11}$$

The balance point temperature $T_{bal,h}$ is a constant that differs in the countries and can be adapted as stated in ASHRAE (2005). Typical value used in different countries are presented in table 4.1.

Table 4.1: Value of the balance point temperature $T_{bal,h}$ in different countries

Country	$T_{bal,h}$ [°**C**]
UK	15.5
US	18.3
France	16
Canada	18

In some countries such as Switzerland, heating degree day are computed as below (SIA, 1982):

$$HDD(T_{mean}) = \begin{cases} T_{room} - T_{mean} & \text{if } T_{mean} \leqslant T_{lim}; \\ 0 & \text{if } T_{mean} > T_{lim}. \end{cases} \tag{4.12}$$

T_{room} and T_{lim} are respectively the indoor temperature and the heating temperature limit. T_{lim} is considered to account for internal gains in the building. These temperatures are usually set respectively at 20°C and 12°C.

More complex formulations for degree days are available in the literature. Some of them not only consider the average temperature of one day but also the maximum and the minimum temperatures of the day (Matarakis and Balafoutis, 2004). This kind of formulations were not judged relevant for the applications considered in this work.

4.2.1.2 Cooling degree-days: definitions in different countries

Similarly to heating degree days, cooling degree days for a given day are defined as

$$CDD(T_{mean}) = max[0,\ T_{mean} - T_{bal,c}] \tag{4.13}$$

$T_{bal,c}$ is usually taken as 18°C according to ASHRAE (2005).

Heating or cooling degree days for a given period such a month are simply obtained by summing up the heating or cooling degree days of each day in the period. A method for approximating monthly heating degree days based on the monthly mean temperature is available in ASHRAE (2005). However, experience of the author shows that the accuracy of this method is in some cases lower than if equation (4.11) is used with the monthly average temperature and then multiplied by the number of days in the month. The reader is referred to appendix D.1 for more details on methods for approximating degree days.

4.3 Application example

4.3.1 Fuel consumption

For the sake of demonstration, the concepts presented have been applied in a food factory in Switzerland. The factory produces three main products ($n_p = 3$). The selected independent variables to estimate the monthly fuel consumptions y_i^f are the monthly production volumes $v_{i,p}$ (ton/month) of each product p together with the heating degree days computed with equation (4.12). The average ambient temperature of day i in month j ($T_{i,j}$) has been obtained from a meteorological station located nearby the factory. The database built up for this study covers a period of 36 months ($n_{month} = 36$) from January 2000 to December 2002. The resulting linear model is

$$y_i^f = \sum_{p=1}^{n_p} a_p^f \cdot v_{i,p} + h^f \sum_{j=1}^{n_{days_i}} HDD(T_{i,j}) + k^f \cdot n_{days_i} + \epsilon_i^f \tag{4.14}$$

where a_p^f (GJ/ton of product p) are the production regression coefficients, h^f (GJ/d/°C) is the degree days regression coefficient, k^f (GJ/d) is the base load regression coefficient, ϵ_i^f is the random error of month i and n_{days_i} is the number of days in month i. It has to be mentioned here that the monthly fuel consumptions used in the model do not correspond to the consumption recorded during a calendar month. Indeed, production volumes are available weekly and cannot be determined for a given month. As each month is composed of four or five weeks ($n_{days_i} = 28$ or 35 days), equation (4.14) has to be normalized by the number of days in the month in order to match the pattern of equation (4.1):

$$\frac{y_i^f}{n_{days_i}} = \frac{1}{n_{days_i}} \sum_{p=1}^{n_p} a_p^f \cdot v_{i,p} + \frac{1}{n_{days_i}} h^f \sum_{j=1}^{n_{days_i}} HDD(T_{i,j}) + k^f + \epsilon_i^{f*} \tag{4.15}$$

The coefficients obtained by the least square estimation are presented in table 4.2, together with the coefficient of determination R^2. This table highlights that the computed F-value (equation (4.7)) is higher than the table value (2.68) at 0.05 level of significance (or 0.95 of level of confidence) and (4,31) degrees of freedom. As a consequence, the null hypothesis (H_0) for the test on the significance of the model can be rejected. This result could have been expected given the high value of the coefficient of determination R^2 (equation (4.5)), which intervenes in the computation of the F-value. Regarding the validity of each of the coefficients of the model, the null hypothesis for coefficient a_3^f cannot be rejected because the computed t-value is lower than the table value of 1.96 at 0.05 level of significance and 31 degrees of freedom. This means that product 3 does not significantly affect the energy consumption. As a consequence, a model without the variable $v_{i,3}$ should be used for further analysis.

Table 4.2: Results of the regression for the monthly fuel consumption (T_{lim} = 12°C and T_{room} = 20°C)

Analysis of Variance

	DF	SS	MS	F value	Prob > F
Model	4	39500.9	9875.2	147.1	1.08E-19
Error	31	2080.7	67.1		
Total	35	41581.6			

R^2	0.950
$F_{0.95}[4;31]$	2.68
$t_{0.95}[31]$	1.96

Parameter estimates

	Unit	DF	Estimate	Std err.	t value	Prob > $\|t\|$
k^f	$[\frac{GJ}{d}]$	1	61.48	9.30	6.61	2.18E-07
a_1^f	$[\frac{GJ}{T}]$	1	1.56	0.44	3.57	0.0012
a_2^f	$[\frac{GJ}{T}]$	1	1.71	0.65	2.64	0.0129
a_3^f	$[\frac{GJ}{T}]$	1	-0.31	0.45	-0.68	0.4990
h^f	$[\frac{GJ}{°C \cdot d}]$	1	4.18	0.22	19.08	1.08E-18

DF: degrees of freedom, SS: sum of square, MS: mean square.

With the aim of improving the model, the sensitivity of the T_{lim} and T_{room} values in equation (4.12) has been studied. The resulting coefficients of determination are presented in table 4.3. All the 9 models in this table did satisfy the significance tests described above with 3 independent variables ($v_{i,1}$, $v_{i,2}$, HDD) except for the model with T_{lim}=14°C and T_{room}=22°C, in which the test on the significance of the coefficients showed that product 2 ($v_{i,2}$) also had to be excluded from the model. It can be seen that T_{room} has fewer impact on the coefficient of determination R^2 than T_{lim} and that shifting from T_{lim} =10°C to T_{lim}=8°C reduces significantly the regression quality. It should be mentioned that T_{lim} and T_{room} should have been taken into account in the optimisation calculation. However, as these values are related to a conditional equation, this would have made the optimisation problem more difficult to solve due to the discontinuities. According to the results of table 4.3, T_{lim} =10°C and T_{room} =22°C are the most appropriate values for computing heating degree days for this example. The estimates of the coefficients as well as the results of the tests obtained with these values can be found in table 4.4.

Table 4.3: Effect of T_{lim} and T_{room} on the coefficient of determination R^2

	T_{lim}=8°C	T_{lim}=10°C	T_{lim}=12°C	T_{lim}=14°C
T_{room}=22°C	0.932	0.954	0.946	0.932
T_{room}=20°C	0.930	0.953	0.949	0.944
T_{room}=18°C	0.923	0.950	0.950	0.947

Table 4.4: Results of the regression for the monthly fuel consumption(T_{lim}=10°C and T_{room}=22°C)

Analysis of Variance

	DF	SS	MS	F value	Prob > F
Model	3	39688.4	13229.5	223.61	1.54E-21
Error	32	1893.2	59.2		
Total	35	41581.6			

R^2	0.954
$F_{0.95}[3;32]$	2.90
$t_{0.95}[32]$	2.04

Parameter estimates

	Unit	DF	Estimate	Std err.	t value	Prob > $\|t\|$
k^f	$[\frac{GJ}{d}]$	1	56.68	6.59	8.59	8.02E-10
a_1^f	$[\frac{GJ}{T}]$	1	1.42	0.407	3.50	0.0014
a_2^f	$[\frac{GJ}{T}]$	1	2.46	0.594	4.14	0.0002
h^f	$[\frac{GJ}{°C \cdot d}]$	1	3.77	0.154	24.49	2.68E-22

DF: degrees of freedom, SS: sum of square, MS: mean square.

The model itself as well as all the coefficient being significant, the last test to be performed concerns the multicollinearity. The variance inflation factors computed according to equation (4.10) are presented in table 4.5. Since all of them are considerably below 5, multicollinearity is not an issue for this model.

The model being fully validated, the resulting estimated monthly fuel consumptions can

Table 4.5: VIFs for the monthly fuel model (table 4.4)

Variable	VIF
a_1^f	2.97
a_2^f	2.89
h^f	1.05

then be compared with the measured consumptions. This is illustrated in figure 4.2. The figure shows as well the contribution of the different independent variables on the overall fuel consumption over the period. As all the months do not have the same length, the base load computed according to equation (4.14) is not a constant as illustrated in the figure. It can be noticed that more than half of the fuel consumption (61%) is not directly correlated with the production and that the base load represents 39% of the consumption. This relatively high base load can be partially explained by the fact that the production takes place only 5 days a week, while some pieces of equipment are kept hot during the whole period. However, such base load stresses the need for changing operation practices during stand-by periods of the process.

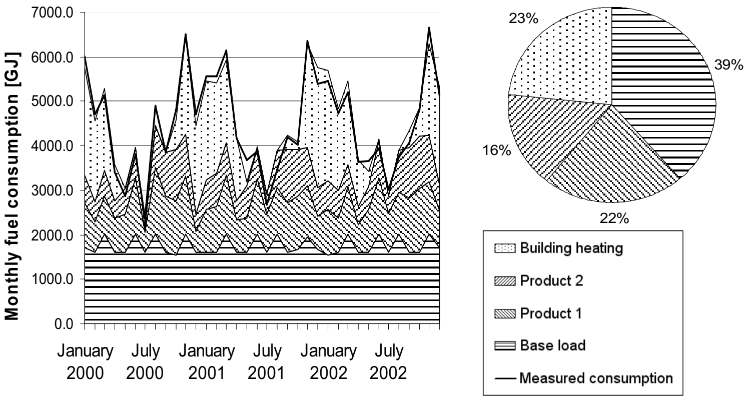


Figure 4.2: Comparison between monthly measured fuel consumption and estimation from the model, and contribution of independent variables.

4.3.2 Electrical consumption

A model similar to the one presented in equation (4.15) is used to estimate the monthly electricity consumption y_i^e:

$$\frac{y_i^e}{n_{days_i}} = \frac{1}{n_{days_i}} \sum_{p=1}^{n_p} a_p^e \cdot v_{i,p} + \frac{1}{n_{days_i}} h^e \sum_{j=1}^{n_{days_i}} CDD(T_{i,j}) + k^e + \epsilon_i^e \tag{4.16}$$

The independent variables are the same as for the fuel model except for the climate contribution, which is characterized by the cooling degree days ($CDD(T_{i,j})$) instead of the heating degree days. This is based on the fact that no electrical devices are used for heating during the heating period (winter). The cooling degree days have been computed according to equation (4.13) with T_{room} taken as 18°C. It has to be mentioned here that the electricity consumptions used in the model are not the ones available through the monthly bills (which cover the period from the first to the last day of a month), but from measurements taken daily in the factory.

Similarly to the fuel model, the tests for the significance of the model and of the coefficients as well as the test for multicollinearity has also been implemented in this case. The best result for the electricity model for the same period as the fuel model (January 2000 to December 2002) is presented in table 4.6. It can be again observed that product 3 ($v_{i,3}$) does not significantly influence the electricity bill. More surprisingly, the climate does not have an impact on the electricity consumption according to the model. This could have been explained by the value of T_{room} that has been used in equation (4.13). Indeed, as stated in ASHRAE (2005), this value is to be carefully chosen. However, the fact that the same result is observed with T_{room}=10°C, 12°C, 14°C, 16°C and 20°C leads to the rejection of this assumption. Table 4.6 also points out that the quality of the model, which has a coefficient of determination of 0.872, is lower than for the fuel model. Regarding multicollinearity, table 4.7 shows that, as for the fuel case, there is no correlation among the independent variables.

From the daily measurement made at the factory, it can be seen in figure 4.3 that the model predicts quite well the base load consumption. The black line on the figure represents the base load consumption as identified by the model (coefficient k^e) which has a value of 81.5 GJ/d or 22639 kWh/d. It predicts well the electricity consumption in non production periods (week-end and holidays). It has to be noticed that during some days in April and December, the consumption is lower than the base load. This can be explained by the fact that some of the equipments are switched off during these periods. The fact that the estimated coefficient for the base load has a physical meaning strengthen the relevance of the approach.

The monthly electricity consumption predicted by the model as well as the contribution of the independent variables is presented in figure 4.4, where it is compared to the measured value. It can be seen that the values obtained for November 2001 and November 2002 clearly under-predict the measured consumptions. The reasons for these gaps were not

Table 4.6: Results of the regression for the monthly electricity consumption

Analysis of Variance

	DF	SS	MS	F value	Prob > F
Model	2	13271.8	6635.9	112.63	1.804E-15
Error	33	1944.2	58.9		
Total	35	15216			

R^2	0.872
$F_{0.95}[2;33]$	3.28
$t_{0.95}[33]$	2.04

Parameter estimates

	Unit	DF	Estimate	Std err.	t value	Prob > $\|t\|$
k^e	$[\frac{GJ}{d}]$	1	81.50	5.96	13.69	3.7E-15
a_1^e	$[\frac{GJ}{T}]$	1	1.67	0.40	4.19	0.0002
a_2^e	$[\frac{GJ}{T}]$	1	3.03	0.59	5.12	1.308E-05

DF: degrees of freedom, SS: sum of square, MS: mean square.

Table 4.7: VIFs for the monthly electricity model (table 4.6)

Variable	VIF
a_1^e	2.88
a_2^e	2.88

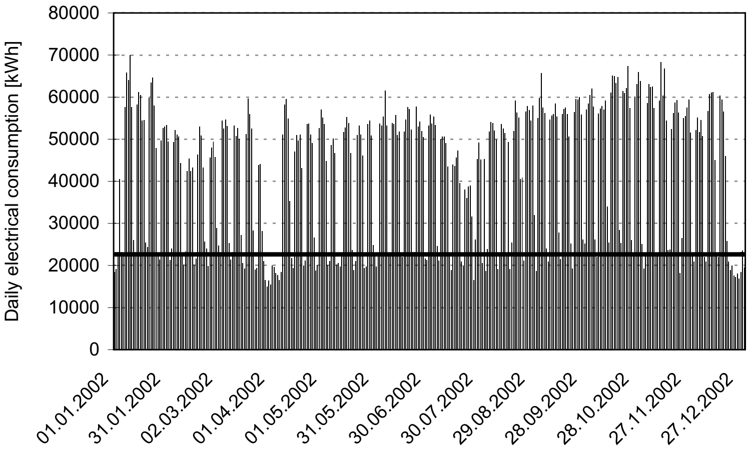


Figure 4.3: Measured base load consumption versus model prediction in 2002

clearly identified, but some assumptions have been formulated, such as the temporary change of process operation. Similarly to fuel consumption, it can be seen on the figure that the contribution of the base load in the total consumption is important. According to the model, it represents 55% of total electricity consumption. Clearly, it is one of the points to take into consideration when using the bottom-up approach to identify energy saving opportunities.

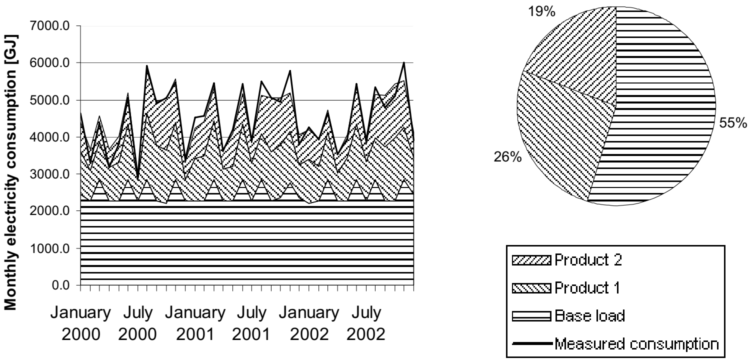


Figure 4.4: Comparison between monthly measured electricity consumption and estimation from the model, and contribution of independent variables

4.3.2.1 Breakdown of electricity consumption

Multi-linear regression can also be used inside the factory to correlate the consumption of converted energies, such as chilled water, with independent variables. The only requirement is to have a data record for that energy consumption. As an example, we have looked in more detail at the main refrigeration unit which is supposed to be an important consumer when referring to its installed power. The unit is a single stage NH_3 unit, with two screw compressors, that cools down a mixture of glycol and water from 6°C to 0°C. As a cold source, the unit uses river water, whose temperature is assumed to be constant. The objective is to model the electricity consumption of the chiller based on independent variables. Since the only data record on the refrigeration plant is the distributed energy through the chilled water, a procedure to link it to the electricity consumption of the chiller has been implemented. It is presented in figure 4.5.

In a first step, a steady-state thermodynamic model of the unit is developed. From the measurements of some operating conditions, the model allows for the identification of the

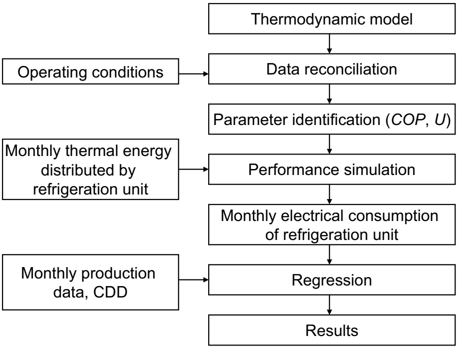


Figure 4.5: Procedure applied when using a thermodynamic model

simulation model parameters through a data reconciliation and parameter identification procedure. In the example, the more important parameter is the coefficient of performance (COP), which allows to link the thermal energy distributed at the condenser of the unit $\dot{Q}$ with the electricity consumed by the compressor $\dot{W}$ as shown in equation (4.17):

$$COP = \frac{\dot{Q}}{\dot{W}} \tag{4.17}$$

This parameter is highly influenced by the efficiency of the compressors which has also been identified. These parameters are presented in table 4.8 together with the condensing and evaporating temperatures. Since the condensing and evaporating pressures are maintained constant all over the year, the COP can be considered as constant in first approximation.

Table 4.8: Characteristics of the NH_3 refrigeration cycle as identified by data reconciliation

Condensing temperature	30.4°C
Evaporating temperature	-3.3°C
Isentropic efficiency of compressor	75.2 %
COP	5.1

Once the parameters of the model become known, it is possible to simulate the monthly electrical consumptions of the chiller from the data record of the distributed energies. From these simulations, it appears that this unit consumes 8.3% of the factory electricity. The monthly consumptions can then be used together with the independent variables (monthly production data, CDD) in a regression analysis to model the electricity consumption of the chiller.

This analysis has been performed on a smaller data set (12 months) that was available in the factory. The results (see table 4.9) show that the relevant variables are the products 2 ($v_{i,2}$) and 3 ($v_{i,3}$) as well as the CDD. The contribution of these different variables in the electricity consumption of the refrigeration cycle are 55.6%, 35.5% and 8.9% respectively. On the one hand, we can observe here that the refrigeration unit does not contribute significantly to the high base load that is observed for the electricity consumption (figure 4.4). On the other hand, the CDD seem to be relevant to model the electricity consumption of the chiller although they are not at the factory level (see table 4.6). This can be explained by the fact that the contribution of CDD is low in the consumption of the chiller (8.9%). As a consequence, they become negligible at the factory level. Indeed, their contribution to the factory consumption is $8.9\% \cdot 8.3\% = 0.7\%$.

Table 4.9: Results of the regression for the refrigeration cycle

Analysis of Variance

	DF	SS	MS	F value	Prob > F
Model	3	1262.9	421.0	236.5	3.78E-08
Error	8	14.2	1.78		
Total	11	1277.1			

R^2	0.989
$F_{0.95}[2;8]$	4.46
$t_{0.95}[8]$	2.31

Parameter estimates

	Unit	DF	Estimate	Std err.	t value	Prob > $\|t\|$
a_2^r	$[\frac{GJ}{T}]$	1	0.56	0.084	6.67	0.00016
a_3^r	$[\frac{GJ}{T}]$	1	0.36	0.090	3.95	0.00422
h^r	$[\frac{GJ}{°C \cdot d}]$	1	1.39	0.309	4.49	0.00202

DF: degrees of freedom, SS: sum of square, MS: mean square.

4.3.3 Weekly regressions

The same modeling approach can be used on a weekly basis provided that the needed data (energy consumption, production volumes, outside temperatures) are available with this frequency. This has been done in the factory under study for the same period as for monthly data (January 2000 to December 2002), representing 159 weeks. The equations used to model the fuel y_i^{fw} and electricity consumption y_i^{ew} are:

$$y_i^{fw} = \sum_{p=1}^{n_p} a_p^{fw} \cdot v_{i,p} + h^{fw} \sum_{j=1}^{n_{days_i}} HDD(T_{i,j}) + k^{fw} + \epsilon_i^{fw} \tag{4.18}$$

$$y_i^{ew} = \sum_{p=1}^{n_p} a_p^{ew} \cdot v_{i,p} + h^{ew} \sum_{j=1}^{n_{days_i}} HDD(T_{i,j}) + k^{ew} + \epsilon_i^{ew} \tag{4.19}$$

It has to be noticed in these two equations that each period has the same length (seven days). Consequently, the base load coefficients k^{fw} and k^{ew} do not need to be normalized as done for the monthly models (see equations (4.14) and (4.16)). The results for these two regressions are presented in appendix E. It can be observed in tables E.1 and E.2 that the models for the electricity and the fuel were the same as for the monthly models, i. e. the same independent variables are rejected after the tests of the coefficients. The estimated coefficient are very similar to the monthly models except for product 2 where an important deviation is observed. The coefficients of determination obtained are lower than for the monthly modeling (0.86 for the fuel model and 0.65 for the electricity model). This can be explained by the fact that the data are less accurate[1]. These inaccuracies are particularly evident for the period of December 2000 for instance. In July 2000, the production stopped for 3 weeks. It can be clearly seen on figure E.1 that some pieces of equipment were turned off since the measured consumption is less than the base load identified.

4.4 Systematic selection of relevant independent variables

As we have seen above, all the independent variables selected by the user to estimate a dependent variable have not a significant impact. Although adding variables to a model might increase its precision, the cost of obtaining and maintaining information is high. As a consequence, an algorithm is to be used to keep only the statistically significant terms in the model. A wide range of method are available in literature to tackle this problem (Draper and Smith, 1998). These different techniques applied to the same problem will not always lead to the same result although they would in many case. A popular strategy is the so

[1]The sum of the data for four or five weeks should have coincided with the monthly data used in the monthly models. However, this was not always the case

called "stepwise regression procedure". In that algorithm, the most statistically significant term is added at each step of the method after comparing its t statistic with a given *t-enter* value. When a variable is added to the model, the smallest t statistic of all the variables of the model is tested against a *t-remove* value to determine if it has to be removed from the model. Such a procedure to select the best regression from a set of independent variables is available in computing software such as Matlab (e.g. *stepwisefit.m* function).

4.5 Conclusion

In the proposed methodology, the top-down approach implemented using the factory model described in Chapter 2 is aimed at allocating the costs among the production units and at guiding the next step of the method: the bottom-up approach (see Chapter 5). This chapter has demonstrated that the use of multi-linear regressions can effectively support the definition of the factory model through the interpretation of the coefficients of the independent variables. These coefficients highlight the main variables (climate, volume of production) affecting the consumption of a given energy. In that sense, they should point out areas where the modeling effort should be focused using for example punctual measurements. This chapter also introduces tests used to validate the "statistical" significance of the model developed as well as the individual significance of each independent variable included in the model. A test demonstrating that there is no correlation among independent variables has also been presented.

In the example considered in this chapter, the developed multi-linear regressions show that 61% of the fuel consumption and 55% of the electricity consumption do not correlate with production volumes. In the fuel case, the base load explains approximately two third of this consumption while the last third is due to building heating. As regards electricity, the 55% identified is due to the base load consumption since the effect of the climate on the consumption is insignificant according to the model. Tackling these high base load consumptions is especially important for production sites with low volumes of output since fixed cost absorption is limited, which makes it harder for these sites to remain competitive compared to other production sites. The prospects of loosing further production volumes will result in a vicious circle, which will increase the specific cost of output units.

Compared to similar analyses (Bieler et al., 2003), the use of linear regression models appears to be more appropriate in the present context than in other processes, such as chemical batch plants. This can be explained by the fact that the product mix does not vary as much as in multi-products and multipurpose chemical batch plants. The main advantages of multi-linear regressions in the context of cost allocation are their simplicity and the little effort that is needed to put them in place provided that data history is available. They also permit to highlight the base load of the energy consumptions, which is not possible with the factory model described in Chapter 2. The models developed in this chapter have also been used for consumption forecasting and budgeting exercises. They have allowed for the detection of errors in the production volume records. They can also be easily used for targeting-monitoring in order to detect deviations in the process efficiency.

Chapter 5

Bottom-up approach

5.1 Introduction

The top-down approach supported with statistical tools allows for the identification of the main energy drivers in a factory, mainly through the analysis of the energy conversion units and of the distributed energies (see Chapter 2, 3 and 4). Such an analysis helps identifying inefficiencies in the energy conversion units but does not allow for the identification of energy saving opportunities in the process. Energy savings in the process will result from the implementation of good-housekeeping measures and best practices (fixing steam and air leakages, insulating steam pipes, turning off unnecessary units, etc), as well as of efficient technologies (e.g. efficient lighting and motors), an improved automation of the process, etc. These techniques have demonstrated their relevance in many case studies and the related documentation is largely available on the Internet or in books. However, further savings can be achieved by better analyzing the requirements of the process unit operations (using exergy concepts for instance) and analyzing their possible optimal integration. Another approach, called bottom-up, is used for that purpose. Referring to the figure 2.1, the objective of the bottom-up approach is to maximize the horizontal flows while minimizing the vertical ones, minimizing therefore both the energy bill of the process and the environmental impact. This technique is widely used in the chemical process modeling community and offers an excellent basis for pinch analysis (Marechal et al., 1997) given the large amount of information made available by the process models. If applied on all the units of a factory, the global consumption of the utilities can be obtained by aggregation of the individual consumptions of the units. Then, based on the analysis of the energy conversion units, the purchased energy consumptions and, consequently, the bills can be recomputed. In cases where measurements are lacking, the bottom-up approach will even be applied in parallel to the top-down approach helping to identify the main energy drivers by determining theoretically the energy consumption of large units.

5.2 Defining the process requirements

The first step of the bottom-up approach aims at defining the requirements of the main process unit operations (PUO) identified through the top-down approach. For this purpose, a Block Flow Diagram (BFD) is established describing the recipes of the different products manufactured. Referring to the figure 2.1, the block flow diagram describes the necessary process unit operations to transform raw materials into products (horizontal transformation). The BFD also includes the enabling operations, such as logistics (e.g. packaging, storage), cleaning (e.g. bottle washing), atmosphere control and waste treatment. Considering the different types of utility streams it consumes, each block of the BFD can be described according to its function in the production. We consider, for example, the heating and cooling requirements, the water requirements and the electricity requirements among others. When analyzing the process requirements, it is important to bear in mind the system representation of figure 2.1 since it includes the definition of the first principle of thermodynamics, which states that the resources and raw materials entering the system will leave the system either as useful material and energy in the product streams or as waste streams either as heat losses or as hot gases, solid wastes or hot water wastes. From this analysis, each stream leaving the system should be as close as possible (equilibrium) to the ambient conditions. Therefore, when analyzing the transformations in the processes, it is important to define the possible recovery that could result from streams leaving the system at a state with a remaining energetic value.

5.2.1 Triple representation

Thermal energy requirements of a process (***thermodynamic requirements***) are typically fulfilled by a utility stream (***utility requirements***). These two representations of the same operation involve the same amount of energy (assuming there is no heat losses) but present a difference as regards exergy since their temperature profiles are different. This dual representation was introduced by Brown et al. (2005) in the study of a pulp and paper mill. In many industrial applications, including the food industry, an equipment is often used at the interface between the process and the utility to convert the energy supplied by the utility (distributed energy) into useful energy for the process. This leads to a third representation of a process requirement that we call ***technological requirements***. In the food industry, this third representation typically takes the form of hot or cold water loops. This extension of the dual representation, described in detail in Ruiz (2006), is defined as the triple representation (thermodynamic, technological and utility representations) of a process requirement (thermodynamic, technological and utility requirements).

An illustration of the triple representation is shown on the left-hand side of figure 5.1. The thermodynamic requirement of a given process (in this example the vaporization of a process stream) is characterized in terms of energy requirement and temperature level in a temperature-enthalpy diagram. Generally, the temperature levels are known since they are often critical parameters to be controlled to ensure a good quality of the product while the energy requirements are usually determined by measurement of either the consumption of utility or of the technological requirement. Finally, the utility consumption can be easily linked to the purchased energy consumption by studying the energy conversion units. In the example of figure 5.1, this is represented by the boiler fumes that are proportional to the fuel consumption. This figure emphasizes that in many industrial processes high-quality energy (such has the energy contained in the boiler fumes) is often used for low temperature demands on the process side, resulting in a downgrading of the energy quality (exergy losses). The exergy losses are better quantified by replacing the temperature axis of the temperature-enthalpy diagram with the Carnot factor $(1 - \frac{T_a}{T})$. The exergy delivered then corresponds to the area between the composite curve and the enthalpy axis. Consequently, the exergy loss through heat exchange is given by the difference between the area of the hot stream and the area of the cold stream exchanging heat. The exergy losses resulting from the heat exchange between the boiler fumes and the utility ("conversion exergy losses"), between the utility and the technological requirement ("distribution exergy losses") and between the technological and the thermodynamic requirement ("technology exergy losses") are shown on the right-hand side of figure 5.1.

This figure clearly emphasizes that even if the process requirement seems to be fulfilled with a 100% efficiency in terms of energy, as shown in the left-hand side of the figure (assuming there is not heat losses in the exchange between the different requirements), the right-hand side shows a poor second-law efficiency (or high exergy losses) meaning that improvements can be achieved by the introduction of technologies, such as CHP or heat pumps, which provide heat at a lower temperature level. This will be discussed in more detail in section 5.4.6.

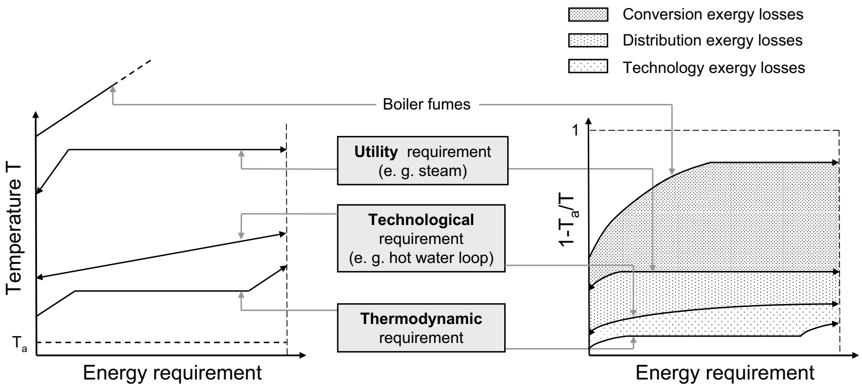


Figure 5.1: Triple representation of a process requirement

5.2.2 Validating steam consumption using the utility representation

We have mentioned earlier that the bottom-up approach can be applied locally to analyse a given PUO or globally to recompute the global consumption of a utility for all the PUOs of a factory over a given period (a month, a year). In this case, the consumption of a utility for the whole site is obtained by aggregating the individual utility requirements of the different PUOs in the sub-periods (days, weeks) constituting the period. Mathematically, this can be expressed as:

$$U_m = \sum_{t=1}^{n_t} \sum_{i=1}^{n} u_{m,i} \cdot T_{i,t} \tag{5.1}$$

where U_m is the consumption of the utility m during the period considered, $u_{m,i}$ is the nominal consumption of utility m in unit i, and $T_{i,t}$ are the running hours of unit i during the sub-period t, n is the number of units considered and n_t is the number of sub-periods (days, weeks, etc) in the period.

This global bottom-up modeling approach has been applied in the same factory as the one taken as an example in Chapter 4. Although such an analysis is often not justified in real energy management exercise due to the time-consuming effort required to collect all the necessary data, it has been carried out here in order to validate the relevance of the 80/20 rule introduced in the factory model. In the factory under study, 155 PUOs have been identified and four utilities have been considered (steam, chilled water, water and electricity). The collection of data for the determination of the utility representation, technological representation and thermodynamic representation has required an engineer at full-time for 3 months. The results obtained for the bottom-up modeling of the annual steam consumption are presented here while those of the other utilities can be found in Ruiz (2006). The sub-period considered is the week as records of running hours of the PUOs are available with this frequency in the production department. Figure 5.2 presents the results obtained through bottom-up modeling for the fuel consumption resulting from the steam consumption in 2005. The conversion from steam to fuel assumes an average efficiency of 83.6% for the boilers. The results are compared with the weekly measurements available in the factory.

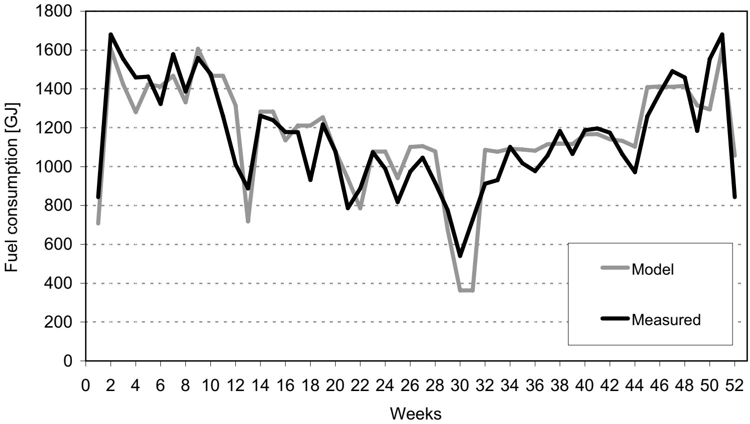


Figure 5.2: Weekly fuel consumption obtained through bottom-up modeling of the steam utility in 2005

It would be interesting to compare the results obtained with the ones resulting from the weekly top-down model presented in figure E.1 (see appendix E). However, the latter are only available for a period ranging from January 2000 to December 2002, which renders the direct comparison impossible. In addition, the production volumes for the three main types of products were not available to the author for the year 2005, making it impossible to compute values for 2005 with the weekly top-down model. Consequently, the comparison of the bottom-up and top-down models has been performed by computing the ratio of the residual sum of squares SS_R to the total sum of square SS_T (see definition in section 4.1). The definitions of SS_R is:

$$SS_R = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{5.2}$$

where y_i is the observed value for the sub-period i and $\hat{y}_i$ is the value estimated by the model for the same sub-period. In the case of models obtained through least square fitting (see Chapter 4), the following additional relationship links SS_T with SS_E and SS_R:

$$SS_T = SS_E + SS_R \tag{5.3}$$

Based on equation (4.5), the computed ratio is related to the coefficient of determination R^2 by the following relationship for least square models:

$$\frac{SS_R}{SS_T} = 1 - R^2 \tag{5.4}$$

The results of the comparison are presented in table 5.1. For the top-down modeling approach, both the monthly and the weekly models are presented. We can observe that the results obtained with the bottom-up modeling are less accurate than those of the top-down modeling. However, due to the large number of parameters in the model (running hours of 155 units for 52 weeks and utility consumption of 155 units), the results of the bottom-up modeling can be considered as very satisfying. Indeed, the same models applied to other utilities that are less documented in the factory lead to much less accurate results (see Ruiz (2006) for more details).

Table 5.1: Comparison between the top-down and the bottom-up modeling approaches for fuel consumption

	Top-down modeling		**Bottom-up modeling**
	Monthly	**Weekly**	**Weekly**
Nr of observations	36	159	52
SS_E	39’688	11’204’970	5’593’719
SS_R	1893	1’816’838	895’623
SS_T	41’581	13’021’808	3’616’251
SS_R/SS_T	4.55%	13.95%	24.77%

5.3 80/20 rule: increasing the efficiency of the data gathering process

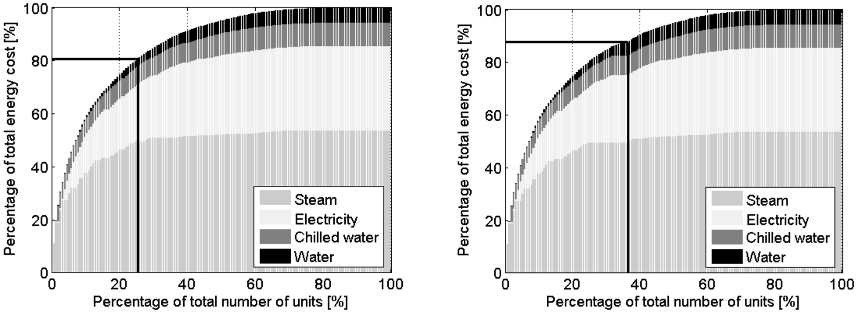
Obtaining and maintaining information has a high cost. Thus, collecting data has to be kept to the minimum for cost-efficiency reasons. However, we have also seen that the top-down approach is not sufficient on itself for identifying energy saving actions. The triple representation introduced in section 5.2.1 as a base of the bottom-up approach is, consequently, a necessary but resource-consuming step. In an industrial context, the cost of collecting the data for the triple representation is too high to be applied globally to a site. Intuitively, we know that many small energy consumers have a limited energy saving potential and are not worth being studied. As a consequence, the application of the triple representation has to be limited to a given number of relevant PUOs. In that context, rules of the thumb such as the 80/20 rule (Ho, 1994) should be kept in mind during the application of the bottom-up approach. In the context of energy management, this rule can be read as: 80% of the energy consumption results from only 20% of the PUOs of a factory. As mentioned in section 5.2.2, the triple representation has been applied to the entire factory under study for the sake of demonstration. Based on this information, the 80/20 rule has been applied at two levels for the utility representation:

- A first level aims at targeting a reduced set of PUOs that explains 80% of the modeled energy bill[1].
- A second level aims at targeting a reduced set of PUOs that explains, in addition, 80% of the consumption of each utility.

One could argue that the first level is sufficient. However, to be sure to include streams that are significant not from a financial perspective but from an energy management one, the second level has been introduced. The results of this analysis are presented in figure 5.3.

Figure 5.3(a) highlights that 25.2% of the PUOs (39 out of 155 units) accounts for 80.5% of the modeled energy bill (total consumption of steam, water, chilled water and part of the total electrical consumption). The slope of the curve after the 39th PUO clearly shows how the last percents of the energy bills are costly to obtain. Ensuring that 80% of the consumption of each utility (except electricity) is explained, implies to consider a subset of 56 PUOs (36.1% of the total) as illustrated in figure 5.3(b). Characterizing the utility usage of this subset of units explains 87% of the modeled energy bill.

[1]We focused here in the modeling of the thermal requirement of the PUOs. Consequently, only the electricity consumption that was somehow linked to thermal requirements was modeled. The global electricity bill is therefore not explained



(a) Targeting 80% of the energy bill modeled

(b) Targeting 80% of the consumption of each utility

Figure 5.3: Demonstration of the 80/20 rule in the factory under study

If we have demonstrated with this example the relevance of the 80/20 rule in the context of energy management, one should keep in mind that applying the rule in an unknown case will lead to some additional work. This is due to the fact that the biggest consumers are unknown a priori and that intuition can set the focus on PUOs that will appear to be of secondary importance after the study. This will nevertheless result in an increased knowledge of the factory.

5.4 Process integration

In addition to the analysis of the energy usage in PUOs, the triple representation is also relevant to identify heat recovery potentials among PUOs through process integration. Process integration is a well established method in the pulp and paper industry (Brown et al., 2005; Noel and Boisvert, 1998; Soderman J. and Pettersson, 1999; Wising et al., 2005) and the chemical industry (Wang et al., 2003; Ebrahim and Kawari, 2000) where it takes its roots. In the food industry, most of the studies available in literature have focussed on a limited range of products such as meat processing (Fritzson and Berntsson, 2006; Dalsgard et al., 2000) and sugar processing (Urbaniec et al., 2000). In the latter industry, pinch technology is often used locally on specific energy-intensive units, such as evaporators.

In conventional process integration approaches, as applied in the chemical industry, the focus is on the process (thermodynamic representation). Consequently, the integration potential of the utilities is usually disregarded. Energy and water flows are considered as inputs of the process, sometimes with a cost that is a function of its quality (temperature). Particularly in the food industry, numerous opportunities result from the appropriate integration of the utilities with the processes taking place at a limited temperature level. This offers opportunities for integrating combined heat and power production or heat pumping. Another characteristic of the food industry is the importance of the energy consumption of heating ventilation and of the cooling of production buildings and offices. This is particularly relevant in production plants that do not operate on a permanent basis.

Clément (1992) highlighted the difficulties encountered when applying process integration in a chocolate factory. They include the fact that streams are not always in pipes, the presence of a large number of small streams and the seasonal aspects leading to discontinuous processes. In an application in a brewery, Krummenacher (2002) also faced the problem of the large number of small streams. In addition to these elements, another frequent barrier to implementing process integration is the complexity this method introduces in the process, which is in contradiction with the flexibility and the simplicity desired by production managers. Based on the experience acquired in the food industry, Dalsgard et al. (2002) recommend four steps to simplify the process integration problem and to overcome some of the previously mentioned barriers:

- **Step 1**: The problem is divided into possible sub-problems on the basis of location, temperature and/or time.
- **Step 2**: The effort of recovering heat is firstly focused on the production of hot water.
- **Step 3**: The unimportant streams are discarded.
- **Step 4**: Basic network configuration and initial economic optimization.

The triple representation as well as the 80/20 rule have been introduced in this context of simplification. The triple representation allows for an increased flexibility during the process integration since the study can be performed on the technological representation and not necessarily on the process (thermodynamic representation), as usually done in the chemical industry. Indeed, an important share of the streams of the technological representation are water streams that can exchange heat much more easily than process streams. The 80/20 rule is an efficient means of discarding small streams and thus dramatically reducing the size of the problem.

5.4.1 Applying the triple representation for process integration

In section 5.2.1, the triple representation has been introduced for the modeling of the process requirements. One of the advantages of the triple representation is to have three different perspectives of energy usage in the factory, which results in three different process integration problems. Figure 5.1 has been used to present the concept of the triple representation. In this figure, it is assumed that there is no energy losses among the different representations since each of them has the same energy requirement. This case applies when the technological representation consists of a hot or cold loop. Even if this configuration is often encountered in the food industry, alternative configurations, such as the one represented in figure 5.4, are also possible. In this case, the intermediary fluid T of the technological representation needs to be brought from the ambient temperature (T_a) to the required inlet conditions ($T_{tech,in}$) to fulfill the process requirement P (thermodynamic requirement). The corresponding energy is denoted $\dot{Q}_{technological}$. The thermodynamic requirement (energy $\dot{Q}_{thermodynamic}$ between temperatures $T_{therm,in}$ and $T_{therm,out}$) is then fulfilled by cooling the fluid T down to the temperature $T_{tech,out}$. The further cooling of the stream down to the initial temperature T_a is referred to as the **technology recovery representation** R. Part of the recovery (from a temperature $T_a + \Delta T_{min}$ to the ambient temperature T_a) is considered as a loss L resulting from the hypothesis of the minimum approach temperature ΔT_{min} in heat exchangers. Consequently, we have the following relationship between the different representations:

$$\dot{Q}_{themodynamic} = \dot{Q}_{technological} - \dot{Q}_{recovery} - \dot{Q}_{losses} = \dot{Q}_{utility} - \dot{Q}_{recovery} - \dot{Q}_{losses} \tag{5.5}$$

In the simpler case of figure 5.1 ($\dot{Q}_{recovery} = \dot{Q}_{losses} = 0$), this expression is reduced to

$$\dot{Q}_{themodynamic} = \dot{Q}_{technological} = \dot{Q}_{utility} \tag{5.6}$$

It might happen that one of the representations is too difficult to obtain for a given PUO or is simply not available. For instance, when a thermodynamic requirement is fulfilled directly by the utility representation, there is no technological requirement. In the case where one of the representations is missing, the following rules are applied when defining the process integration problem:

- **Thermodynamic representation:** the thermodynamic requirement is used. If the thermodynamic requirement P is not available, the technological requirement T is used instead, together with the technology recovery representation R. If T and R are not available for this unit, the unit is discarded from the problem.
- **Technological representation:** the technological requirement T is used with the technology recovery representation R. If T and R are not available for this unit, the thermodynamic requirement P is used.

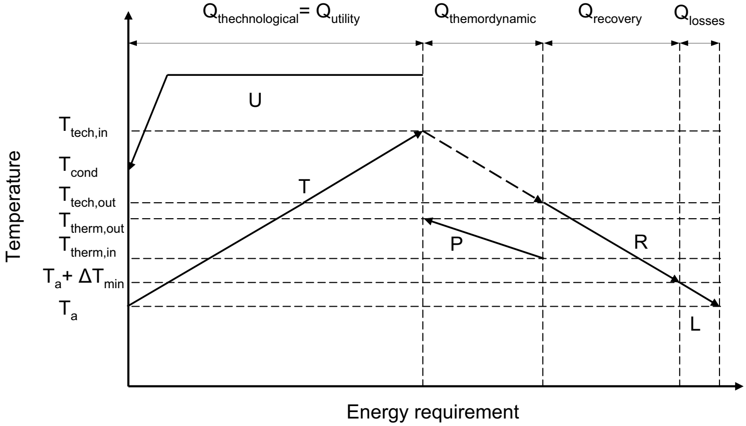


Figure 5.4: Definition of a process requirement with heat recovery

- **Technological representation:** the utility requirement U is used with the technology recovery representation R.

5.4.2 Dealing with multi-period problems

One of the difficulties of the process integration study that has not been tackled yet in this work is the discontinuous and seasonal pattern inherent in most of the food processes. This aspect is illustrated in figure 5.2, where the effect of climate variation and changes in the production volumes on fuel consumption are clearly visible. Rigourously, the modeling should take into account daily or even hourly variations. However, in practice, this would require the gathering of a large amount of data, which is not always available in factories, or would result too difficult and time consuming. In addition, the resulting problem would involve a prohibitive number of decision variables when solving the process integration problem. Consequently, in this work, a methodology developed in Ruiz (2006) has been used for selecting a set (six in this case) of relevant periods, which will represent the operation during the whole year. The selection of these periods is based on the weekly data used for the bottom-up modeling. The data needed includes the running hours of each PUO for each week of the year, the nominal utility consumption of each PUO as well as the costs of the utilities. As heat storage between periods is not considered in the process integration, the time sequence of the weeks is not important. This offers the possibility to group similar weeks and to represent them using a reference week for the group. The operating conditions

for a given group of weeks are thus defined by a reference week and by an operating time obtained by multiplying the number of weeks in the period by the number of hours in a week. The methodology adopted for grouping the weeks as well as selecting a reference week for each group of weeks is briefly presented here. The selection process starts by comparing the energy cost of each PUO for each week with the equivalent cost of an arbitrarily chosen week of the year. For each week, the sum of the cost differences between these two weeks and its relative error with respect to the total cost is computed. If the relative error for a week is inferior to a given threshold set when starting the selection, the arbitrarily chosen week is said to be representative of the considered week. This procedure is repeated until each week of the year has been chosen as the "arbitrarily chosen" week. Consequently, each week in the year can be considered as representative of a variable number of other weeks. We will refer to this number of weeks as the *efficiency*. The week with the highest efficiency together with all the weeks it represents are chosen for a second selection process, which will determine which week will represent this sub-set of weeks as the reference week of the period. This second selection is similar to the first one but, in this case, the sum of the square of the differences is computed for each week. The week that minimizes the sum of the square difference of each week is selected as the reference week. Then, the subset of weeks represented by this period is removed from the total set of week and the procedure continues until reaching the number of periods desired.
The six periods identified (reference weeks) in the factory under study as well as the number of weeks and hours that they cover are presented in table 5.2. It can be observed that periods 2 and 3 cover nearly 70% of the year.

Table 5.2: Periods selected to model the yearly operation of the factory

Period	**Reference week**	**Number of Weeks included in the period**	**Duration (t_p) [Hours]**
1	22	5	840
2	34	23	3864
3	6	13	2184
4	50	3	504
5	30	2	336
6	16	6	1008
Total		52	8736

Figure 5.5 compares the weekly fuel consumption modeled using the six periods with the measured consumption. The consumption obtained with the bottom-up modeling approach (see figure 5.2) is also represented in this figure and referred to as "weekly model". This figure shows that an intelligent selection of the periods substantially simplify the size of the problem while guaranteeing a satisfactory modeling of the consumption. Table 5.3 extends the comparison to the industrial water and chilled water. As steam (and therefore fuel) is the

best monitored utility in the factory, it is, not surprisingly, the utility that is best modeled. For chilled water and industrial water, the results of the models can be considered as good since very few data is available for these utilities in the factory. It is also interesting to notice for these two utilities that the models based on the six periods give a better estimate of the yearly consumption than models based on the effective running hours of the units for each week.

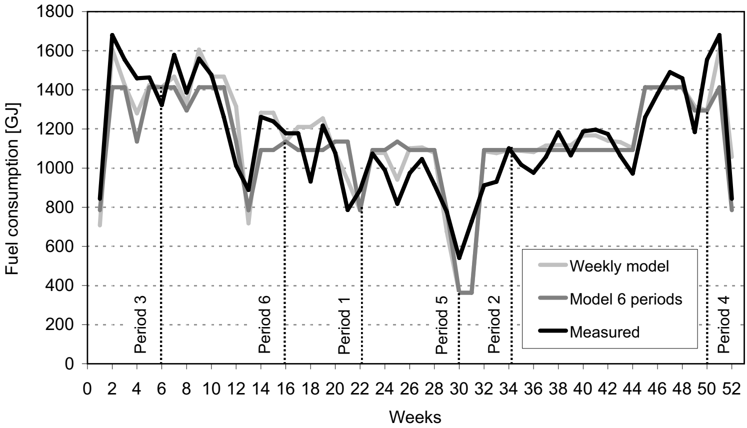


Figure 5.5: Weekly fuel consumption obtained when considering only six periods

Table 5.3: Effect of the introduction of 6 periods on the modeling of the utilities in 2005

Utility	**Unit**	**Measured**	**Weekly model**		**Model 6 periods**	
Fuel	[GJ/y]	59'790	60'599	1.4%	58'837	-1.6%
Ind. water	[m^3/y]	1'278'694	1'100'362	-13.9%	1'157'168	-9.5%
Ch. water	[GJ/y]	19'018	17'454	-8.2%	18'251	-4.0%

Based on the running hours of the reference week of each period p, the level of operation that will be considered in the process integration study ($L_{i,p}$) for each PUO i is obtained by dividing the running hours of the PUO during the reference week by the total number of hours in a week. The heat load of the hot and cold streams that will be taken into account for a given PUO in a given period is then obtained by multiplying the nominal heat load of these streams by the level of operation previously defined (a figure between 0 and 1).

5.4.3 Applying the 80/20 rule for process integration

In section 5.3, it has been shown that by focusing on 56 units out of a total of 155, it was possible to explain 80% of the modeled energy bill and 80% of the consumption of each utility (except electricity). In order to limit the complexity of the process integration problem, the latter should be limited to this subset of units. However, when it comes to integrating the utilities, the total energy requirements should be considered to allow the comparison of the results with the present situation. The solution adopted to address this problem consists of modeling the requirements of the 99 PUOs not considered by the 80/20 rule with the different utility representations. For each period p represented by its reference week, the consumption of the non-modeled PUOs $\dot{U}^{20}_{p,k}$ for the utility k is computed as:

$$\dot{U}^{20}_{p,k} = (U_{p,k} - \sum_{i=1}^{n_{80}} u^{80}_{i,p,k} \cdot T^{80}_{i,p}) \quad \text{for} \quad p = 1, ..., n_p \quad \text{and} \quad k = 1, ..., n_u \tag{5.7}$$

where $U_{p,k}$ is the measured consumption of utility k in the reference week of period p, $u^{80}_{i,p,k}$ is the nominal consumption of utility k in the PUO i during the reference week of period p, $T^{80}_{i,p}$ are the running hours of PUO i during the reference week of period p, n_{80} is the number of units modeled after applying the 80/20 rule, n_u is the number of utilities modeled and n_p is the number of periods.

5.4.4 Minimum energy requirements (MER)

The definition of the hot and cold streams of the different PUOs as well as of the non-modeled PUOs for the three representations allows us to define for each representation two enthalpy-temperature profiles referred to as the hot and cold composite curves. These curves can be seen as hot and cold streams that can exchange heat using counter-current heat exchangers. Assuming a minimum approach temperature (ΔT_{min}) and that all feasible heat exchanges may be envisaged, the maximum heat recovery possible is obtained by shifting the cold composite curve horizontally until the smallest vertical distance between the two composite curves reaches the ΔT_{min} value. This point, located where the heat transfer is most difficult, is referred to as the pinch point. Mathematically, the location of the pinch point is determined by introducing corrected temperatures for each stream that constitutes the hot and cold composite curves. These temperatures are obtained by reducing the initial and target temperatures of the hot streams by $\frac{\Delta T_{min}}{2}$ and by increasing the same temperatures of the cold streams by $\frac{\Delta T_{min}}{2}$ as shown in equations (5.8) and (5.9).

$$T_h^* = T_h - \frac{\Delta T_{min}}{2} \quad \forall h \in \{hot\, streams\} \tag{5.8}$$
$$T_c^* = T_c + \frac{\Delta T_{min}}{2} \quad \forall c \in \{cold\, streams\} \tag{5.9}$$

In corrected temperatures, the two composite curves touch each other at the pinch point temperature. The overlapping of the two composite curves defines the heat recovery achievable, as illustrated in figure 5.6. By heat balance, defining the maximum heat recovery allows to compute the minimum energy requirements (MER) of the system. As illustrated in figure 5.6, the hot MER ($\dot{Q}^+$) is the additional heat to be supplied to the system in order to balance the cold stream requirements. The cold MER ($\dot{Q}^-$) is the heat to be withdrawn from the hot streams that cannot be used to preheat the cold streams. The composite curves (CC) obtained for each representation and for each period are presented in appendix F (see figures F.1, F.2 and F.3). Particularly, we can notice in figure F.2 and F.3 the use of the utility representation to model the units that have been discarded when applying the 80/20 rule. For instance, the flat profile at a temperature of approximately 460 K (except for period 3) corresponds to the equivalent steam demand of these units.

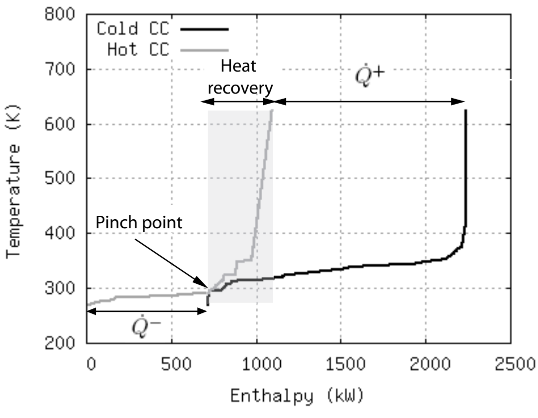


Figure 5.6: Hot and cold composite curves for the thermodynamic representation during period 3

The corrected temperatures define an ordered list of $n_r + 1$ increasing temperatures. A temperature interval r is defined by two successive temperatures : from T_r^* to T_{r+1}^*. Considering R_r, the heat cascaded from the system at a temperature higher than T_r, the energy balance may be written for each temperature interval. The heat cascade model (equation

(5.10)) defines the minimum energy required $\dot{Q}^+ = R_{n_r+1}$ to balance the needs of the cold streams when recovering the maximum energy from the hot streams by counter-current heat exchange and cascading the heat excess to the lower temperatures.

$$\min_{R_r} \dot{Q}^+ \tag{5.10}$$

subject to heat balance of the temperature intervals:

$$\begin{aligned} R_r = & R_{r+1} \\ & + \sum_{h_r \in \{\text{hot streams in interval } r\}} \dot{M}_{h_r} c_{p_{h_r}} (T^*_{r+1} - T^*_r) \\ & - \sum_{c_r \in \{\text{cold streams in interval } r\}} \dot{M}_{c_r} c_{p_{c_r}} (T^*_{r+1} - T^*_r) \end{aligned} \quad \forall\ r = 1, ..., n_r \tag{5.11}$$

and the heat cascade feasibility

$$R_r \geq 0 \quad \forall r = 1, ..., n_r + 1 \tag{5.12}$$

Finally, the heat cascaded from the last temperature interval R_1 corresponds to the heat to be withdrawn from the system using a cold utility ($\dot{Q}^-$). The corrected temperature at which $R_r = 0$ is the pinch point temperature.

Table 5.4 presents the total annual energy of the cold and hot streams (enthalpy changes in the hot and cold composite curves),the annual hot and cold MER and the annual heat recovery potential for the three representations. The annual values are simply obtained by multiplying the value observed in each period by the operation time of the period t_p which is available in table 5.2. The difference in energy observed between the hot and cold streams is mainly due to one PUO, where heat resulting from a mechanical work in the unit has to be removed. Table 5.4 highlights the limited potential for heat recovery in the utility representation. This can be clearly seen in picture F.1 where the overlapping of the hot and cold composites is small for the 6 periods. The table also gives the pinch point location for the three representations. While the pinch points occur always at the same temperature for the utility representation, its location slightly varies from one period to the other in the technological and thermodynamic representations. For these two representation, it is interesting to notice that the pinch point occurs slightly above the ambient temperature, offering opportunities for integrating heat pumps and CHP units.

Table 5.4: Hot and cold MER obtained with the 6 periods and the 80/20 simplification

	Utility	**Technological**	**Thermodynamic**
Cold streams [GJ/y]	49'883	51'076	41'492
Hot streams [GJ/y]	61'764	65'104	57'338
Hot MER [GJ/y]	48'474	40'444	30'147
Cold MER [GJ/y]	60'355	54'472	45'993
Pinch temperature [°C]	82	24-36	22-36
Heat recovery potential [GJ/y]	1408	10'632	11'345

5.4.5 Integration of current utilities for the three representations

The integration of the utilities for the multi-period problem defined in the previous section leads to the definition of mixed-integer optimization problem. An extensive review of the use of mixed-integer programming for the synthesis of process, including the integration of utilities, can be found in Grossmann (1985). Mathematically, the optimization problem can be formulated as follows in a generic way (Marechal and Kalitventzeff, 2003):

$$\min_{y_p, x_p, y, s} \sum_{p=1}^{n_p} t_p \cdot c(x_p, s) + I(y, s) \tag{5.13}$$

subject to:

$$h_p(x_p, s) = 0 \quad \forall\ t = 1, ..., n_p \tag{5.14}$$

$$g_p(x_p, s) \geq 0 \quad \forall\ t = 1, ..., n_p \tag{5.15}$$

$$y_p \leq y \quad \forall\ t = 1, ..., n_p \tag{5.16}$$

$$y_p, y \in 0, 1 \quad \forall\ t = 1, ..., n_p \tag{5.17}$$

where

$c(x_p, s)$	is the operating cost during the period p
$I(x_p, s)$	is the total annualized cost of the equipments of size s
$h_p(x_p, s)$	is the set of modeling constraints during the period p
$g_p(x_p, s)$	is the set of inequality constraints during the period p
x_p	is an array representing the operating conditions of equipments during the period p

y_p	is an integer variable representing the use or not of an equipment during the period p
s	is the array of the sizing parameters of the equipments
y	is the array of integer variables representing the choice to invest or not in the equipments
t_p	is the operating time of period p
n_p	is the number of period

This definition of the problem points out that the continuous variables (array x_p) are associated to flowrates while integer variables are associated to the existence of the unit or not (array y) and its use in a given period (array y_p).

At first, we will consider the integration of the current utilities (fuel combustion in the boiler [2], NH_3 chiller, industrial water) on the utility representation of the multi-period problem without considering heat recovery between the hot and cold streams. As this situation corresponds to the present configuration in the factory, the annual flowrates of utilities obtained after the integration should approximately match the present consumption of utilities in the factory. In order to prevent heat exchanges between the process hot and cold composite curve, the integration problem is decomposed into two sub-problems: the integration of the cold utilities (NH_3 chiller, industrial water) is performed on the hot composite curve alone and the integration of the combustion only takes into account the cold composite curve. In practice, the choice of using or not a given utility in the integration problem (obvious in this case) is made by the optimizer based on a predefined superstructure that includes all the utilities available. Since we do not consider the possibility of investing in new utility equipments, the definition of the mixed-integer problem to be solved (equations (5.13) to (5.17)) can be rewritten more explicitly as:

$$\min_{R_r^p, y_w^p, f_w^p y_w^{max}, f_w^{max}} \sum_{p=1}^{n_p} \left(\sum_{w=1}^{n_w} (c_w^p \cdot f_w^p) + c_{imp}^p \cdot W_{imp}^p \right) \cdot t_p \tag{5.18}$$

subject to:

[2]By considering directly the heat from the fuel, we can avoid to represent the steam utility explicitly. The overall efficiency of the boilers is taken into account to model the fuel required based on the heat requirement of the process.

Heat balance of the temperature intervals:

$$\sum_{w=1}^{n_w} f_w^p \cdot q_{w,r} + \sum_{i=1}^{n} Q_{i,r} \cdot L_{i,p} + R_{r+1}^p - R_r^p = 0 \quad \forall p = 1, ..., n_p, \forall r = 1, ..., n_r \tag{5.19}$$

Electricity consumption:

$$\sum_{w=1}^{n_w} f_w^p \cdot w_w + W_{imp}^p - W_c \cdot L_{c,p} \geq 0 \quad \forall p = 1, ..., n_p \tag{5.20}$$

Other additional constraints:

$$\sum_{w=1}^{n_w} a_x^{i,p} \cdot f_w^p + c_w^{i,p} \cdot y_w^p + \sum_{k=1}^{n_x} d_k^{i,p} \cdot x_k^t \overset{\leq}{\underset{\geq}{=}} b_i^p \quad \forall i = 1, ..., n_e, \forall p = 1, ..., n_p \tag{5.21}$$

$$xmin_k \leq x_k^p \leq xmax_k \quad \forall k = 1, ..., n_x, \forall p = 1, ..., n_p \tag{5.22}$$

Existence of operation w during the time period p:

$$fmin_w \cdot y_w^p \leq f_w^p \leq fmax_w \cdot y_w^p \quad \forall w = 1, ..., n_w, \forall p = 1, ..., n_p \tag{5.23}$$

Thermodynamic feasibility of the heat recovery and utility systems:

$$W_{imp}^p \geq 0 \tag{5.24}$$

$$R_1^p = 0,\ R_{n_{r+1}}^p = 0,\ R_r^p \geq 0 \quad \forall r = 1, ..., n_{r+1}, \forall p = 1, ..., n_p \tag{5.25}$$

Maximum size of operation w:

$$f_w^{max} - f_w^p \geq 0 \quad \forall w = 1, ..., n_w, \forall p = 1, ..., n_p \tag{5.26}$$

$$x_k^{max} - x_k^p \geq 0 \quad \forall k = 1, ..., n_x, \forall p = 1, ..., n_p \tag{5.27}$$

Use or not of operation w:

$$y_w^{max} - y_w^p \geq 0 \quad \forall w = 1, ..., n_w, \forall p = 1, ..., n_p \tag{5.28}$$

with: y_w^p the integer variable associated with the use of the technology w during the time period p;

y_w^{max}	the maximum value of the integer variable associated with the use of the technology w over the overall time period.
c_w^p	the proportional cost of using the technology w during the time period p;
t_p	the total operating time of period p;
n_w	the number of technologies proposed in the superstructure of the utility system;
n	the number of specified process streams;
n_p	the number of periods;
n_r	the number of temperature intervals;
R_r^p	the energy cascaded from the temperature interval r to the lower temperature intervals in the time period p;
Q_{ir}	the heat load of the reference level of process stream i in the temperature interval r; $Q_{ir} > 0$ for hot streams and ≤ 0 for cold streams;
$L_{i,p}$	the level of operation of stream i during the time period p;
n_p	the number of time period in the problem;
q_{wr}	the heat load of the technology w in the temperature interval r for a given reference flowrate, $q_w r > 0$ for a hot stream;
f_w^p	the multiplication factor of the reference flowrate of the technology w in the optimal situation during the time period p;
f_w^{max}	the maximum value of the multiplication factor for technology w over the overall time period;
w_w	the mechanical power produced by the reference flowrate of technology w; $w_w < 0$ for a mechanical power consumer and > 0 for a producer;
c_{imp}^p	the electricity cost during the time period p;
W_{imp}^p	the net import of electricity during the time period p;
W_c	the overall mechanical power needs of the process; $W_c < 0$ if the overall balance corresponds to a mechanical power production
$L_{c,p}$	the level factor of the mechanical power requirement W_c during the time period p
x_k^p	the (n_x) additional variables used in the additional equations of the technology models for time period p.
$a_w^{i,p}$ / $c_w^{i,p}$	respectively the coefficients of the multiplication factor / the integer variables of technology w in the constraint i in the effect models during the time period p.
$d_k^{i,p}$ / b_i^p	respectively the coefficients of the additional variables / the independent term in the constraint i in the effect models during time period p;
$xmin_r$ / $xmax_r$	respectively the *minimum* / *maximum* bounds of x_r.
$fmin_w$ / $fmax_w$	the *minimum* / *maximum* values accepted for f_w^p

As shown by equation (5.18), the optimization is performed with the minimization of the operating cost as an objective. As all the equality and inequality constraints are linear, the resulting MILP problem can be solved using a standard branch and bound algorithm. In this work, we have used Easy2, an energy integration software under development at LENI that implements such a solving method. The characteristics of the utilities included in the superstructure are briefly described here. The NH_3 chiller has an evaporation temperature of -13°C and a condensation temperature of 27°C. The resulting COP is approximately 4. The industrial water inlet temperature is 10°C and the maximum allowed outlet temperature is 27°C. The fuel LHV is 42'700 kJ/kg and the efficiency of the boiler is 83.6%. This efficiency represents in reality the overall efficiency of the boilers in the factory and consequently includes stand-by losses.

The results obtained are presented in table 5.5 where they are referred to as "basecase". The annual consumption of the three utilities is compared in the table with the annual measured consumption. The value obtained for the fuel is almost the same as the one measured while deviations are observed for industrial water and chilled water (represented in this table by the electrical consumption of the chiller). The difference observed for the industrial water has two main explanations. Firstly, the consumption of water is not optimized in the current configuration of the factory. Some of the water leaves the factory at a temperature inferior to the limit authorized (27°C) and could, consequently, be used for other cooling applications. Secondly, during winter months, the inlet temperature of the industrial water is approximately 5°C and can, as a consequence, substitute part of the chilled water for given operations during these months. This also explains why the chilled water consumption in the basecase is higher than the measured consumption. As the 6 periods defined do not only match seasonal patterns but also production patterns the inlet temperature of the cooling water has been set constant over the year [3]. Thus, this effect cannot be taken into account in the problem with the current modeling approach.

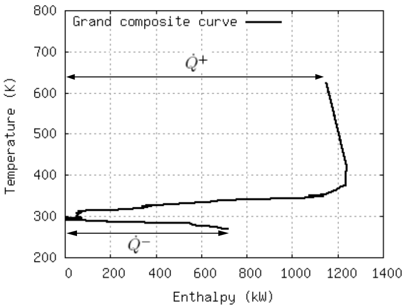
Table 5.5: Integration of the current utilities without considering heat recovery in the process

Utility	**Unit**	**Basecase**	**Measured**	**Difference**
Fuel	[GJ/y]	59'647	59'790	-0.2%
Industrial water	[m^3/y]	972'861	1'278'694	-23.9%
Chiller consumption	[GJ_{el}/y]	5'175	4'778	8.3%

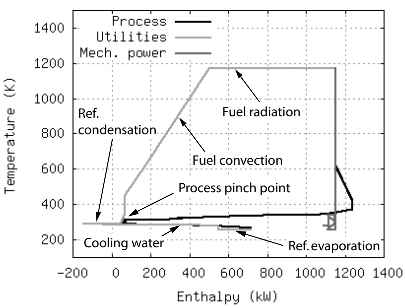
In a second step, the integration of the same utilities is performed on the three representations, this time considering heat exchanges between the hot and cold streams. When considering heat recovery in the process, the integration of utilities is well represented using the process grand composite curve (GCC). The GCC is constructed from the enthalpy (horizontal) differences between the composite curves at the different temperature levels. On

[3]It can be, however, observed in figure 5.5 that period 3 and 4 represent most of the winter weeks

the GCC, the horizontal distances separating the curve from the vertical axis at the top and the bottom of the temperature scale show the overall hot ($\dot{Q}^+$) and cold ($\dot{Q}^-$) MER. As an example, the GCC for the thermodynamic representation during period 3 is given in figure 5.7(a). Based on the same GCC (although the change of scale in the y axis has flattened the curve), an example of integration of utilities is presented in figure 5.7(b). The curve representing the utilities is represented in light grey. The streams corresponding to the different utilities are highlighted in the figure. The heat available through the combustion of the fuel is divided in two contributions: a flat profile representing radiation at high temperature and a convective part that is available from the radiation temperature to the stack temperature. It can be noticed in this figure that the large temperature difference between the fuel streams (radiation and convection) and the demand of the process above the pinch point results in high exergy losses.



(a) Process GCC



(b) Process GCC with current utilities

Figure 5.7: Integration of the current utilities on the thermodynamic representation for period 3 (pinch temperature: 22°C)

Table 5.7 presents the results obtained for the integration of the three utilities for the three representations. As said above, the heat recovery potential is small for the utility representation. This explains why for this representation, the consumption of utility is very similar to the one observed for the basecase. Not surprisingly, the fuel consumption decreases when passing from the utility representation to the technological representation and then to the thermodynamic representation. This is a direct consequence of the better integration of the hot and cold composite curves. This aspect has been highlighted when analysing the hot and cold MER (see table 5.4). As regards the consumption of cold utilities (chilled water and industrial water), it is interesting to notice that passing from the utility representation to the technological representation results in a shift of utility from chilled water to industrial water. The chilled water consumption for the technological representation is almost 64% smaller than for the utility representation, while, at the same time, the industrial water consumption increases by 25%. This phenomenon is due to the higher temperature level of the hot streams in the technological representation in comparison with the utility representation, which permits to use a cheaper utility - industrial water - to fulfill some of the cooling requirements. The electricity consumption reported in the table corresponds to the actual consumption corrected by the difference of consumption resulting from the chiller. Based on the energy prices available in table 5.6, the annual operating cost is computed for each case. The energy prices are considered constant over the 6 periods of the problem. Table 5.7 confirms that the utility representation offers a very limited saving potential (0.8%) while this potential amounts to 16.1% for the thermodynamic representation. However, it has to be noticed here that the "technical difficulties" to implement the possible heat recovery will also be proportional to the potential saving. Indeed, the heat recovery potentials in the utility representation are usually easy to implement since they involve only modifications and heat exchanges in the utility system. Heat recovery potentials associated to the technological representation are more difficult to implement as they imply changes in the way the PUOs are connected with the energy distribution systems or require direct heat exchanges among PUOs. Finally, implementation of the heat recovery of the thermodynamic representation implies the modification of the technologies used in the different PUOs. In that sense, the results obtained with this representation are not relevant for the retrofit of installations due to the high investment that would be required, but could be useful for the design of factories to be built.

Table 5.6: Current energy prices in the factory

c_f	[CHF/kWh]	0.0387
c_w	[CHF/m^3]	0.0293
c_{imp}	[CHF/kWh]	0.0978

Table 5.7: Results of the integration of the utilities

			Representation		
	Unit	**Measured**	**Utility**	**Techno.**	**Thermo.**
Fuel	[GJ/y]	59’790	57’963	47’296	34’703
Industrial water	[m^3/y]	1’278’694	970’056	1’219’547	1’134’091
Chiller consumption	[GJ$_{el}$/y]	4’778	5’175	1’879	1’879
Electricity	[GJ$_{el}$/y]	57’600	57’997	54701	54701
Operating cost	[CHF/y]	2’273’896	2’254’820	2’052’388	1’907’760
Saving potential	[%]	-	0.8	9.7	16.1
CO_2 emissions (Swiss mix)*	[Tons/y]	6’172	6’050	5’162	4’232
CO_2 reduction potential	[%]	-	2.0	16.4	31.4
CO_2 emissions (UCTE mix)*	[Tons/y]	11’612	11’527	10’328	9’399
CO_2 reduction potential	[%]	-	0.7	11.1	19.1

* Swiss electricity mix: 110 kg/MWh, UCTE electricity mix: 450 kg/MWh, fuel: 73.8 kg/GJ (see table 2.2).

5.4.6 Multi-objective optimization for integration of CHP and heat pumps

The relatively low temperature level of the process under study (see figures F.3 and F.2) makes it a good candidate for the rational conversion of energy resources by integrating combined heat and power or heat pumping solutions. Particularly, the location of the pinch point temperature at a low level of temperature for the thermodynamic and technological representations (see table 5.4) makes it possible to consider the use of heat pumps across the pinch. For instance, the shape of the GCC available in figure 5.7(a) presents two flat profiles just below and just above the pinch point, which occurs at a temperature of 295 K. This configuration is ideal to integrate a heat pump: the evaporation at constant temperature of the working fluid can take place just below the flat profile below the pinch point while the condensation at constant temperature is located just above the flat profile above the pinch point. By so doing, the heat in excess below the pinch point is pumped, through an additional mechanical work, above the pinch - where there is a deficit of heat - permitting to save both hot and cold utilities. The shape of this GCC also provides the opportunity to integrate a cogeneration engine since the heat requirements above the pinch point occur at a temperature inferior to 350 K. This enables the use of the heat from the exhaust of the engine (from approximately 750 K to 400 K) and of the the cooling of the engine (from approximately 373 K to 363 K) as a hot source for the process. This is illustrated in figure 5.8, which shows the integration of an engine, a heat pump and a refrigeration cycle on the GCC. The residual heat at low temperature is withdrawn using cooling water. The analysis of the different thermal streams of the utilities highlighted in this figure shows that the evaporation of the working fluid of the heat pump is not only use to remove heat from the process but also from the condenser of the refrigeration cycle.

5.4.6.1 Multi-objective optimization

Two effects will be taken into account while integrating CHP units and heat pumps: the impact on the annual operating cost and the investment required to buy the units. The introduction of a second dimension in the optimization problem (the investment required) can be tackled in two ways. A first solution is to consider one single objective that includes the two dimensions by computing, for example, the total annual cost (the investment cost is annualized) instead of the annual operating cost (see equation (5.13)). Although valid, this approach has the main drawback of providing as a result only one optimal solution. A second solution, which is more interesting from an engineering point of view, is the use of a multi-objective approach. This optimization technique gives as a result a trade-off

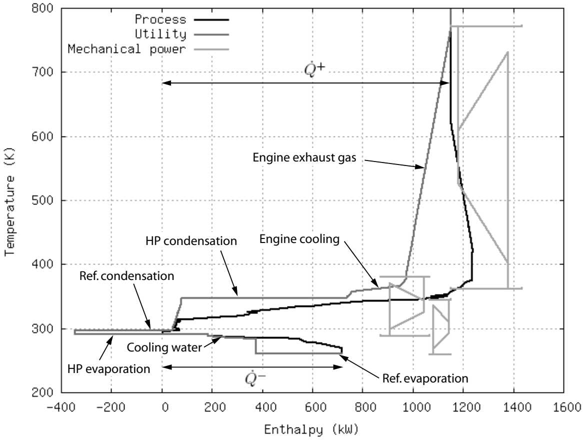


Figure 5.8: Opportunities to integrate CHP units and heat pumps in low temperature processes (thermodynamic representation during period 3, pinch temperature: 22°C)

curve - called Pareto optimal front - between two conflicting objectives (here the operating cost and the investment required). This curve separates the domain of infeasible solutions from the domain of sub-optimal solutions in the objective space (Deb, 2001). As regards design problems and decision-making, multi-objective optimization appears to be the best option, since it provides the engineer with a large number of solutions ranging from low investment and low saving solutions to high investment and high saving ones. The use of multi-objective optimization has a second advantage over mono-objective optimization in the context of process integration: it can handle non-linear problems. This is important since the effect of the size of the CHP and heat pump units on their efficiencies as well as on the investments required will be modeled using non-linear functions. It has to be emphasized that these functions could have been linearized (see Grossmann (1985) for an example) in order to solve the problem using a MILP approach. However, this possibility has not been considered here. If the use of multi-objective optimization has several advantages over classical optimization methods, it has to be mentioned that it has the major drawback of being more time-consuming.

The strategy adopted here to solve the optimization problem encompasses two steps. At first, the multi-objective optimizer is used to generate sets of decision variables. The decision variables chosen for this problem are: the sizes of the equipments (CHP units and heat pumps), the temperature levels of the heat pumps as well as the ratio of the imported electricity price to the fuel price. Subsequently, the operating conditions of the equipments that results in the minimum operating cost (first objective) are computed using the MILP method presented earlier. The determination of the second objective (required investment) is performed in parallel in a separate function. This strategy has been implemented using *Osmose*, a matlab-based optimization framework developed at LENI by R. Bolliger and F. Palazzi (Bolliger et al., 2005; Marechal et al., 2005). It integrates, among others, the evolutionary algorithm QMOO (queueing multi-objective optimizer) developed at LENI by Molyneaux (2002) and Leyland (2002) and Easy2. QMOO has been successfully used to solve a wide range of multi-objective optimization problems dealing with the design of complex energy systems (Buerer, 2003; Pelet, 2004; Li, 2006). This optimizer includes a clustering technique that preserves diversity in the population and permits the identification of several local optima simultaneously. The configuration of *Osmose* that has been considered is illustrated in figure 5.9 and is briefly discussed here. At first, QMOO sends a set of decision variables x for evaluation . The decision variables are used in a pre-computation function to compute the investment costs (y_2, second objective) and the efficiency of the cogeneration units to be used in the process integration problem. The input file for process integration is created by combining these efficiencies with a template of input file for Easy2 containing the definition of the hot and cold streams for the different periods. The input file is then processed by Easy2, which gives as a result the optimal operating conditions. Finally, the latter are used in a post-computation function to compute the annual operating cost (y_1, first objective). As illustrated by the dotted line in the figure, the model that sends back the objective functions y_1 and y_2 based on the decision variables x is seen as a black-box by QMOO.

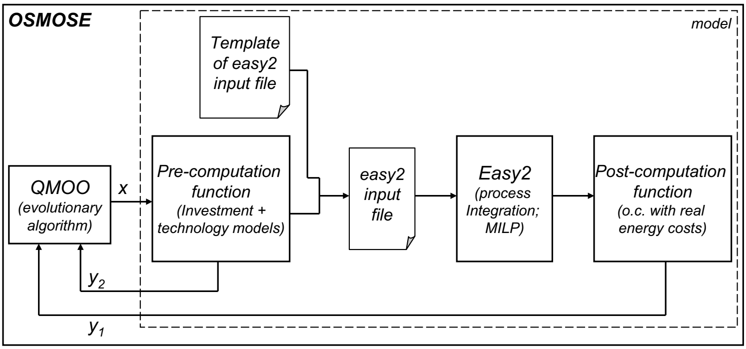


Figure 5.9: Multi-objective optimization combined with process integration in *Osmose*. The two objectives considered are the annual operating cost y_1 and the investment required y_2.

5.4.6.2 Problem definition

In order to avoid direct heat exchanges between process streams and to keep a maximum of flexibility in operation, the technological representation has been chosen for the integration of the utilities. The energy conversion technologies available to QMOO are: two diesel engines and two heat pumps. In addition, a boiler, cooling water and a refrigeration cycle are defined in the template file of Easy2 and cannot be modified by QMOO. The characteristics of the boiler, the cooling water and the refrigeration cycle are identical to the ones considered in section 5.4.5. As mentioned earlier, the decision variables include the sizes of the two engines and the two heat pumps as well as the temperatures of evaporation and condensation of the two heat pumps. The motivation for proposing two heat pumps and two engines is driven by the possibility for the optimizer to buy two small units instead of a large one and to operate only one in periods with limited energy demands, such as period 5. The potential of integration of heat pumps and CHP units will mainly depend on the fuel and electricity prices. Although these prices are fixed for a given optimization, the ratio of the price of the imported electricity to the fuel price (the price of fuel is fixed to the current value in the factory) has been included in the set of decision variables in order to facilitate the convergence of the optimizer used to solve the MILP process integration problem. The "real" operating cost based on the actual electricity price is computed in a post-computation function as shown in figure 5.9. The decision variables as well as their bounds are summarized in table 5.8.

Table 5.8: Decision variables considered in the multi-objective optimization problem

Decision variable	**Unit**	**LB***	**HB***
Size of engine nr. 1 $P_{eng,1}$	[kW$_{mec}$]	0	2000
Size of engine nr. 2 $P_{eng,2}$	[kW$_{mec}$]	0	1000
Size of heat pump nr. 1	[kW$_{th}$]	0	1500
Evaporation temperature of heat pump nr. 1	[K]	278	300
Condensation temperature of heat pump nr. 1	[K]	325	338
Size of heat pump nr. 2	[kW$_{th}$]	0	3000
Evaporation temperature of heat pump nr. 2	[K]	278	300
Condensation temperature of heat pump nr. 2	[K]	325	338
Electricity imported/Fuel cost ratio	[-]	2	4

* LB: lower bound, HB: higher bound

Compared with the problem defined in section 5.4.5, the introduction of cogeneration engines in the superstructure of the utility system makes the export of electricity to the grid possible. Consequently, equation (5.18) has to be replaced by the following equation in the definition of the MILP problem:

$$\min_{R_r^p, y_w^p, f_w^p y_w^{max}, f_w^{max}} \sum_{p=1}^{n_p} (\sum_{w=1}^{n_w} (c_w^p \cdot f_w^p) + c_{imp}^p \cdot W_{imp}^p - c_{exp}^p \cdot W_{exp}^p) \cdot t_p \tag{5.29}$$

where W_{exp}^p is the net export of electricity during the time period p and c_{exp}^p is the selling price of electricity during the time period p. Here, we will consider that this price is constant over all the periods and has a value of 90% of the price of imported electricity ($c_{exp}^p = 0.9 \cdot c_{imp}^p$). In addition, the exportation of electricity must satisfy the following constraints:

$$\sum_{w=1}^{n_w} f_w^p w_w + W_{imp}^p - W_{exp}^p - L_{c,p} \cdot W_c = 0 \quad \forall p = 1, ..., n_p \tag{5.30}$$

$$W_{imp}^p \geq 0 \quad \forall p = 1, ..., n_p \tag{5.31}$$

The influence of the size of an engine on the different energy services it provides (mechanical work, thermal energy in the fumes and thermal energy in the cooling water) is computed according to the equations available in table 3.16. The inlet and outlet temperatures of the two thermal streams of the engine are set at 500°C and 120°C for the fumes and at 100°C and 90°C for the cooling water. If an engine is used, its level of operation has to be between 40% and 110% of the nominal power ($fmin$=0.4 and $fmax$=1.1). As regards the heat pumps, their COP is supposed to be independent of their size.
While the operating cost (expressed in CHF/year) is computed according to equation (5.29), the investment cost IC (expressed in CHF) linked to the purchase of the two engines ($C_{eng,1}$ and $C_{eng,2}$) and the two heat pumps ($C_{HP,1}$ and $C_{HP,2}$) is given by:

$$IC = C_{eng,1} + C_{eng,2} + C_{HP,1} + C_{HP,2} \tag{5.32}$$

$C_{HP,1}$ and $C_{HP,2}$ are computed according to the following equation (Puigjaner and Heyen, 2006):

$$C_{HP} = 814 \cdot \dot{Q}_{th}^{0.673} \quad [€] \tag{5.33}$$

where $\dot{Q}_{th}$ is the thermal power delivered at the condenser of the heat pump. The exchange rate used to convert the investment in Swiss franc is 1€ = 1.59 CHF. For the engines, the investment cost function has been adapted from table 3.16 in order to have a null investment cost if the size of the engine is null:

$$C_{eng,i} = \begin{cases} 2163.85 P_{eng,i} & \text{if } 0 \leqslant P_{eng,i} < 200; \\ -0.0391(\frac{3}{4}P_{eng,i})^2 + 850.89\frac{3}{4}P_{eng,i} + 306016 & \text{if } 200 \leqslant P_{eng,i} \leqslant 1000; \\ 1687 P_{eng,i}^{0.9009} & \text{if } P_{eng,i} > 1000. \end{cases} \tag{5.34}$$

It has to be noticed that the investment cost considered here includes the purchase of the equipments but not of the heat exchangers necessary to implement the optimized configuration in the factory. This is an important limitation of the present approach.

5.4.6.3 Results

The Pareto optimal front obtained after 7000 evaluations of the objective functions is presented in figure 5.10 [4]. It is divided in four clusters, which correspond to 4 subsets of the entire populations. Cluster 4 corresponds to solutions using preferably the second engine (the smallest), while solutions of clusters 1, 2 and 3 make a larger use of the first engine. Regarding heat pumps, the cluster 1, 3 and 4 make use of the first heat pump while the second heat pump is used in all the clusters. It has to be noticed that even if some solutions use a combination of two, three or even four units, the majority of solutions includes one engine and one or two heat pumps. The changes of slope in the Pareto curve for operating cost of approximately 1.8 MCHF and 1.5 MCHF correspond to the discontinuities in equation (5.34), which is used to compute the investment required for the engines.

Solutions with operating costs lower than 1.93 MCHF (corresponding to low investments) only employ heat pumps. This is better highlighted in figure 5.11(a), which plots the total fuel consumed, the fuel consumed in the engines, the electricity imported as well as the heat delivered by the heat pumps as a function of the operating cost. The use of heat pumping decreases the total fuel consumption and slightly increases the electricity consumption as shown in the figure. Considering the Swiss electricity mix (based principally on nuclear and hydro), the solution that produces the minimum of CO_2 emissions will be obtained by substituting a maximum of combustion (boiler) by heat pumping without using engines. As illustrated in figure 5.11(b), this solution has an operating cost of 1.93 MCHF. Solutions ranging from this operating cost down to 1.5 MCHF integrate engines with an installed capacity lower than 1 MW. The effect of introducing cogeneration units is better observed in figure 5.11(a). In this range of operating costs, the total fuel consumption increases, but, on the other hand, the share of fuel used in the boiler (difference between blue and red points)

[4]with a CPU time of 40 seconds per evaluation, the time required for the optimization is approximately 80 hours

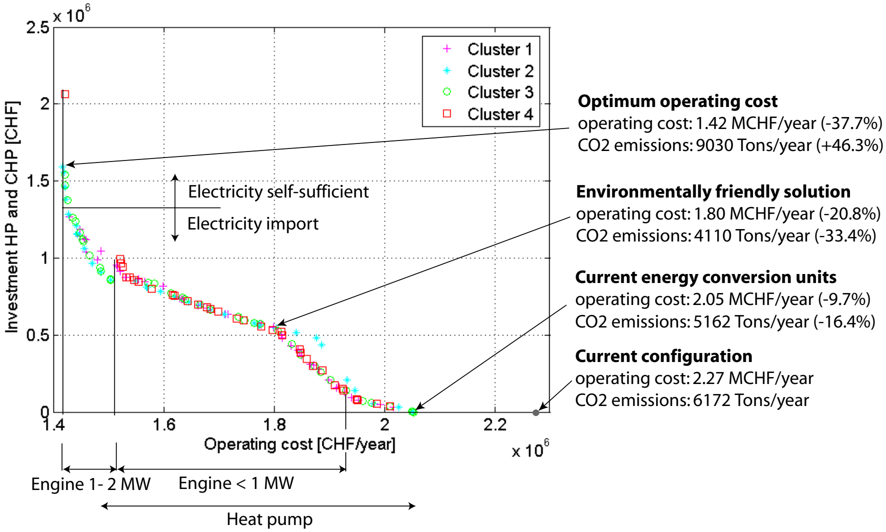
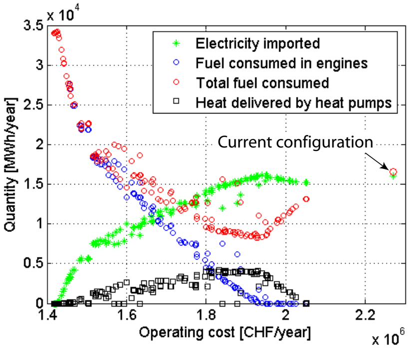


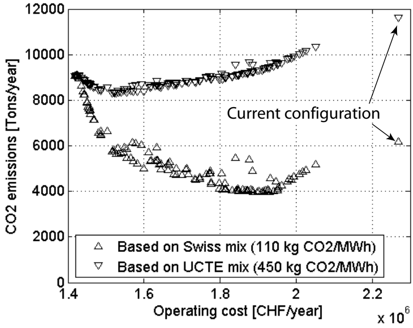
Figure 5.10: Pareto optimal front (energy costs considered are available in table 5.6)

decreases to nearly 0 at an operating cost of 1.5 MCHF. At the same time, the electricity produced by the engines permits to decrease the amount of electricity to be imported from the grid. The positive effect on the operating cost is however undermined by an increase in CO_2 emissions if we consider the Swiss electricity mix as a reference for computing these emissions. If, for example, the factory were to consume electricity from the UCTE grid for example, the impact on the CO_2 emissions would be positive, as illustrated in figure 5.11(b). Indeed, after deduction of the CO_2 emissions that can be attributed to the useful heat released by the engine, the production of electricity generates less CO_2 per unit of produced electricity than the UCTE mix. Solutions that integrate engines with an installed power higher than 1 MW are nearly self-sufficient as regards heat, as illustrated in figure 5.11(a). For these points, the total fuel consumption coincides with the fuel consumption of the engines. Solutions with engines larger than 1.7 MW (corresponding to investments higher than 1.4 MCHF) are also self-sufficient with the electricity they produce (see figure 5.11(a)). For these solutions, the CO_2 emissions are independent of the electricity generation mix of the grid (see figure 5.11(b)). It has to be noticed, however, that the possibility to sell electricity to the grid is not considered by the optimizer. Indeed, given the ratio of the electricity price to the fuel price (2.4) and the fact that the heat produced cannot be used in the process, the cost of the electricity produced by the engine (based only on energy costs) is higher than the market price. For instance, the electricity produced by a 2 MW engine costs

0.0915 CHF/kWh while the selling price of export to the grid is 0.0878 CHF/kWh (90% of the import price).



(a) Energy consumption



(b) CO_2 emissions

Figure 5.11: Detail of solutions of the Pareto optimal front

The Pareto curve of figure 5.10 presents a set of sub-optimal solutions for operating costs between 1.84 and 1.95 MCHF. As shown in figure 5.11(a), these 5 sub-optimal solutions present larger engines and smaller heat pumps than solutions of the Pareto curve with similar operating costs. The discontinuity observed in the Pareto curve for an operating cost of approximately 1.5 MCHF is linked to a discontinuity in the investment cost function for engines. Indeed, from equation (5.34), engines from 1000 kW to 1090 kW are slightly cheaper than a 1000 kW unit.

The optimal solution for the operating cost (1417 kCHF with a related investment of 1589 kCHF, see "optimum operating cost" in figure 5.10) is obtained with an engine of 2 MW (upper bound of the first engine) and no heat pumps. At the other end of the curve, the solution with the lower investment (see "current energy conversion units" in figure 5.10) corresponds to the solution presented in table 5.7 for the technological representation. The details for the two optimal solutions are available in table 5.9. It has to be noticed that although the introduction of a cogeneration engine allows for cutting the operating cost by 37.7%, it increases the CO_2 emissions by nearly 50% if the Swiss electricity mix is considered. However, the Pareto optimal frontier resulting from the optimization provides the engineer with a large number of interesting alternative options. For example, figure 5.11(b) shows that it is possible to reduce the operating cost by approximately 33.6% while more or less maintaining CO_2 emissions to the current level (6172 tons/year). Indeed, an operating cost of approximately 1520 kCHF (-33.1%) is achievable with a reduction of 6.7% of the CO_2 emissions (5755 tons/year). An interesting solution in terms of environmental impact (CO_2 emissions) occurs for an operating cost of approximately 1800 kCHF. It allows for decreasing the CO_2 emissions by 33.4% and the operating cost by 20.8% compared with the present situation (see "environmentally friendly solution" in figure 5.10).

Table 5.9: Results for the two optimal solutions

			Multi-objective optimum	
	Unit	**Measured**	**Investment**	**Operating cost**
Fuel	[GJ/y]	59'790	47'296	122'360
Industrial water	[m^3/y]	1'278'694	1'219'547	1'229'635
Electricity	[GJ_{el}/y]	57'600	54'701	0
Operating cost	[CHF/y]	2'273'896	2'052'388	1'417'338
Saving potential	[%]	-	9.7	37.7
CO_2 emissions (Swiss mix)*	[Tons/y]	6'172	5'162	9'030
CO_2 reduction potential	[%]	-	16.4	-46.3
CO_2 emissions (UCTE mix)*	[Tons/y]	11'612	10'328	9'030
CO_2 reduction potential	[%]	-	11.1	22.2

* Swiss electricity mix: 110 kg/MWh, UCTE electricity mix: 450 kg/MWh, fuel: 73.8 kg/GJ (see table 2.2).

Figure 5.12 presents a sensitivity analysis of the ratio of the imported electricity price to the fuel price on the Pareto optimal frontier. At first, the operating conditions obtained from the Pareto points are not changed. The related curves obtained for a price ratio of 2, 2.4 (present situation) and 3 corresponds to the red, black and green curves in the figure. The black curve correspond to the present situation and is equivalent to figure 5.10 except that the different clusters are not highlighted. The green curve corresponds to a situation where the price of electricity is higher than in the present case. This results in higher operating costs for solutions for which electricity has to be imported. In contrast, solutions that are self-sufficient in electricity (corresponding to an investment higher than 1.3 MCHF) have a similar operating cost as solutions obtained with the current energy prices (black curve). The same phenomenon is observed for these solutions when lower electricity prices are used (ratio of 2 between electricity and fuel prices). When electricity has to be imported from the grid, lower electricity prices naturally lead to operating costs lower than in the present situation. It is interesting to notice that, for this curve, the current operation is not optimal for investments higher than 1 MCHF. Indeed, the operating costs augment with increasing investments till reaching the point of self-sufficiency in electricity. This is explained by the fact that when the size of the engine increases, the process can no longer absorb all the heat released by the engine. In this case, the cost of the electricity produced becomes, at a certain point, higher than the market price and, consequently, producing additional electricity with the engine is no longer optimal.

In the present context of high and volatile energy prices, it is thus interesting to determine what is the optimal operation for the invested units in a low and high electricity price

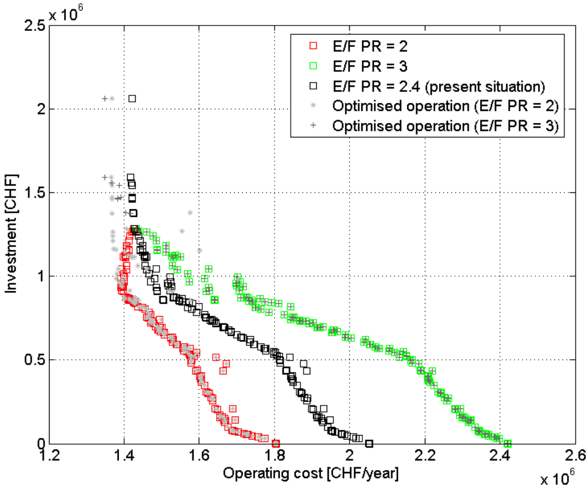


Figure 5.12: Sensitivity analysis on ratio of electricity to fuel price (E/F PR)

environment. Both cases are represented in the figure by the grey crosses and light grey points. If the electricity price is high compared to the fuel price (ratio of 3), the optimal operation is identical to the one of the Pareto curve for points that are not self-sufficient in electricity (see grey crosses). For solutions that are self-sufficient in electricity in the Pareto curve (investments higher than 1.25 MCHF), the cost of the electricity produced by the engine is competitive with respect to the market price and the optimal operation consists in selling electricity to the grid. This results in lower operating costs than the ones of the Pareto curve, as illustrated in the figure. The optimal operating cost (1.348 MCHF) is obtained for an investment of 1.589 MCHF. For this solution, 3832 MWh of electricity are sold to the grid per year. When considering a lower ratio of the imported electricity price to the fuel price (ratio of 2), which applies in the present situation of high fuel prices, the operating conditions are identical to the ones of the Pareto curve as long as the heat produced by the engine(s) can be used in the process. As mentioned earlier, when this is not the case, producing additional electricity results in higher operating costs. Consequently, the optimal operating conditions for these points in the new price environment are created when the production of electricity is limited in such a manner that that all the generated heat can be absorbed by the process. The resulting operating costs remain relatively constant at 1.37 MCHF as illustrated in the figure by the light grey points at investments higher than 1 MCHF. It has to be mentioned here that 3 points out of the 151 points of the Pareto curve do not converge when recomputing the optimal operation with a low electricity price. In addition, several points that have been recomputed are largely sub-optimal. This is particularly obvious for the 3 points with operating costs of approximately 1.6 MCHF and investments ranging from 1.15 to 1.4 MCHF. One would expect the optimizer to find at least the solutions represented by the red squares that correspond to the operating conditions of the Pareto curve. These "errors" result from a criterion of end in the branch and bound algorithm that is too high for this particular application.

5.5 Examples of initiatives based on the bottom-up approach

Based on the case study presented in Chapter 4 and in this chapter, examples of energy savings are discussed here. Although the web application and, consequently, the factory model developed in this work were not available for this case study, the proposed methodology has, however, been implemented. Thus, the results of the top-down approach have been used to guide more detailed analysis conducted with the bottom-up approach. In this context, the significant base loads in the two major utilities (electricity and fuel) identified in Chapter 4 (see figures 4.2 and 4.4) made them natural priorities for tracking energy saving opportunities. One example of an energy saving action is presented here for each utility.

5.5.1 Compressed air

From the top-down approach and the process records, it appears that 7.5% of the electricity consumption base load comes from the compressed air production. In this consumption, the process unit sealing accounts for 70%. Unit sealing is used to maintain a neutral atmosphere above the process units. The thermodynamic requirements of this operation is 16.1 Nm^3/h of 0.5 barg air [5]. Assuming an isentropic compression, the power needed is 0.2 kW. This is to be compared with its technological implementation, which consists of using the 7.5 bars compressed air of the network. In this system, compressed air is produced by screw compressors with an isentropic efficiency of 76% identified from the measurements. Consequently, the power required to produce the sealing air is of 1.9 kW. When compared with the requirement, there is therefore a maximum saving potential of 1.7 kW or 89% of the present load. The solution proposed to implement this saving is to supply sealing air by a dedicated blower. Due to the lower isentropic efficiency of the blower (35%), the consumption will

[5]even when the concept of triple representation introduced in this chapter was applied on heat requirements, it can be extended to other requirements as illustrated in this example

be of 0.6 kW. Considering 8000 hours of operations per year, the annual energy saving is therefore estimated to 68% of the process units sealing consumption.

5.5.2 Vacuum production in dryers

Another example is the production of vacuum of 25 mbars needed in a dryer. Presently, the vacuum is created by a liquid ring pump coupled with a high pressure steam ejector. Both devices are used simultaneously to create and maintain the required vacuum conditions. A thermodynamic model of the vacuum production sub-system has been developed to optimize its efficiency. This model has been validated through tests on site. The model shows that the steam ejector is needed only for the creation of the vacuum at starting of the process and that low pressure steam could be used for that application. Once the vacuum is established after the starting phase, the steam ejector can be shut down since the liquid ring pumps are sufficient to maintain the desired vacuum. The savings associated with the new operation are of approximately 15,000 liters of fuel per year together with the corresponding cooling and de-mineralized water savings. A more detailed discussion can be found in Ruiz (2005).

5.5.3 Summary of energy savings

If part of the energy savings are identified using the bottom-up approach, the implementation of best practices and good housekeeping measures also lead to energy savings without great efforts. Among others, it consist in fixing the compressed air leakage and improving the insulation of high pressure steam distribution systems that contribute to the high base load observed in both fuel and electrical consumption. Table 5.10 presents the main yearly energy savings obtained in this application. When modifications require investment, they have been classified into three different categories:

- Solutions with a payback of less than one year. These investment are normally not subject to discussion and will be realized directly.
- Solutions with a payback of between 1 and 3 years. In this case, a more detailed analysis with a sensitivity analysis of the major parameters will be carried out and cost break-even will be identified to have a better assessment of the investment-related risk;
- Solutions with a payback of more than 3 years will have to find other justification, such as unit refurbishment, throughput increase, etc.

Table 5.10: Summary of some energy savings identified

Measure	Energy saving [MWh/year]	Estimated payback
Replace compressed air usage by dedicated blowers*	166	2
Regulation of HVAC*	80	< 1
Removing stand-by of air compressors with a VFD unit*	69	23
Fixing compressed air leakage*	50	< 1
Insulating pipes of high temperature condensate return**	338	1.5
Vacuum production in dryer**	178	1
Regulation of steam user**	50	< 1

Notes: *, ** denote electricity and fuel savings respectively.

These results confirm the results of similar studies (Motiva, 2001; Kreith and West, 1997), which showed that a significant part of the savings can be considered as good housekeeping and require no or few investments. Although all the energy saving actions identified are not presented here, the results in this factory (approximately -5% on the operating cost) are lower in magnitude than in other factories studied. One possible explanation for this outcome is the fact that the focus, in this case study, has been largely on possible heat recovery in the process, thus, overlooking other saving potentials in electricity consumption, such as the implementation of efficient motors or lightings.

The results obtained by process integration are summarized in table 5.11. The integration of the current utilities on the three representations are presented together with three solutions obtained with the multi-objective approach for the integration of CHP units and heat pumps. As mentioned earlier, the latter approach provides the engineer with a set of solutions that are a trade-off between two conflicting objectives. The first solution minimizes the operating cost, but results in high CO_2 emissions. The second solution shows the reduction of the operating cost achievable while maintaining relatively the same CO_2 emissions. The last solution is the optimal configuration as regards environmental impact. Although the required investments for the CHP units and heat pumps have been estimated in the multi-objective optimization, the payback for all these solutions cannot be computed since the costs related to the implementation of the optimal heat exchanger network have not been estimated.

5.6 Conclusion

In the developed methodology, the bottom-up approach is used to identify and quantify energy saving potentials in the process. The implementation of best practices as well as good-housekeeping measures usually leads to energy savings that require few or no investment.

Table 5.11: Saving potentials by process integration

	Representation	OC reduc.	CO_2 reduc.*	Payback
PI with current utilities	Utility	0.8%	2%	TBD
PI with current utilities	Techno.	9.7%	16.4%	TBD
PI with current utilities	Thermo.	16.1%	31.4%	TBD
PI with CHP and HP	Techno.	37.7%	-46.3%	TBD
PI with CHP and HP	Techno.	33.1%	6.7%	TBD
PI with CHP and HP	Techno.	20.8%	33.4%	TBD

PI: process integration, TBD: to be determined, OC: operating cost. * CO_2 emissions for electricity are computed according to the Swiss electricity mix (110 kg/MWh).

Application of such measures on the high base load observed in the factory under study has allowed to identify approximately a 5% reduction potential on the operating costs. It has to be emphasized that the application of such measures has not been extended to the use of efficient motors or lighting, which could have undoubtedly lead to further savings.

A significant amount of effort has been directed in this case study to identify energy savings by a better integration of the processes and utilities. Even when such an approach would not have been considered as a priority based on the criteria developed in the methodology (the combined annual cost of fuel and water represent only 30% of the total energy cost), it has been considered here for the sake of demonstration and to develop strategies to simplify such studies for other future applications. In that context, a triple representation of the process requirement is used to link the top-down approach and the bottom-up approach. The top-down approach (see Chapter 2) has described the conversion of purchased energies into distributed energies (utility representation). In the bottom-up approach, we add to this representation the description of the use of these energies to fulfill the thermodynamic requirements of the process (thermodynamic representation) through a technological implementation (technological representation). Gathering information for defining the three representations requires a good thermodynamic knowledge and is time-consuming (an engineer full-time during 3 months for this particular case). With the aim of reducing the time needed, the relevance of the 80/20 principle has been demonstrated. In addition, the seasonal pattern of the annual production has been modeled using 6 periods represented by six reference weeks, which has permitted to further simplify the problem.

The results have shown that heat recovery in the process together with a better integration of the current utilities could lead to a saving potential up to 16.1% when considering the thermodynamic representation. The corresponding reduction of CO_2 emissions amounts to 31.4% when considering electricity of the Swiss electricity mix. However, implementing the related heat exchange network would reduce the operability of the process and seems somewhat impractical in food process due to the nature of the streams involved. In that sense, considering the technological representation appears to be much more realistic. In this case the potential saving is of approximately 9.7% with the current utilities resulting in a reduction of 16.4% of the CO_2 emissions. The integration of CHP and heat pumps units using multi-objective optimization has shown a potential reduction of 37.7% for the operating cost. However, substituting electricity from the grid, produced essentially with CO_2-free technologies in the case of the Swiss mix, with cogeneration engines results in an increase in CO_2 emissions (+ 46.3%). When considering the UCTE mix, which is much more carbon-intensive, the introduction of cogeneration engines would result in a decrease of 22.2% of the CO_2 emissions. The use of multi-objective optimization provides, however, a large range of solutions. It has been shown that another configuration allows for decreasing the operating cost by 33.7% while maintaining the same level of CO_2 emissions. Finally, the optimal solution as regards CO_2 emissions (-33.4%) results in a 20.8% decrease of the operating cost.

It has to be emphasized here that the investment needed to realize these savings, in addition to the purchase of the equipments, has not been studied here. However, these results allow to set an objective for heat recovery that might be implemented in several steps. It also has to be noticed that if the effort invested has been important, it will result in an improved knowledge of the site, which will be certainly useful in the future.

Chapter 6

A global application for energy management

The developments presented in Chapters 2 and 3 are well suited to be locally applied in factories. However, in large companies, the potential benefits of such tools can be much higher by integrating them in a global web framework. The emergence of web applications in recent years has allowed to create applications where the transfer of information and knowledge is facilitated, where the knowledge and data can be stored in a centralized system and be redistributed later. The possibility for a company to gather and store all the factory models presented in Chapter 2 in a central application means that the different users of the application (managers, engineers in factories and energy experts in head office) can have access at any time and from their computers to information regarding performance and energy usage of factories worldwide. In addition, such a centralized application offers, for example, opportunities for benchmarking factories, identifying key issues in energy management at an early stage, setting priorities for the allocation of resources in energy management, facilitating all the reporting processes, etc. Furthermore, in companies that have technology and engineering support departments in the head office, such an energy management application is an ideal framework to make use of their knowledge (best practice, best available technologies), to give an indication of the quality of an indicator (e.g. overall boiler efficiency) and to identify energy saving potentials. This results in a "win-win" situation for the engineers in factories and for the technology experts in head office. Indeed, by providing energy-related information of his factory through the factory model, an engineer will be able to compare his performance with the ones of other factories and will also get an information of where the improvement potentials are the highest. As regards energy experts, the web application is an efficient means to disseminate their knowledge across the company and will provide them with pertinent information to evaluate more in detail energy saving actions. In order to assess and quantify the benefits of changing operating conditions, the developed web application will also integrate, in the future, simulation capabilities. Although not yet available in the current version, we will introduce, in this chapter, the prototype of a simulation platform developed in this work for performing the so called "what if?" scenarios. This platform offers users in factories with a comprehensible interface to perform advanced simulation, based on complex thermodynamic models such as those presented in Chapter 2. By providing a pre-assessment of the profitability of changing operating conditions, "what if?" scenarios limit the interaction between engineers in factories and energy experts to cost-effective cases needing further study. Consequently, the time invested by the expert to develop and validate simulation modules is made profitable since it provides a means to filter the requests from engineers in factories. To summarize, using a web application should bring a change in the manner of working and an increase in the efficiency of engineers in factories, energy experts in the head office and managers concerned with energy management. This chapter will address the opportunities offered by this web-dimension of energy management while all the IT technical considerations will be dealt with in Chapter 7.

6.1 Sharing factory models

One major advantage of having a worldwide application dedicated to energy management in a large company is the possibility of sharing information with all the agents involved in energy management around the world. Indeed, the factory model introduced in Chapter 2 has as a first aim to gather energy-related data and, as a second major aim, to offer a user-friendly interface that allows users to have quick access to essential information (see section 2.4). The factory model, being "browsable", allows a user to navigate this model in a manner similar to website surfing. Thus, by implementing the factory model in a web application as illustrated in figure 6.1 allows all the users worldwide to select and browse factories which have been modeled in the application. This means that an engineer in a factory can, for example, browse the model of a similar factory located in another continent, compare the performance of both factories and eventually contact the engineer of that factory for more information on the better performance of this factory when compared to his. As regards managers in the head office, they can use the factory models available in the application to rationally allocate the resources for energy management. Although the access of the models of worldwide factories is a clear added-value for energy management, the large amount of information potentially available in the web application (the industrial partner with which this application is developed has over 500 factories worldwide) can make the extraction of relevant data a difficult task. In order to overcome this obstacle, two strategies are adopted in the web application: benchmarking, which is the subject of section 6.2, and a rating mechanism for performance indicators. The latter is based on the knowledge of the energy experts in the company (best practice, best available technology). This knowledge, which is sometimes only available in the form of documents (best practices), will be implemented in the web application and, more particularly, in the factory model as illustrated in figure 6.1.

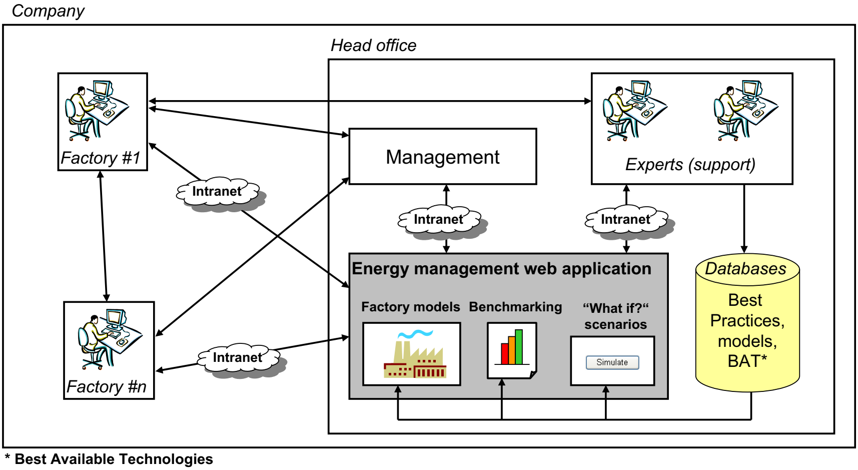


Figure 6.1: Structure of the web application developed

6.1.1 The traffic light system as a rating mechanism

When developing the factory model (see Chapter 2), an important effort was devoted to the standardization of the different modules that constitute the global model while keeping in mind that the model has to be flexible enough to be applied in a maximum number of factories. This effort was necessary to guarantee that the performance of factories be judged on a fair basis and that comparison along factories make sense. The importance of standardization was also taken into account when defining the performance indicators at factory level but also at the level of its sub-system. The value of the indicator itself is important for the user, however, even more important to him is to know if this value can be judged as "good", "fair" or "bad". For this purpose, indicators are compared, for example, with the indicator of other factories, with indicators of best available technologies available from the energy experts, etc. The results are displayed in the different representations of the factory (level 1 and 2) using a color that is attached to each performance indicator. Indeed, when an engineer submits a model of his factory to the web application, he is rewarded by obtaining in return an assessment of his performance. To be as intuitive as possible, the set of colors chosen for displaying the results is taken from traffic-light system: green means that the performance is good, yellow reflects a fair performance while a red color indicates a performance below the standard. This color code has been used in a wide range of applications as a rating mechanism (see for example Rozich and Resar (2002); Hargrave (2002); Wikipedia (2007)). Its use in a factory representation is illustrated in figure G.4, which is a selected frame of the level 2 representation of the boilerhouse given in Chapter 2 (see figure G.3). For this particular case, the interpretation of the color code highlights that the condensate return rate and the blowdown rate are good according to the standards that have been set. The total cost per ton of steam (energy costs and overhead costs) is, on the contrary, too high, meaning that the potential of improvement is important. As the variable cost per ton of steam is rated here as fair, the potential of improvement is to be found in the overhead costs.

Different options are possible to set threshold values that will distinguish a good performance from a fair performance and a fair performance from a bad one. These values can correspond, for instance, to standards or recommendations issued by the top management or the group of energy experts. Particularly, for factory sub-systems such as the energy conversion units, the fact that threshold values are set by experts in the field increase the value of the information provided by the web application. Another strategy is to compute the average value and the standard deviation of all the values of a given indicator available in the database of factory models in the web application. The thresholds can then be set at values corresponding to the average plus half the standard deviation and minus half the standard deviation. The advantage of having all the data of the factory models gathered in a centralized web application becomes evident here when compared to stand-alone solutions. Similarly, the threshold values that are set by management or the energy experts can be changed at any time with an immediate effect worldwide.

As explained above, the traffic-light rating mechanism will serve as a way to guide the user in browsing the factory models. Let us consider the example of figure G.1. This level 1 representation was purposefully taken from an early version of the software that did not implement the traffic-light features. The representation shown in this picture is the result a user gets after he selects a factory in the list of available factory models. Such a representation is useful since it gives the user the values of the main indicators of the factory. However, it fails to show wether it is worthwhile spending more time in this factory model, since there is no information that indicates if a given value for an indicator is a good or bad value for that factory. If for the same representation, the traffic-light are added, the user will have supplementary information, which will make its navigation more efficient. Indeed, if two out of the four indicators are red, the user knows that it might be worthwhile looking into the level 2 representation (sub-system level) to find more details about the causes of the bad performance as well as solutions to fix it. On the other hand, if all the indicators of level 1 are green, he will know that this factory is not a priority in terms of energy management.

6.2 Benchmarking worldwide KPIs

Benchmarking is the second strategy used in the web application to extract rapidly relevant information. Contrary to the rating mechanism introduced in the previous section, benchmarking does not provide an assessment of a given indicator based on standards, but by comparison with the indicators of its peers. Benchmarking will therefore come up with a classification of the factories according a given indicator. Thus, this mechanism will easily points out the factories with the biggest improvement potentials in a given area. In addition to contributing to the identification of these factories, benchmarking will also have a stimulating effect on them, which will make every effort to be ranked higher in the classification. This is another advantage of large companies compared to small and medium-sized enterprizes as regards energy management: as benchmarking can be performed internally in the company, there is an assessment of the performance and a competition among factories that guarantees a continuous improvement. Benchmarking is often not possible for small and medium-sized enterprizes due to their size [1]. The modular structure of the factory model allows for benchmarking not only high level indicators available for all the factories, such as energy usage per ton of finished goods, but also indicators of cross-cutting technologies, such as the boilerhouse.

As an example, figure G.5 illustrates the results of benchmarking the condensate return rate of a group of factories in the web application [2]. The ordering of factories by increasing performance will clearly have a positive effect on the least performing factories, which will strive to improve and leave their non-enviable positions to be occupied by others. However, benchmarking can also lead to a self-satisfied attitude on the part of the best performing factories, which is not desired. This is one of the disadvantages of the benchmarking approach: it assess the performance of individuals with respect to its peers, but does not provide an assessment of the potential for improvement for both the best and low performing factories. Consequently, other mechanisms, such as the comparison with best available technologies or best practices available from the energy experts, are to be used in complement to benchmarking to evaluate efficiency gaps and, consequently, improvement potentials (see section 6.5). From the factory management perspective, benchmarking will provide a basis to allo-

[1] It has however to be mentioned that some commercially available energy management tools propose the possibility of benchmarking performances with typical values from companies in a given sector.

[2] It has to be noticed here that the color code used in this figure does not relate to the traffic-light system introduced in the previous section

cate resources to areas of the factory with the highest improvement potentials. A factory will focus the use of its resources on improving indicators that reflect low performance when compared to other factories. Similarly, benchmarking higher level indicators, such as the energy use per ton of finished goods in a factory, will allow a top manager responsible for several factories to allocate resources to low-performing factories.

6.2.1 Filters

While the results of benchmarking give interesting and worthwhile trends, they have to be interpreted carefully. As said earlier in this work, each factory operates in a context that will influence its performance. External factors, such as energy prices, climate, etc, will have an important impact on performance indicators. Chapter 4 has highlighted that, in some factories, the heating of buildings can represent almost a quarter of the fuel consumption. Obviously, such factories will compare badly in indicators such as the energy use per ton of finished goods with similar factories located in areas where winter is not so severe. Even if efforts can be made to reduce the gap in heat consumption by improving insulation, for example, it will not be possible to totally bridge said gap. However, by considering the overall efficiency of boilers, instead of the energy used per ton of finished goods, factories can be compared in a more rational way. Results of benchmarking on energy used per ton of finished goods will also depend on production patterns. In factories operating with three shifts seven days a week, fixed cost absorption (base load consumption and heating requirements) will be much higher than in a factory operating with a single shift. The configuration of the production site will also influence the results of the benchmarking. Production sites that includes R & D activities or that have large administrative surfaces will have higher heating/cooling and water requirements than typical production sites. Similarly, other external factors, such as the local energy prices or the average wage of an operator, will affect the financial indicators. In the example of figure G.4, assuming that the threshold values have been set based on the average value and the standard deviation as discussed earlier, the red color of the indicator "Total cost per ton of steam" means that this factory has a higher cost of steam than the average factories included in the database. Although this indicator seems to highlight an important improvement potential, this cost might be at its minimum achievable value given the context in which this factory operates.

Energy performance indicators are also affected by the type of production in the factory. Some processes, such as milk powder processing, use energy-intensive equipments like evaporators or dryers while other processes, such as chocolate production, are much less energy-intensive. Comparing a factory from the first category with another from the second is equivalent to comparing an apple with an orange. The comparison is obviously not relevant. In order to help the user of the web application in the process of benchmarking, filters have been introduced in the application. For example, benchmarking can be limited to factories that produce ice creams. The application of filters is made possible by the structure of the factory model presented in Chapter 2, which distinguishes energy consumption from production lines and administrative buildings and which obliges the user to define the production type of each production line (23 product types are considered). The case of multi-product factories is also solved using filters. Indeed, it is not rare to encounter factories that produce more than one category of products and where these products are totally different (ice cream and soup, for example). Benchmarking indicators of individual production lines instead of global indicators of the factory using filters permits a sensible comparison.

As regards energy conversion, the same problems might occur but at a minor level. Let us consider the example of the indicator "overall efficiency of boiler". Even if it is possible to compare the efficiency of all boilerhouses included in the data base, the benchmarking results will obviously highlight that, in average, gas-fired boilerhouses are more efficient than boilerhouses burning HFO, for instance. This is principally due to the minimum allowable stack temperature, which is much lower in gas-fired boilers than in HFO boilers. Once again, by adding a filter on the energy source, the results of benchmarking are made much more relevant.

6.3 "What if?" scenarios

The top-down factory representations (level 1 and level 2) with the help of the traffic-light system as well as benchmarking allow to identify areas where improvements are possible. The next natural step of the approach is to provide the user with a way to quantify the potential of improvement. While this is done using the bottom-up approach introduced in Chapter 5 as regards improvements in the process, improvement potentials in energy conversion units can be quantified in the web application based on the thermo-economic models presented in Chapter 3. We will deal with this subject in the section and will present "what if?" scenarios. The philosophy of "what-if?" scenarios is illustrated in figure 6.2. In a first step (point 1 in the figure), a potential of improvement is identified in a specific area through a top-down vision of a factory (level 1 and level 2 representations), using the support provided by benchmarking and/or by the traffic-light rating. Provided that a simulation module is available in that area, simulation parameters are sent to the simulation module (point 2). These parameters include values describing the present state of the sub-system, but also new values that correspond to the desired state after the simulation. Based on these parameters, the simulation module determines the new state of the sub-system (point 3). The new simulated values are sent back to the factory model (point 4) to determine not only the new state of the sub-system (denoted level 2* in the figure), but also the impact on the global system (Level 1*) in a bottom-up vision (point 5).

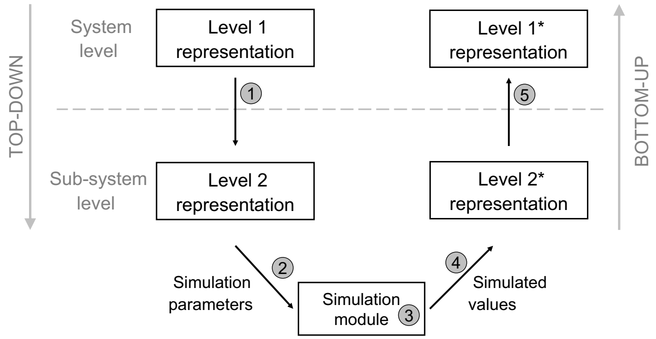


Figure 6.2: "What-if?" scenarios

6.3.1 Perspectives of experts and engineers in factories

The energy experts available for support in the head office play an important role in the definition of a "what if?" scenario in a specific area. Firstly, they define the criteria that determine the availability of a given "what if?" scenario in a specific case. For instance, a boilerhouse with a 2% blowdown rate will not be eligible for a "what if?" scenario to recover heat from the blowdown. By experience, it is known that investing to recover this waste heat will not be profitable. Indeed, these criteria serve as a first filter to propose the engineer in the factory only relevant "what if?" scenarios in a given case. Secondly, the experts define or, at least validate, the thermo-economic models used for the simulation. This guarantees that the results of the simulation are reliable and prevents the engineer from contacting the experts for projects that do not deserve further study.

From the perspective of the engineer in the factory, the results of the simulation are presented in the form of new level 1 and level 2 representations (denoted 1* and 2* in the figure) and of detailed profitability and risk analysis reports. Said reports provide the engineer with a clear image of the impact that a potential retrofit or change in operating conditions could have on a factory. Based on the analysis of the results, the engineer might contact the expert in the specific area investigated for the validation of the simulation results and for further details regarding the practical implementation within the factory.

To summarize, the implementation of "what if?" scenarios in the web application should benefit both the engineers in the factories and the experts in the head office. For the engineers, the possibility of receiving suggestions of ways to improve energy efficiency as well as a reliable quantification of the potential benefits should greatly help them in reducing energy costs in their facilities and in reaching the targets set by the management. With respect to experts, the definition of reliable "what if?" scenarios, although time consuming, permits to disseminate their know-how throughout the company. Subsequently, it is also a means of filtering the requests of engineers in factories as regards energy efficiency projects. Indeed, engineers will contact experts only for projects that have been evaluated as profitable through "what if?" scenarios.

6.3.2 "What if?" scenarios for the boilerhouse

At the time of writing this thesis, "what if?" scenarios had not been implemented in the web application. However, their relevance has been demonstrated through the prototype of a web-based simulation platform developed in this work in parallel to the web application. A more detailed discussion about IT issues of this prototype will be given in Chapter 7. The developed simulation platform implements "what if?" scenarios on the boilerhouse. The boilerhouse has been chosen to demonstrate the concept for various reasons. Firstly, it is to be found in nearly all factories in the food industry. Consequently, the developed scenarios can be applied in a majority of the factories of a food company. Secondly, it is a large consumer of fossil energy and, consequently, a large source of CO_2 emissions. It is thus a particularly interesting area for reducing greenhouse gases emissions. Thirdly, since some of its performance indicators (condensate return rate and blowdown rate) influence not only the fuel consumption but also the water consumption (impact on other utilities such as compressed air or electricity is not considered here), it will also have an important impact on the environmental performance of a factory. The different "what if?" scenarios that have been considered for the boiler house are:

- condensate return increase
- steam consumption reduction
- blowdown decrease
- blowdown heat recovery (2 configurations)
- addition of an economizer

6.3.3 Addition of an economizer

Adding an economizer is a well-established conservation measure in a boilerhouse. The economizer allows for preheating the incoming feedwater with the fumes that are leaving the boiler. This configuration is often preferred to an air preheater since it requires less investment and less fan horsepower for the combustion air. By reducing the stack temperature of a boiler, the addition of an economizer will decrease the stack losses as shown in equation (3.10). The parameters to be used in this equation depend on the type of fuel in use in the boilers and are provided in table 3.6. The type of fuel will also determine the minimum allowable temperature at the outlet of the economizer. Fuels with a high sulphur-content (HFO for instance) have their dew-point temperatures increased compared to low-sulphur fuels, as shown in section 3.2.1.2. Indeed, a combination of water with SO_3 in the fumes leads to the formation of H_2SO_4, which will cause corrosion problems in the economizer. It is recommended to maintain the temperature at the outlet of the economizer at least 40°C above the dew point temperature in order to avoid condensation at the economizer walls. To maintain the necessary heat transfer surface in an acceptable limit, a minimum temperature difference of 40°C is also recommended between the feedwater inlet temperature and the fumes outlet temperature.

6.3.3.1 Simulation model

The strategy adopted to compute the new fuel consumption is illustrated in figure 6.3. As the data available in the web application is annual, the overall efficiency of boilers is computed based on the annual fuel consumption of all the boilers in the boiler house. For instance, the consumption of an eventual stand-by boiler is taken into account. According to the performance indicators introduced in section 3.2.4, such consumption will be accounted in the so called "other losses". The value of these losses, expressed as a percentage of the total energy supplied by the fuel, is computed by deducting the heat content of the steam, of the stack losses and of the blowdown losses from the total heat of the fuel burnt. As the addition of an economizer will not reduce these losses, they have to be excluded from the computation when computing the new fuel consumption (point 1 in the figure). The impact of the addition of an economizer on the stack losses is then computed by introducing the new expected stack temperature after the addition of the economizer in equation (3.10) (point 2). Finally, the contribution of the "other losses" is integrated to compute the new fuel consumption as well as the new overall efficiency of boilers (point 3).

The computation of the new fuel consumption and the related fuel savings are the first step of the simulation. The second step consists in estimating the heat transfer surface that is

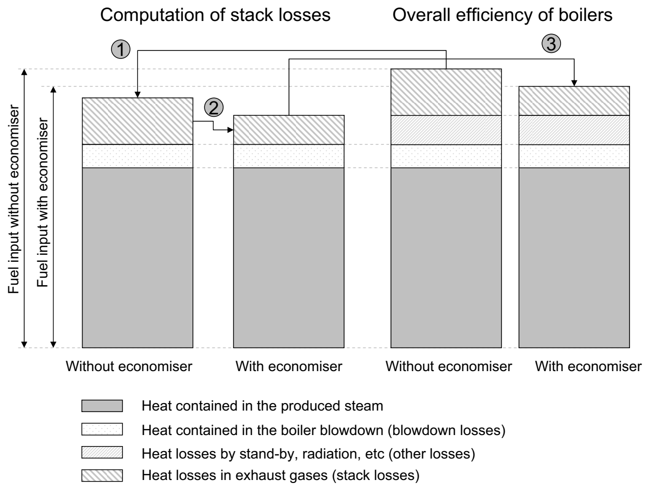


Figure 6.3: Modeling strategy adopted to compute fuel saving when adding an economizer in a boilerhouse

required for the economizer and the related investment. This is achieved by first computing the average load $\dot{Q}_{eco}$ (expressed in kW) of the economizer based on the average steam production. This enables the computation of the expected temperature of the feedwater at the outlet of the economizer. The inlet and outlet temperature of the feedwater and the fumes being known, the heat transfer surface required A can be estimated from the following equation:

$$\dot{Q}_{eco} = U \cdot A \cdot F \cdot \Delta T_{lm} \tag{6.1}$$

where U is the global heat transfer coefficient and ΔT_{lm} is computed according to equation (C.2) and (C.4). The value of U will depend on the economizer designs and on the material, as explained in appendix C.2. For this simulation, we will consider the two types of economizers introduced in section 3.2.6.1: carbon steel and stainless steel economizers. The corresponding global heat transfer coefficients U are available in table 3.9. The surface required being identified, the estimated investment cost can be computed according to equation (3.14).

In addition to the energy aspect, other parameters are relevant when evaluating the possibility to add an economizer. They include: space availability for heat recovery, adequacy of fans and pumps to overcome increased resistance of heat-recovery equipment. A comparison of various economizer designs with respect to such practical considerations is presented in table 6.1.

Table 6.1: Characteristics of various economizer designs (Vandagriff, 2001)

Tube arrangements		**In-line**			**Staggered**	
Tube surface	**Spiral fin**	**Stud**	**Bare**	**Spiral fin**	**Stud**	**Bare**
Price	Low	Moderate	Very high	Low	Moderate	High
Space required	Small	Medium	Large	Small	Medium	Large
Gas pressure drop	Medium	Medium	High	High	High	High
Weight	Medium	Medium	High	Low	Medium	High
Number of welds	Low	Medium	High	Low	Medium	High
Average life years	10-15	20	30 plus	5-10	10	15-20
Operational avail.	Low	Fair	Good	Low	Moderate	Good

6.3.3.2 Input form of the "what if?" scenario

The parameters to be used in the simulation model to compute the new state of the system (see point 2 in figure 6.2) are collected in the developed simulation platform using an input form. As an example, the form corresponding to the simulation presented here is shown in figure 6.4. The simulation parameters includes values describing the present state of the system in the first part, additional parameters to characterize the present operating conditions of the boilers in the middle section and finally, the parameters that will be used to define the new state of the system. It has to be emphasized here that for a maximum user-friendliness, all values already available in the application are already introduced by default and cannot be modified (see first section). Additional features include a pop-up graph (available in figure A.1) to help the user define the air excess in the boilers (defined here through the oxygen content in the flue gases). A pop-up window with the scheme of the boilerhouse is also available (see the link at the bottom of the input form). When the user click the "simulate" button, the parameters are passed to the simulation model that computes the new state of the system. Once available from the model, the results of the simulation are presented on the screen as shown in figure 6.5. They include the saving in terms of fuel, water and CO_2 and the estimated investment. The user can then optionally generate a PDF report of the simulation or make a more detailed profitability analysis. These functionalities will be treated in section 6.4 and 6.6.

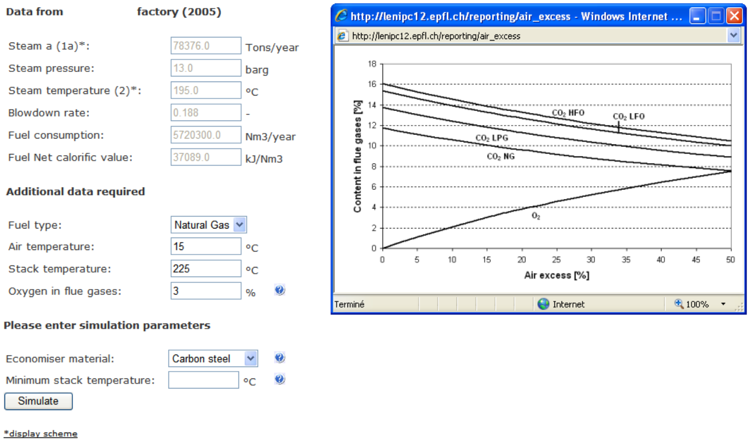


Figure 6.4: Input form for adding an economizer in the developed simulation platform

Annual saving in factory by adding an economiser

	Original	Simulated	Difference
Stack temperature [°C]	225.0	150.0	75.0
Stack losses [%]	9.9	6.3	3.5
Overall boiler efficiency [%]	87.6	91.0	3.4
Fuel [Nm3/y]	5,720,300	5,503,646	216,654
CO2 [Ton/y]	11,902	11,451	451
Water [m3/y]	40,052	40,052	0
Fuel cost [CHF/y]	1,870,538	1,799,692	70,846
CO2 cost [CHF/y]	254,707	245,060	9,647
Water cost [CHF/y]	374,863	120,156	0
Total cost [CHF/y]	2,245,401	2,164,908	**80,493**

Estimated investment [CHF]	**101,862**

Generate PDF report

The simulation result showed a positive saving. Suggested next step:

Estimate investment profitability

Back

Figure 6.5: Results of the "what if?" scenario

6.3.4 Other simulations

6.3.4.1 Condensate return increase

Even when in some cases part of the steam condensate cannot be returned to the boilerhouse because steam has been either directly injected in the process or in contact with substances that can cause hygienic problems, best practice for the boilerhouse suggests returning the maximum amount of condensate to the boilerhouse. This is motivated by the fact that steam condensate represents a large amount of energy (usually they are returned at a temperature of approximately 90°C), which would be lost if not returned, and by the impact that it has on the makeup water consumption. Indeed, condensate return will substitute part of the makeup water and, consequently, reduce the amount of water to be treated. This will decrease the consumption not only of fresh water but also of the chemicals needed for its treatment. In theory, the change in condensate return will have an impact on the blowdown rate. Indeed, the returned condensate typically has a very low conductivity, in the range of 0-10 μS/cm, since it results from the condensation of pure steam. It is only when circulating it in the pipes that its conductivity will slightly increase. On the other hand, make-up water has a higher conductivity even when treated. Its value is approximately in the range 100 - 300 μS/cm. Since the condensates and the makeup are mixed to form the feedwater, an increase of the amount of condensate returned will decrease the feedwater conductivity, which will, in turn, decrease the blowdown rate. For simplification purposes, this effect is not taken into account here and the blowdown rate is assumed to remain constant.

Referring to figure 3.4, increasing the condensate return rate will mean an increase of the massflow of stream nr 2 while maintaining constant the steam produced that is sent to the process (point b). For this "what if?" scenario, the user is asked to specify a new value for the condensate return rate (cr) as well as the impact on the average temperature of the condensates (stream nr 2). Indeed, if the condensates that are newly returned to the boilerhouse are at a higher temperature than the actual average temperature of the condensates, this average temperature will be increased. The resulting system of equation to solve is identical to the system (3.5). The unknowns are now $\dot{m}_1$, $\dot{m}_2$, $\dot{m}_4$, $\dot{m}_5$, $\dot{m}_6$, $\dot{m}_7$, $\dot{m}_a$.

6.3.4.2 Steam consumption reduction

This simulation assumes that the quantity of steam sent to the process (stream b in figure 3.4) is decreased. The user is asked to specify the new quantity of steam that is not returned to the boilerhouse and the new quantity of steam returned. These two values define a new quantity of steam sent to the process and a new condensate return rate. As the average temperature of the condensate might change, the user is asked to update it if necessary. The resulting problem to solve is identical to the previous case (condensate return increase).

6.3.4.3 Blowdown reduction

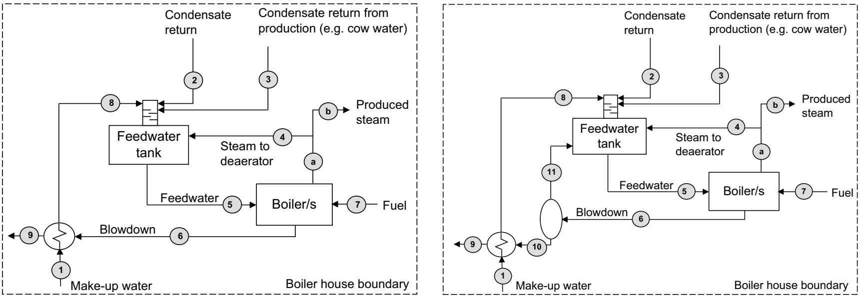
The blowdown is necessary to reduce levels of suspended and total dissolved solids (TDS) in the boiler. Indeed, if these solids left by the evaporated water in the boiler are not eliminated, they will form sludge or sediments, a situation which degrades heat transfer. The blowdown contains a substantial amount of energy since it leaves the boiler as a saturated liquid at boiler pressure. Consequently, the blowdown rate has to be optimized in order not to loose too much energy, water and chemicals while maintaining a low level of deposits. The means to reduce the blowdown are:

- Increasing the quality of feedwater.
- Allowing a higher level of TDS in the boiler drum.
- Improve the blowdown control.

In this simulation, the user is asked to specify the new value of the blowdown rate (br). The system of equation to solve is identical to the system (3.5). The unknowns are $\dot{m}_1$, $\dot{m}_2$, $\dot{m}_4$, $\dot{m}_5$, $\dot{m}_6$, $\dot{m}_7$, $\dot{m}_a$

6.3.4.4 Simulation: Blowdown heat recovery

If, for any reason, a large blowdown cannot be decreased, it is possible to recover part of its heat. Two configurations have been considered here. The first one simply consists in preheating the makeup water with the heat of the blowdown using a heat exchanger (see figure 6.6(a)). The second one is more complex and will also allow for the recovery of part of the water from the blowdown as low pressure steam. The principle, illustrated in figure 6.6(b), is to reduce the pressure of the blowdown in a flash vessel. The resulting low pressure flash steam is sent to the feedwater tank and will decrease the amount of high pressure steam required for this unit (point 4 in the figure). The low pressure liquid at the outlet of the flash vessel (still at a temperature of approximately 100°C) goes then through a heat exchanger to give part of its heat to the makeup water.



(a) Simple heat recovery (b) Flash heat recovery

Figure 6.6: Configurations considered for blowdown heat recovery

In both cases, the user is asked to specify the temperature of the blowdown after the heat recovery exchanger (point 9 in both figures). In the second configuration, the pressure of the flash vessel is set at 1.3 bars just above the pressure in the feedwater tank [3]. By adding the recovery unit, the size and the complexity of the problem has been increased. For the first configuration, the system of equation (3.5) becomes a 10 x 10 nonlinear system of equations, which is available in appendix G. The nonlinearity comes from the fact that both the massflow and the temperature of the makeup water after the heat recovery are unknown. A discrete Newton algorithm from the GNU scientific library [4] is used to solve this system of equations. As regards the second configuration, the problem to solve is a 12 x 12 nonlinear system of equations, which is available in appendix G.

6.4 Profitability and risk analysis in "what if?" scenarios

The decision of undertaking an energy efficiency project will mainly depend on the profitability of the project even if some other aspects are also important such as operability, safety, etc. In the case of retrofitting, the profitability analysis will compare a given investment option with a "do nothing option". Many economic analysis can be performed in order to asses the profitability of a project. However, when it comes to assessing energy efficiency projects, a study of behavior of Australian firms showed that three main rules are used (Harris et al., 2000):

[3] A flash at higher pressure is also possible. The resulting steam can then be sent to a low pressure steam network if there is one in the factory. This case was not considered here.

[4] www.gnu.org/software/gsl/

- Payback is the most widely used decision-making rule (80% of the firms use it).
- 50% of the firms use the rate of return on capital.
- 30% of the firms use positive Net Present Value (NPV).

These three methods are widely described in literature (see for example Turton (1998) or Bejan et al. (1996)). In this work, we have chosen to limit the analysis to the computation of the payback. The payback (PB) can be defined as the time required to recover a capital investment. It is usually measured in terms of month or years. Mathematically, it can be expressed as:

$$PB = \frac{I}{S} \tag{6.2}$$

where I, expressed in monetary units, is the capital investment required for the project and S is the yearly saving after tax. Knowing the tax rate t, S can be determined as follows:

$$S = S_t - (S_t - d) \cdot t \tag{6.3}$$

Where S_t is the yearly saving before tax and d is the annual depreciation allowance. Here, the straight line method is used to compute this allowance d^{SL} based on the capital investment and the lifetime of the equipment n:

$$d^{SL} = \frac{I}{n} \tag{6.4}$$

We can observe that the shorter the payback, the more profitable the capital investment. The success of this profitability criterion can be explained by its simplicity. However, since it does not take into account the time value of money, it should not be considered on its own for assessing projects requiring large investments.

Dalsgard et al. (2000) suggest to use the marginal payback in complement to the simple payback to evaluate the profitability. The marginal payback (MPB) represents the payback of the last invested Swiss franc or Euro (for instance). It is defined as

$$MPB = \frac{dI}{dS} \tag{6.5}$$

The demonstration below shows that the minimum of the payback function will be obtained when the payback equals the marginal payback. The minimum of the payback in a given interval occurs either at the extremities of the interval or where the slope of the function (derivative) is zero inside the interval, provided that the function is convex. Thus, from equation (6.2), we have

$$\frac{dPB(x)}{dx} = \frac{\frac{dI(x)}{dx}S - I\frac{dS(x)}{dx}}{S(x)^2} = 0$$

$$\Leftrightarrow \frac{dI(x)}{dx}S = I\frac{dS(x)}{dx} \Leftrightarrow \frac{dI(x)}{dS(x)} = \frac{I(x)}{S(x)}$$

It has to be noticed that beyond energy, energy saving actions often lead to non-energy benefits that should be quantified and taken into account at the moment of assessing the profitability of the action (Pye and McKane, 2000). These benefits are, for example, increased productivity, reduced costs of environmental compliance, reduced production costs (including labor, operations and maintenance, raw materials), reduced waste disposal costs, improved product quality, improved capacity utilization, improved reliability, improved safety, etc. On the other hand, "hidden costs" such as cost due to loss of production during installation, the cost of training of operators, the risk of production losses due to modifications in the process and the replacement of equipment not fully depreciated, might significantly decrease the profitability of the project and are to be well estimated.

6.4.1 A graphical representation as a decision support tool

As an alternative to the representation showed in figure 6.5 for the addition of an economizer, a graphical representation, such as the one presented on figure 6.7, can be used to identify the solution with an optimal profitability. It represents the annual saving and the investment on the left axis (in CHF) and the payback and the marginal payback on the right axis as a function of the stack temperature. This graph is obtained by decreasing the stack temperature in 10 discrete steps till reaching the minimum allowable temperature specified by the user. At each step, the saving, the investment, the payback and the marginal payback corresponding to this stack temperature are computed. This graph also highlights at which stack temperature occurs the minimum payback. As demonstrated earlier, it corresponds to the temperature at which the payback is equal to the marginal payback. If the minimum payback does not occur at the minimum allowable stack temperature, the optimal temperature is identified by fitting the payback curve around the optimum with polynomial approximation. For a quadratic polynomial, three points of the curve are needed to compute the parameters a_0, a_1 and a_2 in equation (6.6).

$$f(x) = a_0 + a_1 x + a_2 x^2 \tag{6.6}$$

The three points used are the minimum payback obtained with the discrete step approach and the points from the previous and the following steps. The minimum of the quadratic polynomial x^* can then be determined as follows:

$$x^* = -\frac{a_1}{2a_2} = \frac{1}{2}\frac{(x_2^2 - x_3^2)\cdot f_1 + (x3^2 - x_1^2)\cdot f_2 + (x_1^2 - x_2^2)\cdot f_3}{(x_2 - x_3)\cdot f_1 + (x_3 - x_1)\cdot f_2 + (x_1 - x_2)\cdot f_3} \tag{6.7}$$

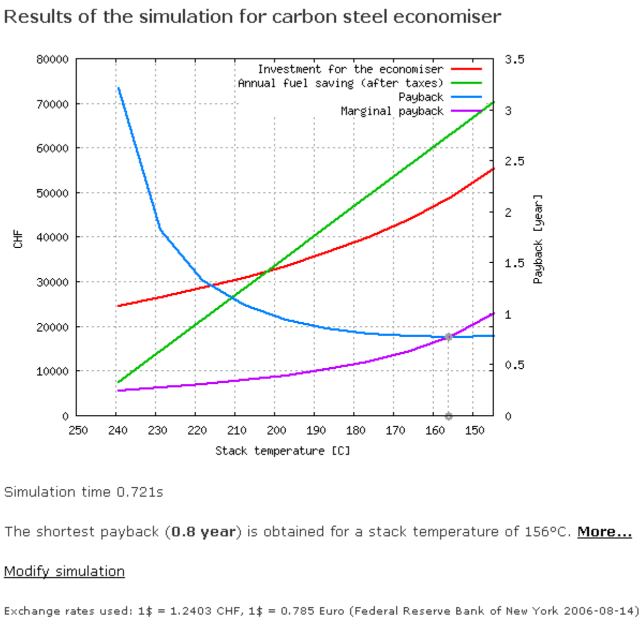


Figure 6.7: Graphical representation of the results of a "what if?" scenario

Compared to the results presented in figure 6.5, such a graphical representation has three main advantages. Firstly, it shows useful trends. For instance, we can see in the figure 6.7 that the investment (linked to the required heat exchange surface) increases in a nonlinear pattern while the saving is almost linear. This confirms the relevance of the rule of thumb, which states that the temperature difference between the flue gases at the outlet of the economizer and the incoming feedwater should not be lower than 40°C (here we have 51°C for the optimal payback). Secondly, such a representation clearly identifies the optimum payback. Finally, the chart can be read in the other direction. For example, the stack temperature to achieve a given saving can be identified.

Even when "what-if?" scenarios provide a powerful decision support tool, interpretation of the results and the feasibility of the project will, however, require expertise in the field. Indeed, this tool should never substitute the expertise of an engineer or of a specialist in the field. As all the users of the platform might not have the required expertise, the tool offers the possibility of contacting, through e-mail, an expert of the company in this area. As all the results of simulations are saved in a database, the expert can have access to the simulation and all its parameters through a link available in the body of the message (see figure 6.8). This enables the validation of the simulation by an expert.

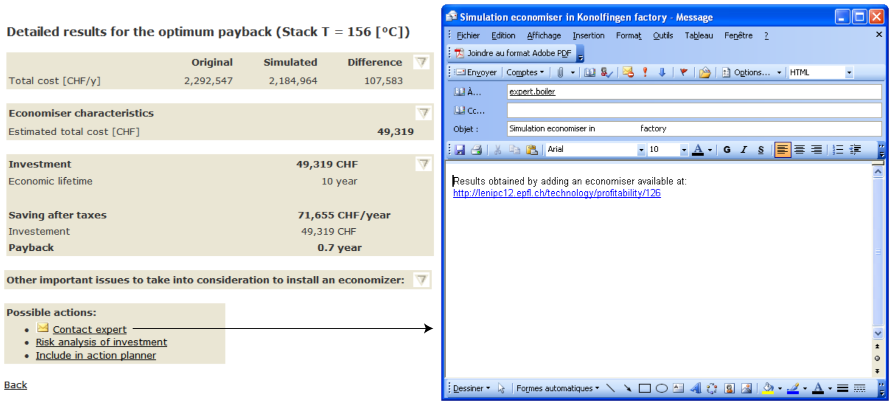


Figure 6.8: Sharing the results of a "what if?" scenario with an expert

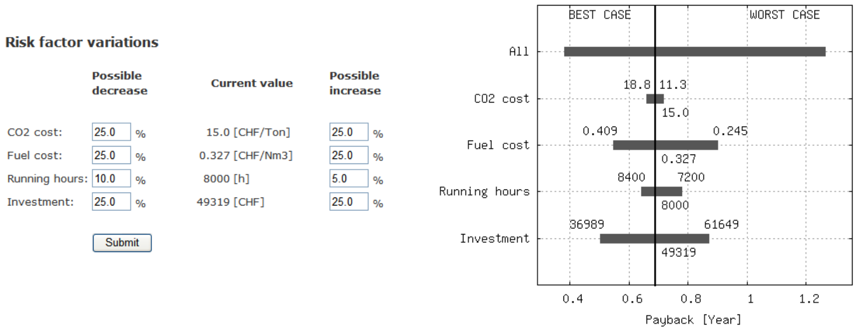
6.4.2 Risk analysis

We have seen back in Chapter 1 that the very conservative attitudes of firms towards risk has a negative impact on the implementation of energy efficiency measures. This is essentially due to the fact that the value of any possible production losses due to modifications in the process are much greater than the value of energy savings. In the opinion of the author, such a barrier can be overcome if experiences in other factories show that similar projects have been successfully implemented. Once again, this emphasizes the importance of sharing information and experience in the company. In the case of the web application, a database of energy saving actions implemented in the company has been included in the application, but is not described in this work. However, other factors can influence the profitability of an energy efficiency investment. They include, for instance, uncertainties in the prices of energy and in the prices of greenhouse gas emission allowances traded in the European Union Emission Trading Scheme (EU ETS). Running hours of the unit on which an investment has been made can also be subjected to uncertainties due to the volume of sales of the final products and can impact the project profitability. Finally, the energy saving and the investment that have been estimated in the project evaluation are also likely to change once implemented. Such "hidden costs" are usually not taken into account in traditional profitability calculations and can influence the final decision (DeCanio, 1998). In that sense, an analysis of the impact of these factors through a risk analysis appears here as a necessity. The analysis of a risk takes into account two components: the likelihood of occurrence of the event (e.g. a rise of 20% of fuel prices) and its impact (e.g. an increase of 50% of the payback). Formally, risk is defined as the product of these two components (Ayyub, 2003). If the models used for simulation are of no help to predict the likelihood of occurrence of events, such as increase in energy prices, they can be used to determine the impact of such factors on the profitability analysis. This has been implemented in the developed simulation platform prototype using what is usually referred to as a Tornado chart [5]. Figure 6.9(b) shows a screenshot of such a chart for the analysis of different risk factors and the combination of all of them (referred to as "All" in the figure). The Tornado chart is based on the current situation (current value of the payback) which is represented by the vertical line at the middle of the chart. Then, for each factor and for the combination of all these factors, a "best case" and a "worst case" is computed and represented here through the resulting paybacks. The definition of these "best case" and "worst case" scenarios are based on values from the user, who defines for each factor the possible variations (see figure 6.9(a)). In the example of figure 6.9(b), the Tornado chart highlights that the risk factors with the highest impacts are the fuel price and the investment. A 25% increase in fuel prices results in an increase of the payback from 0.7 to 0.9 years. This chart also shows that a combination of all the risk factors can nearly double the payback time (from 0.7 to 1.3 year).

6.5 Best in class and best available technology

In section 6.2, we highlighted that benchmarking, while having a stimulating effect for low performing factories, can generate an attitude of self-satisfaction in factories with good

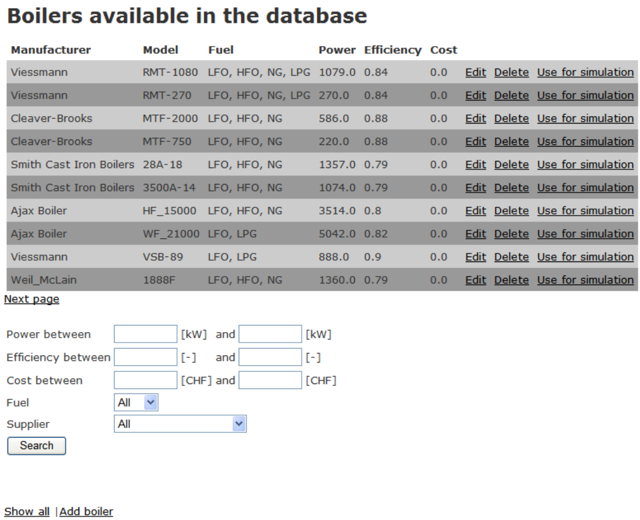
[5]Other tools, such as Monte Carlo simulations (see for example Varma et al. (2007)), are available for dealing with risk and uncertainties but have not been considered in this work



(a) Quantification of risk factors (b) Tornado chart

Figure 6.9: Risk analysis in the simulation platform

indicators. The fact that such factories are performing better than others does not necessarily mean that they cannot improve their performance. In order to assess the performance of these factories with respect to the maximum performance that they could achieve, the concepts of "Best in class" and "Best available technology" are introduced. Best in class refers to the maximum performance that can be achieved in a given context. These values are typically defined by the group of experts in a specific area. Performing a simulation with the best in class value as the new value of a given performance indicator will permit to identify the efficiency gap between the present performance and the maximum achievable. Best available technology refers to the best technology that is currently available in the market. Comparing the present performance of an equipment (an air compressor for instance) with the performance of the best available technology for that equipment also permits to identify a saving potential. Obviously, in most of the cases, shifting from the current technology to the best available technology will make sense only when that equipment needs to be replaced. However, introducing this concept makes the user aware that new efficient technologies exist and could be considered at the moment to improve energy efficiency. Best available technologies will be stored in data bases of equipments, which will be filled by the experts that are continuously in contact with manufacturers. An example of such a database as it would appear to the expert in the application is shown in figure 6.10. It contains entries, such as the manufacturer, the model, the size of the equipment, its efficiency and the cost. Comparing the present efficiency of a boiler with the best available technology will simply consist in picking up the boiler with the highest efficiency for a given fuel and a given size.



Boilers available in the database

Manufacturer	Model	Fuel	Power	Efficiency	Cost			
Viessmann	RMT-1080	LFO, HFO, NG, LPG	1079.0	0.84	0.0	Edit	Delete	Use for simulation
Viessmann	RMT-270	LFO, HFO, NG, LPG	270.0	0.84	0.0	Edit	Delete	Use for simulation
Cleaver-Brooks	MTF-2000	LFO, HFO, NG	586.0	0.88	0.0	Edit	Delete	Use for simulation
Cleaver-Brooks	MTF-750	LFO, HFO, NG	220.0	0.88	0.0	Edit	Delete	Use for simulation
Smith Cast Iron Boilers	28A-18	LFO, HFO, NG	1357.0	0.79	0.0	Edit	Delete	Use for simulation
Smith Cast Iron Boilers	3500A-14	LFO, HFO, NG	1074.0	0.79	0.0	Edit	Delete	Use for simulation
Ajax Boiler	HF_15000	LFO, HFO, NG	3514.0	0.8	0.0	Edit	Delete	Use for simulation
Ajax Boiler	WF_21000	LFO, LPG	5042.0	0.82	0.0	Edit	Delete	Use for simulation
Viessmann	VSB-89	LFO, LPG	888.0	0.9	0.0	Edit	Delete	Use for simulation
Weil_McLain	1888F	LFO, HFO, NG	1360.0	0.79	0.0	Edit	Delete	Use for simulation

Next page

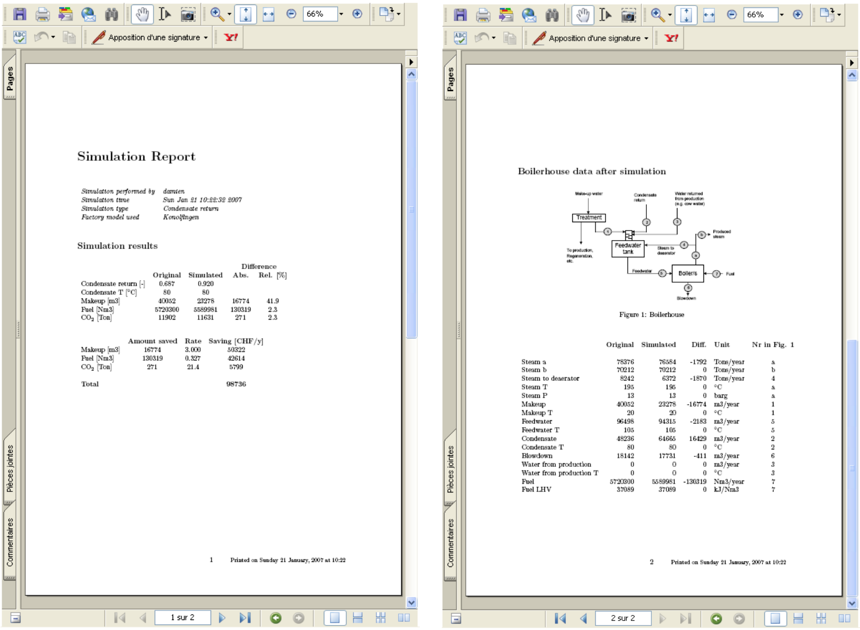
Power between [kW] and [kW]
Efficiency between [-] and [-]
Cost between [CHF] and [CHF]
Fuel All
Supplier All
Search

Show all | Add boiler

Figure 6.10: Database of boilers

6.6 Reporting

Even if the developed simulation platform allows to share the results of a simulation through a web link (see figure 6.8), the possibility of generate a paper report of the result is also available. An example of such a report is presented in figure 6.11 for a simulation where the condensate return has been increased. The report appears as an embedded PDF document in the application frame, which can be printed, saved on a local machine, etc. The first page presents general information regarding the simulation (simulation type, author of the simulation, simulation date, etc) as well as its main results (energy and water saving and corresponding financial impact). As a complement, the second page offers a detailed description of the new state of the sub-system after the simulation. The new values at each point referred in the figure of the sub-system (equivalent to figure 3.4) are displayed. Finally, extended versions of the report include, in addition, a detailed description of the profitability analysis. Obviously, paper reports are not limited to the simulation module and should be made available for other areas such as benchmarking.



Simulation Report

Simulation performed by	*damien*
Simulation time	*Sun Jan 21 10:22:32 2007*
Simulation type	*Condensate return*
Factory model used	*Konolfingen*

Simulation results

	Original	Simulated	Difference Abs.	Difference Rel. [%]
Condensate return [-]	0.687	0.920		
Condensate T [°C]	80	80		
Makeup [m3]	40052	23278	16774	41.9
Fuel [Nm3]	5720300	5589981	130319	2.3
CO_2 [Ton]	11902	11631	271	2.3

	Amount saved	Rate	Saving [CHF/y]
Makeup [m3]	16774	3.000	50322
Fuel [Nm3]	130319	0.327	42614
CO_2 [Ton]	271	21.4	5799
Total			98736

1 Printed on Sunday 21 January, 2007 at 10:22

Boilerhouse data after simulation

Figure 1: Boilerhouse

	Original	Simulated	Diff.	Unit	Nr in Fig. 1
Steam a	78376	76584	-1792	Tons/year	a
Steam b	70212	70212	0	Tons/year	b
Steam to deaerator	8242	6372	-1870	Tons/year	4
Steam T	195	195	0	°C	a
Steam P	13	13	0	barg	a
Makeup	40052	23278	-16774	m3/year	1
Makeup T	20	20	0	°C	1
Feedwater	96498	94315	-2183	m3/year	5
Feedwater T	105	105	0	°C	5
Condensate	48236	64665	16429	m3/year	2
Condensate T	80	80	0	°C	2
Blowdown	18142	17731	-411	m3/year	6
Water from production	0	0	0	m3/year	3
Water from production T	0	0	0	°C	3
Fuel	5720300	5589981	-130319	Nm3/year	7
Fuel LHV	37089	37089	0	kJ/Nm3	7

2 Printed on Sunday 21 January, 2007 at 10:22

(a) (b)

Figure 6.11: Example of a PDF simulation report

6.7 Conclusion

This chapter has demonstrated the potential benefits resulting from the use of web technologies in energy management. This is especially relevant for large companies that have the opportunity to share the know-how available inside the company among subsidiaries through the use of existent IT infrastructure such as the company Intranet. This has been illustrated in this chapter by implementing the proposed methodology in a web application in collaboration with an industrial partner. The deployment of this web application permits to all the agents involved in energy management in the company (managers, engineers, experts in energy) to have access to the energy-related information of factories worldwide.

In order to facilitate the extraction of pertinent data out of the large amount of data made available and to guide users to areas of potential improvement, a traffic-light color code has been implemented to give information on the quality of indicators displayed in the web application. Through the use of a global web application, the threshold values separating distinct performance can be updated easily at any time or could even be set dynamically based on information stored in the database of the application. A benchmarking platform has also been successfully implemented allowing for the comparison of performances among factories worldwide. The relevance of introducing filters to increase the significance of benchmarking results has also been discussed and demonstrated.

The prototype of a simulation platform proposing "what if?" scenarios based on the models of Chapter 3 is presented. The architecture as well as the different possibilities to interact with this platform are discussed in the next chapter. The developed platform provides a user-friendly interface for simulating operation changes in the boilerhouse sub-system. Graphical representations for assessing the profitability as well as the risk of implementing the related energy saving actions are also presented.

In conclusion, the development of this web application and the future implementation of "what-if?" scenarios provide all the tools to guarantee an efficient and sustainable energy management in the company. The application permits different users to work more efficiently. It also allows managers to set priorities when allocating resources available for energy management as well as to monitor worldwide factories. It provides engineers in factory with a means to assess their performance according to standards set by the experts (traffic-light system) and by comparison with other factories worldwide through benchmarking. Based on this information, the engineers can identify areas with important saving potential. In addition, they have the possibility to quantify energy saving options in energy conversion units through "what if?" scenarios that have been validated by experts in the fields. Finally, the latter can disseminate their knowledge in the factories worldwide in a efficient manner, which allows for filtering the request of engineers in factories as regards energy efficiency projects.

Chapter 7

IT implementation

This chapter presents the IT implementation of the simulation platform prototype developed in this thesis. The description of the web application, which includes the implementation of the factory model described in Chapter 2, the storage of models in a database as well as all the implementation of the traffic-light system and the benchmarking described in Chapter 6, is not covered here. However, a description of the underlying philosophy as well as the implementation of an early version of the application can be found in Ferrão (2004). It has to be emphasized here that both the web application and the simulation platform prototype are tightly linked and have been conceived based on the same philosophy developed during this work. In addition, they will be communicating in a near future as the simulation platform prototype will act as the simulation engine of the web application for "what if?" scenarios. The communication between both applications will be realized using web services an innovative technology based on XML. In a first part, this chapter describes the simulation platform as well as its graphical user interface (GUI) while, in a second part, the issues related to the communication between both applications using web services are discussed. Before going into these technical aspects, we will however discuss more in depth the concept and some of the specifications that guided the development of both the web application and the simulation platform prototype.

7.1 Introduction

Very early in this project, it has appeared that the success of the web application would depend on the acceptance of people involved in energy management. The philosophy adopted here has not been to impose the software to engineers in factories and managers in head office but to make it available as a tool to help them in their respective tasks to conserve energy. If the users feel that the application can facilitate their work and represent an added-value, it would sell for itself. In that context, two aspects have been considered as fundamental during its development. Firstly, the application has to be adapted to the needs of the different users and should be based on an efficient and clear methodology that they understand and agree with. Secondly, the methodology has to be available in an interface that has to be as user-friendly and intuitive as possible. This is as important or even more important than the first point as regards the success of the application in the company. Similar conclusions have also been drawn for the transfer of technology to non-researcher (Buchanan, 1993). This need for user-friendliness is particularly relevant in web applications that offer traditionally less interactive interfaces than desktop applications. In this context, recent technologies such as Ajax have emerged to fill this gap between desktop and web applications. The use of such technologies will be illustrated later in this chapter. For the moment, the following specifications are established for the development of the software and the simulation platform:

- Actions by the user are limited to inputting values or selecting predetermined options.
- The software tests and if necessary rejects values outside of the specified ranges.
- The user should not enter twice the same value.
- While being intuitive, the software should provide a "help" that will guide the users that are less familiar with energy management.
- The user should not wait more than 30 seconds for the results of a request.
- The application should provide a feedback on its status (computing, generating a graph) especially for time-consuming requests.

7.2 Developed simulation platform

While fulfilling the specifications listed above, the aim of the simulation platform is to provide the two following services:

- A Graphical User Interface providing access to "what if?" scenarios through a web browser
- A web service that make the same "what if?" scenarios available for the web application.

Based on these specifications, the structure of the developed platform is presented in figure 7.1. It is composed of the following components: a web server that will handle the requests from the remote users, the core application itself a GUI, databases and external applications for specific tasks. These applications include Vali for thermodynamic calculations and Miktex (a LaTeX compiler) to produce PDF reports. Vali has been considered here in addition to the simplified model presented in section 3.2.5. Indeed, when entering the data of a simulation, the user can specify if he wants to use the simplified model that is faster or the corresponding Vali model that is more accurate. Databases have been used to store information such as the users allowed in the simulation platform, information on technologies, weather data, currency exchange rates. The latter are obtained from a web service provided by the Federal reserve bank of New York [1].

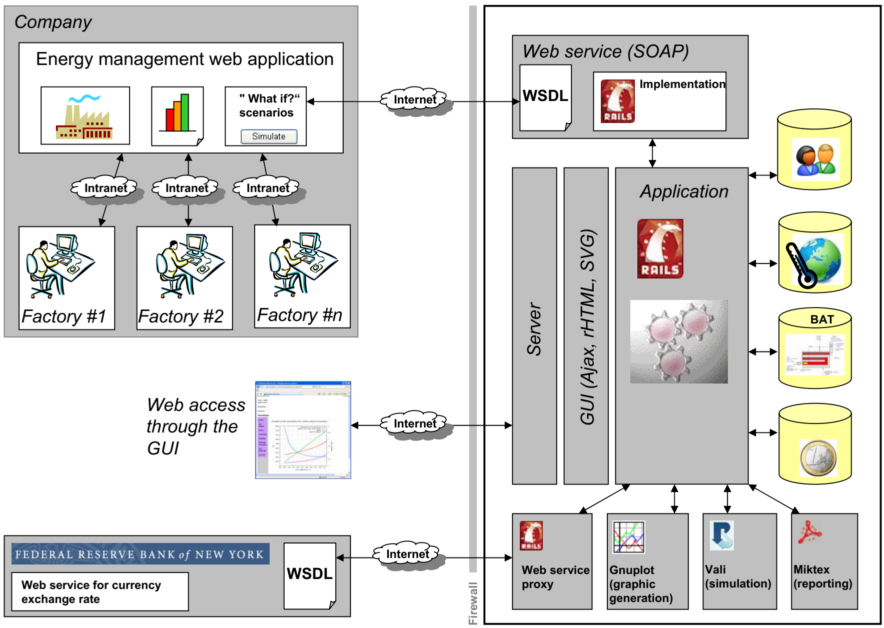


Figure 7.1: Developed simulation platform and interaction with the web application

7.2.1 Ruby on Rails

The core application has been developed using Ruby on Rails [2]. The latter is an application-development framework that has been released in 2004 at Roskilde University. As of June

[1]www.newyorkfed.org
[2]www.rubyonrails.org

2006, it had been downloaded more than 460,000 times [3]. It is based on Ruby programming language, which is an object-oriented and flexible language [4]. The object-relational mapping (O/RM) of Ruby on rails is based on convention over configuration which allows to reduce the configuration time by a factor 10 compared to Java-based applications (Geer, 2006). Unlike many other development environments, Rails is a completely integrated environment which allows to focus on the development of the application itself instead of combining multiple frameworks. Consequently, Rails enables to develop clean web application using less code, making it more and more popular among developers. However, and as with every new technology, rails has to demonstrate it is secure and scalable to impose itself as a framework to replace Java for web application development.

Like other development frameworks (Struts, Tapestry), Rails is based on a Model-View-Controller (MVC) architecture. Each component of the architecture has a well-defined role to play in the application:

- The **model** is the representation of the information on which the application operates. It is often linked to a database to store permanent data. The model can include logic that impose constraints to raw data. For example, the overall efficiency of boilers can be specified to be a number between 0 and 1. It is very important to mention here that the model that is referred to here has nothing to do with the factory model introduced in Chapter 2 or the thermodynamic models introduced in Chapter 3.
- The **view** allows the interaction of the user with the model (GUI). In Ruby on Rails, the view is constituted of HTML pages that are generated with rHTML templates. rHTML is a mixture of HTML and embedded Ruby enabling to generate HTML pages based on dynamic data.
- The **controller** handles all the events such as user actions. It interacts with the model to display the appropriate view for the user.

A typical interaction of the user with the simulation platform is presented in figure 7.2. In a first step, the user enters the data of the simulation in an input form available through the web browser (see figure 6.4 for an example of such a view). When he clicks the "Simulate" button, the bowser sends the request to the controller (point 1). The controller then interacts with the model of this simulation to determine if all the data submitted are valid and then store them in the simulation database. Eventually, the controller makes other queries to the databases to obtain additional information such as currency exchange rates for example. Based on these input data, it computes using the thermodynamic simulation model the new

[3] gems.rubyforge.org/stats.html
[4] www.ruby-lang.org

state of the system and saves the results in the database. This interaction is illustrated by point 2 in the figure. Finally, based on the results of the simulation, the controller invokes the rHTML template (point 3) to render the adequate screen in the browser (point 4). For more details on Ruby and Ruby on Rails, the reader is referred to Thomas (2004, 2005).

As regards the web server, Ruby on Rails provides a built-in server coded in Ruby called Webrick. This server is ideal for development but it is not well suited for production since it is not particularly fast and scalable. A lighttpd server [5] has been chosen at the moment of deploying the simulation platform.

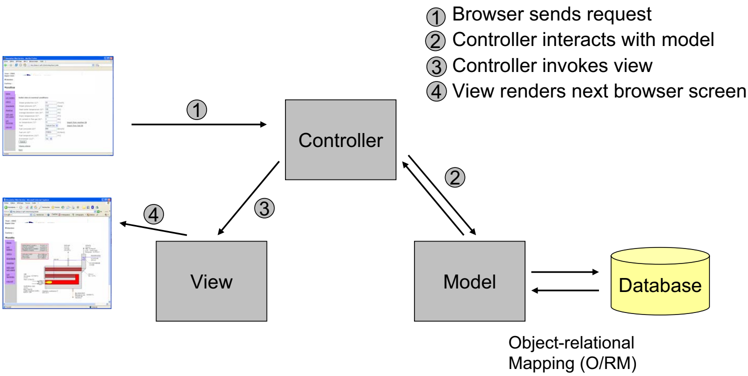


Figure 7.2: MVC architecture as implemented in ruby on rails (adapted from Thomas (2005))

7.2.2 Databases

Databases play an important role in the developed prototype. Figure 7.3 presents some of the databases - implemented using MySQL [6] - that have defined to fulfill the needs of the simulation platform. Each database is defined by a name (boilers, users, etc) and a variable number of fields that characterize data using types such as `FLOAT` or `INTEGER` for number, `CHAR` and `VARCHAR` for strings, etc. The first field, called `id`, is an identifier that allows to easily access rows of data. For instance, the database `users` is used to store the names of the allowed users as well as the password they need to provide to enter the platform. The additional field `administrator`, defines if the user as extended privileges or not in the application. Another database called `definitions` is used to define which information is needed for each simulation and the related physical units. The `boilerhouses` database has

[5] www.lighttpd.net
[6] www.mysql.com

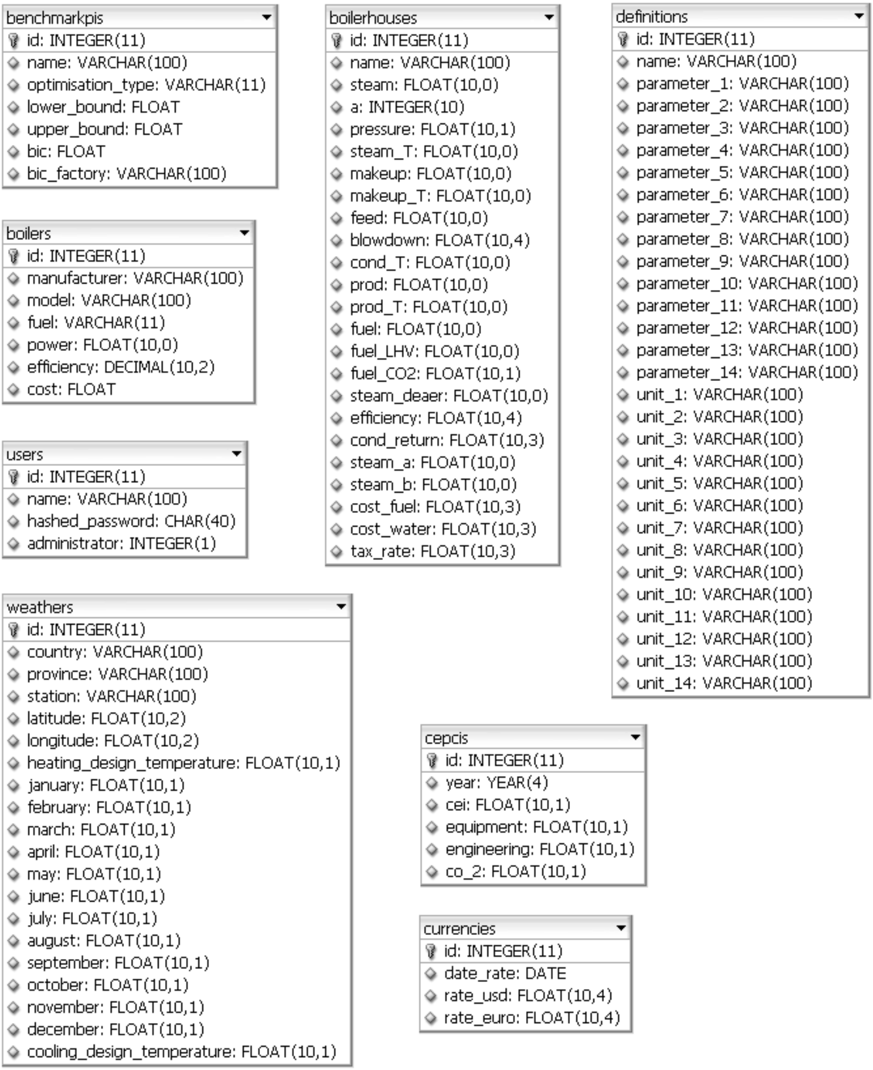


Figure 7.3: Examples of databases used in the simulation platform

been defined here to substitute the factory model [7] and includes all the information required to perform a simulation for the boilerhouse. It also includes general information such as the tax rate that will be used in the profitability analysis. The `boilers` database is an example of the technology databases described in section 6.5. The `cepcis` database gathers the information used to update the prices of equipments according to the inflation. In the simulation platform, the update of the cost of the economizer according to the inflation rate (see equation (3.12)) is computed automatically by querying the database for the value of the CEPCI (field `cei` in the database) for the current year. The `currencies` database stores daily exchange rates of the euro and dollar vis à vis the Swiss franc which is the central currency in the simulation platform. These exchange rate are used to convert prices of equipment into Swiss franc. When used in "what if?" scenarios, the exchange rates are made available to the user as illustrated in the bottom of figure 6.7.

7.3 Improving user-friendliness

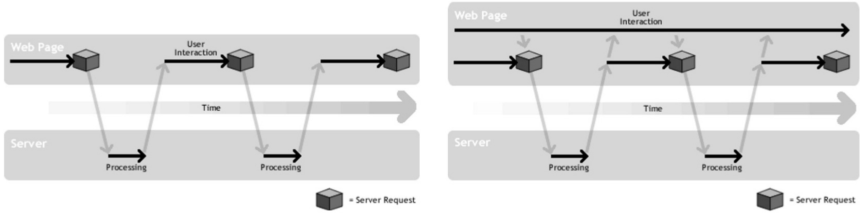
We have seen earlier in this chapter that user-friendliness is a key element for the success of a software or a web application. As said in the introduction of this chapter, the emergence of web application on a large scale has fueled the development of web technologies to make them nearly as user-friendly as desktop applications (drag-and-drop, real-time suggestions [8]). For the sake of demonstration, one of these technologies, Ajax, has been used in the simulation platform to enhance the user-friendliness of the interface.

7.3.1 Asynchronous javascript and XML(Ajax)

Ajax, introduced in Garrett (2005), is not a technology by itself but a group of technologies such as JavaScript and XML. The main idea behind Ajax is to avoid the need of reloading an entire web page each time the user makes a request (synchronous communication) as it is done in most of the web applications. This is realised by the integration of an ajax engine loaded by the browser. This engine is responsible for interacting with both the user and the server according to the user's requests. Indeed, the ajax engine can handle basic actions of the user without the need of information from the server, thus saving many time-consuming interaction with the server. This asynchronous way of interaction (see figure 7.4) between the server and the browser results in a decreased waiting time for the user between each of his actions. The advantages and disadvantages of using Ajax in web application is presented in

[7] the simulation platform prototype assumes that all the data required from the factory model are available
[8] labs.google.com/suggest

table 7.1 (Chanton et al., 2006; Paulson, 2005). To illustrate the use of ajax in the developed application, we will show the example of the display of a waiting screen while a simulation is being performed.



(a) Classical web application (synchronous) (b) Ajax based web application (asynchronous)

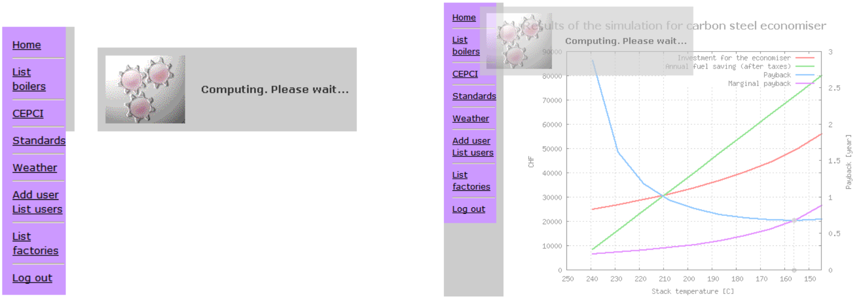
Figure 7.4: Synchronous and asynchronous communication between server and client in a web application (Garrett, 2005).

Table 7.1: Advantages and disadvantages of web applications using Ajax technology

Advantages
• Possibility to develop rich client applications
• Allow for user-friendly web applications (drag and drop,...)
• Browser sends data, not content (minimize traffic with the server)
• Instantaneous check and validation of input fields
• Cost reduction for maintenance and deployment
• User interact with a web application as with a desktop application
• Ajax application are not platform dependent
Disadvantages
• Ajax applications do not behave like traditional web applications
• Compatibility problems with the implementation of javascript across browsers
• Javascript libraries are limited
• Development might be more difficult than for traditional web applications

7.3.1.1 Waiting screen during a simulation

In the introduction of this chapter, we established as one of the specification of the software the fact that it should provide a feedback on its status for time-consuming requests. One of these requests is typically the display of the result in the form of a graphical representation as illustrated in figure 6.7. Computing all the points of the graph as well as generating the graph itself require more or less 3 seconds. In order to avoid having the user waiting in front of a white screen, a waiting screen has been implemented using the Ajax capabilities of Ruby on rails. The waiting screen appears when the user clicks the "simulate" button after filling the simulation input form. As illustrated in figure 7.5(a), it occupies the central frame of the web page. To add a dynamic effect, the use of an animated `.gif` picture makes that the gears are rotating during the display of the waiting screen. When the computation of the simulation terminates and the resulting graph is ready to be displayed, the waiting screen fades out smoothly while the graph appears behind as illustrated in figure 7.5(b).



(a) Waiting screen (b) Transition

Figure 7.5: Use of Ajax to display a waiting screen during simulation

The code that commands this effect is presented here below:

```
<%= form_remote_tag (:update => "update_div", :url => :action => :simulate_economiser,
:loading => 'loading()', :complete => 'loaded()') %>
```

This code is written in the rHTML template that displays the input form of the simulation. It is embedded Ruby (specified by the delimiters `<%` and `%>`) inside an HTML page. What this piece of code do is to launch the simulation through the action `simulate_economiser`. While the action is being performed, the `<div>` corresponding to the main frame of the page (referred to through the id `update_div`) is updated with the javascript function `loading()` that displays the waiting screen. When the `simulate_economiser` action is completed, the `loaded()` function update again the `update_div` with the results of the simulation.

7.3.2 Scalable Vector Graphics (SVG)

Besides ajax-based functions, another strategy implemented to increase the user-friendliness in the simulation platform is the use of SVG to display the results of a simulation on a scheme. The motivation for such a graphic interface is the possibility to encapsulate complex thermodynamic models developed, for example, using Vali in a user-friendly environment. It has the advantage to be understandable and intuitive for the users, which is not always the case when the results are presented, for example, in a table. In addition, an other advantage of this graphical support is the possibility to integrate it easily in paper reports (see section 6.6). On the other hand, it has to be mentioned that developing such an interface necessitates more time and is more complex than classical interfaces.

SVG (extension `.svg`) is a language based on XML for describing vector graphics. It was introduced as an open standard by the W3C in 1999 [9]. Unlike the most common graphics on the web (JPEG, GIF and PNG) that contains information for each pixel of the image, SVG is based on the description of shapes and paths (Bézier curve). As a results, the size of an SVG file is reduced compared to classical graphic files which means faster download speeds when used in web applications. In addition, SVG has many features that make it ideal for web applications. It allows for high-performance zooming inside of graphics without reloading as well as resolution printing. It is also possible to obtain dynamic graphics information through filter and scripting capabilities.
As SVG is XML-based, its tree structure is "human-readable" and easy to edit unlike binary files. In the application developed, this feature has been used to generate dynamic graphics presenting the results of an advanced simulation for a fired-tube boiler as illustrated in figure 7.6. This simulation has not been presented in Chapter 6 since it does not concerns the boilerhouse on itself but goes one step further by focusing on a specific boiler.

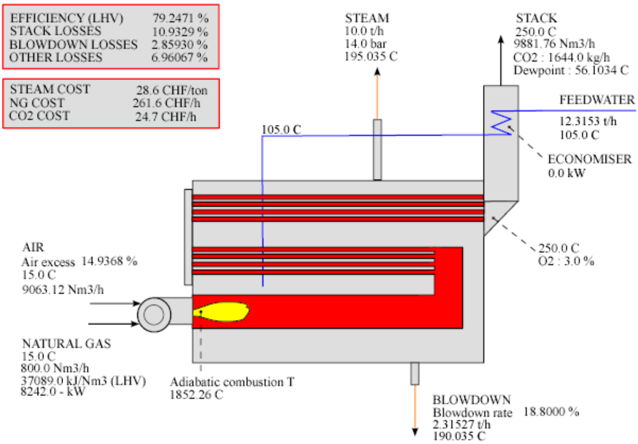


Figure 7.6: Example of SVG used to display the result of a simulation

The steps necessary to generate the SVG file available in figure 7.6 are briefly presented here and are illustrated in figure 7.7. The first step consists in creating a SVG file containing the picture of the boiler together with the locations of the values to be displayed. This file

[9] http://www.w3.org/Graphics/SVG/

is used as a template and is referred to as `Template.svg` in figure 7.7. The values that have to be displayed are identified in the template file using a prefix before the tag name ('`$$`') as shown in the bottom left corner of figure 7.7 for the tag `STACK_T`. The results of the simulation (numerical values) as well as the corresponding units have to be provided in a tab delimited file (see `Data.txt` in figure 7.7) in order to be substituted in the template file. In the example presented here, this file is generated by Vali as explained in section 3.1.1. However, it has to be noticed that this techniques is not limited to application with Vali. Provided that the results are available in a tab file with the same format, any other simulation tool can be used. Once both the template file and the data file are available, the template file is parsed and locations of numerical values to be inserted are identified by searching for the '`$$`' prefix. These expressions are then substituted for each tag by the corresponding numerical value and unit available in the `Data.txt` file. Once this task is completed, the resulting SVG file including the numerical values is saved (`Graphic.svg`) and can then be used to display the results of the simulation in the simulation platform.

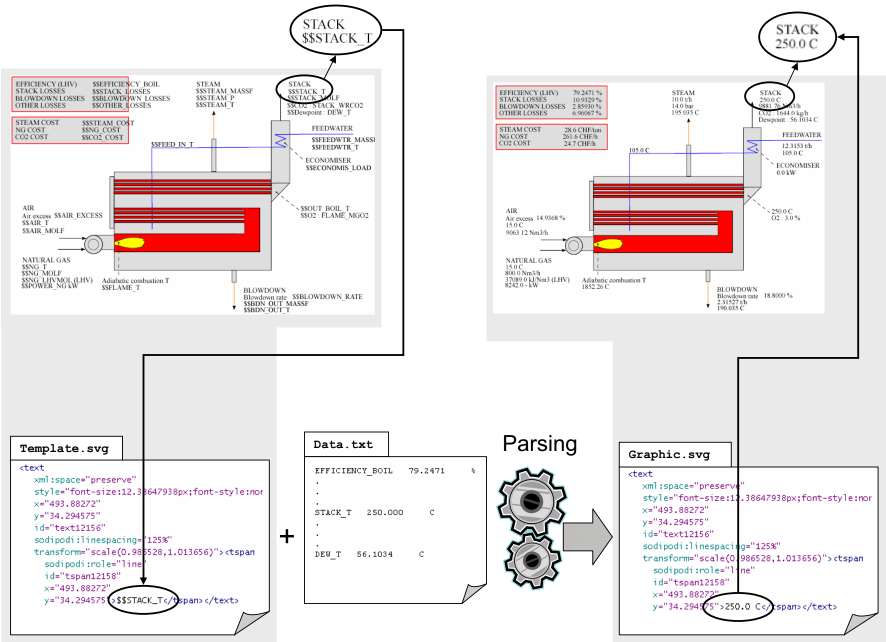


Figure 7.7: Strategy adopted to generate SVG file with the results of a simulation

7.4 Web services

In the developed simulation platform, thermodynamic models are made accessible to users by the web through a graphical user interface. This had the purpose to demonstrate how "what if?" scenarios could look like in the web application. Since this platform has been developed according to the standards of the web application and had demonstrated to be reliable, the possibility for the web application to outsource complex thermodynamic computations used for simulation has rapidly appeared as an interesting option. In such a configuration, the thermodynamic models are made available to the web application through the world wide web. While such a communication between two applications through Internet would have required a heavy infrastructure some years ago (using CORBA or J2EE for example), the emergence of web services in 2002 has made this task much more easier. Web services use standard technology such as XML, HTTP and SOAP to provide a systematic and platform-independent framework for invoking remote services. They act as a front-end to a server on which services are made available through the web. Referring back to figure 6.2 introduced in Chapter 6 to present the concept of a "what if?" scenario, the simulation platform will serve, in the new configuration, as a calculation engine accessible through Internet as illustrated in figure 7.8. For the user, the new configuration is transparent and he will not notice that the calculations have been outsourced to a remote server. Tests showed that the time required for the calculations and the transmission of the information over the Internet is inferior to one second.
A web service system is composed of three main elements:

- **Request dispatch module**. This modules handles the connections made by remote clients using Simple Object Access Protocol (SOAP). It analyzes the requests and dispatches them to the appropriate back-end process in the server.

- **Web Services Description Language (WSDL)**. This XML document (extension `.wsdl`) describes the services available and the ways of interacting with them. It contains the list of the available services, the authentication requirements and the types of argument that are expected and returned by the services. The standards of this language are defined by a working group of the W3C. An example of WSDL is available in figure 7.9.

- **Server**. It hosts the applications that are accessible through web services.

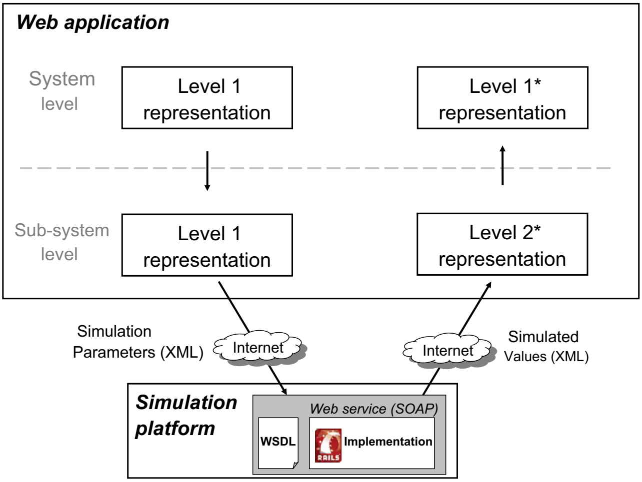


Figure 7.8: Example of a web service implementation

7.4.1 Implementing web services in the simulation platform

Since web services have been conceived to substitute older technologies, they are flexible enough to be rapidly integrated in existing architectures. In the case of the simulation platform, the thermodynamic models as well as the server itself are already in place. Consequently, implementation of web services has required the development of a SOAP interface (see figure 7.1). Based on the definition of this interface, Ruby on Rails generates automatically the WSDL that describes the available service to remote users. As an example, the WSDL generated for the condensate return simulation is presented in figure 7.9. It is constituted of several elements that are briefly described here. The root element of the WSDL is called `<definitions>` and contains attributes such as the name of the service (`Simulation` in our case) and the namespace used in the document (e.g. `xmlns:typens`). For guaranteeing a maximum interoperability all the variables that are returned are defined in the `<types>` element. The XSD[10] is the preferred type system. It includes two main type for data definition: simpleType and complexType. The simpleType determines the constraints about the values of attributes or elements. It contains all the primitive XML data types: string, boolean, float, double, etc. It is used in the `type` attribute of an element. The complexType is used to define elements that may contain attributes and elements. In the example considered here, a ComplexType called `Result` is defined here to represent output variables,

[10]http://www.w3.org/2001/XMLSchema

```xml
<?xml version="1.0" encoding="UTF-8"?>
<definitions name="Simulation" xmlns:typens="urn:ActionWebService" xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/"
        xmlns:xsd="http://www.w3.org/2001/XMLSchema" xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
        targetNamespace="urn:ActionWebService" xmlns:soapenc="http://schemas.xmlsoap.org/soap/encoding/"
        xmlns="http://schemas.xmlsoap.org/wsdl/">
<types>
  <xsd:schema xmlns="http://www.w3.org/2001/XMLSchema" targetNamespace="urn:ActionWebService">
    <xsd:complexType name="Result">
      <xsd:all>
        <xsd:element name="blowdown" type="xsd:double"/>
        <xsd:element name="water" type="xsd:double"/>
        <xsd:element name="steam_T" type="xsd:double"/>
        <xsd:element name="fuel_LHV" type="xsd:double"/>
        <xsd:element name="steam_b" type="xsd:double"/>
        <xsd:element name="water_saved" type="xsd:double"/>
        <xsd:element name="steam_P" type="xsd:double"/>
        <xsd:element name="fuel_saved" type="xsd:double"/>
        <xsd:element name="feedwater" type="xsd:double"/>
        <xsd:element name="condensate" type="xsd:double"/>
        <xsd:element name="fuel" type="xsd:double"/>
        <xsd:element name="error" type="xsd:string"/>
        <xsd:element name="makeup" type="xsd:double"/>
        <xsd:element name="losses" type="xsd:double"/>
        <xsd:element name="to_deaer" type="xsd:double"/>
        <xsd:element name="steam_a" type="xsd:double"/>
        <xsd:element name="water_T" type="xsd:double"/>
        <xsd:element name="makeup_T" type="xsd:double"/>
        <xsd:element name="condensate_T" type="xsd:double"/>
      </xsd:all>
    </xsd:complexType>
  </xsd:schema>
</types>
<message name="condensate_return">
  <part name="key" type="xsd:string"/>
  <part name="steam_b" type="xsd:double"/>
  <part name="steam_P" type="xsd:double"/>
  <part name="steam_T" type="xsd:double"/>
  <part name="makeup" type="xsd:double"/>
  <part name="makeup_T" type="xsd:double"/>
  <part name="blowdown_rate" type="xsd:double"/>
  <part name="water_prod" type="xsd:double"/>
  <part name="water_prod_T" type="xsd:double"/>
  <part name="ov_eff_boil" type="xsd:double"/>
  <part name="fuel" type="xsd:double"/>
  <part name="fuel_LHV" type="xsd:double"/>
  <part name="new_condensate" type="xsd:double"/>
  <part name="new_cond_T" type="xsd:double"/>
</message>
<message name="condensate_returnResponse">
  <part name="return" type="typens:Result"/>
</message>
<portType name="SimulationSimulationPort">
  <operation name="condensate_return">
    <input message="typens:condensate_return"/>
    <output message="typens:condensate_returnResponse"/>
  </operation>
</portType>
<binding name="SimulationSimulationBinding" type="typens:SimulationSimulationPort">
  <soap:binding transport="http://schemas.xmlsoap.org/soap/http" style="rpc"/>
  <operation name="condensate_return">
    <soap:operation soapAction="/simulation/api/condensate_return"/>
    <input>
      <soap:body encodingStyle="http://schemas.xmlsoap.org/soap/encoding/" namespace="urn:ActionWebService" use="encoded"/>
    </input>
    <output>
      <soap:body encodingStyle="http://schemas.xmlsoap.org/soap/encoding/" namespace="urn:ActionWebService" use="encoded"/>
    </output>
  </operation>
</binding>
<service name="SimulationService">
  <port name="SimulationSimulationPort" binding="typens:SimulationSimulationBinding">
    <soap:address location="http://lenipc12.epfl.ch/simulation/api"/>
  </port>
</service>
</definitions>
```

Figure 7.9: Example of WSDL

such as the fuel saved (attribute name is `fuel_saved`), that will be assigned in the web service answer. Following the `<types>` element, `<message>` elements, which consist of one or more logical parts, are used to define input and output information of an operation. In the example presented, two messages elements are used to specify the inputs (attribute name is `condensate_return`) and outputs (attribute name is `condensate_returnResponse`) of the web service. The nature of messages is then defined as input or output in the `<portType>` element. Finally, the protocol used for communication and the address information ("end point") necessary to invoke the web service are defined in the `<binding>` and `<service>` elements.

7.4.2 Invoking the web service

We have seen earlier that web services are platform independent. Consequently, although the web service described above is coded in ruby, the web application, which is coded in another language, can access it. For the sake of demonstration, the previously described web service is invoked here using Matlab. The script used for that purpose is available in figure 7.10(a) and is briefly presented here. The first line of the script creates a Matlab object based on the WSDL of the web service which is accessible through the Internet. This new class is by default named after the name of the web service (SimulationService in this case). The second line creates an instance of the class that will be used as a first argument when calling the web service function in the third line. The invocation of the function is similar to any function invocation in Matlab. The parameters to be sent to the function are described in the first `message` element of the WSDL (see figure 7.9). The first eleventh parameters describe the present state of the boiler house sub-system while the two last parameters defines the new condensate return rate (expressed in %) and the new temperature of the condensates (expressed in °C) [11]. Figure 7.10(b) shows the result of the execution of the script in the prompt. The new state of the system is returned together with the fuel and water savings. This small example illustrates the power of the web service technology: by writing three lines of code we have invoked a remote function and retrieved the results.

7.4.3 Example of a Ruby on Rails function invoking a web service

As shown in figure 7.1, the developed simulation platform not only proposes web services but also invokes a web service to obtain the latest exchange rates for US dollars and Euros. These rates are then stored in the `currencies` database (see figure 7.3) so that the web

[11] The reader is referred to section 6.3.4.1 for more details on this "what if?" scenario

```
createClassFromWsdl('http://lenipc12.epfl.ch/simulation/service.wsdl');
ts = SimulationService;
y = condensate_return(ts, 70134, 10, 184, 40052, 20, 0.1878,...
                                0, 65, 0.865, 5720299, 37089, 85, 80)
```

(a) Script calling the web service

```
>> script_web_services

y =

          fuel: 5.6736e+006
      to_deaer: 6.9324e+003
   water_saved: 1.1712e+004
         error: ''
   condensate_T: 80
        makeup: 2.8340e+004
       water_T: 65
       steam_b: 70134
    condensate: 5.9614e+004
        losses: 0
       steam_P: 10
         water: 0
       steam_a: 7.7066e+004
     feedwater: 9.4886e+004
      fuel_LHV: 37089
       steam_T: 184
    fuel_saved: 4.6672e+004
      blowdown: 1.7820e+004
      makeup_T: 20

>>
```

(b) Execution in Matlab

Figure 7.10: Invocation of the web service for the condensate return simulation

service does not have to be invoked each time exchange rates are required. The function used for that purpose is presented in figure 7.11 and serves here as a basis to discuss web services invocation as well as database query in Ruby on Rails. This function can be divided in four main parts. Firstly, the `currencies` database of the application is queried to obtain the date of the latest rates stored in the application. If they are older from the last 24 hours, the web service from the Federal reserve bank of New York [12] is invoked to obtain the latest rates in a second step. If necessary, the currencies database is updated with the latest rates in a third step. Finally, the rates are returned together with the date at which they were obtained.

Some elements of this piece of code are discussed in more detail here. The query of the `currencies` database on line 962 is performed using the `find()` method on the object of the model class `Currency`. The naming convention in rails automatically associates the class name, which is always singular with the first letter capitalized (e.g. `Currency`), with the corresponding database table name, which is the plural of the class name in lowercase letters (e.g. `currencies`, see figure 7.3). By using convention over configuration, Rails applications use much less code and require less configuration than equivalent Java web applications. The parameters of the `find()` method specifies that the desired line of the database is the more recent one where both exchange rates are available.

The invocation of a web service with rails is just as simple as with Matlab. Based on the WSDL (see line 967), the SOAP library available in rails is used to create a proxy of the service (see line 968). The available services (here `getLatestNoonRate`) can then be invoked on the proxy (see lines 970 and 975). The results are returned in a XML structure and is

[12]WSDL of the service is available at http://www.newyorkfed.org/markets/fxrates/WebService/v1_0/FXWS.wsdl

```
def get_latest_rates
# Web service from the Fed of New York to obtain CHF and EUR exchange rate with $
  present_time = Time.new
  yesterday = Date.new(present_time.year.to_i, present_time.month.to_i, present_time.day.to_i)-1
  latest_rate = Currency.find(:all,
                              :conditions => "rate_usd != 'NULL' and rate_euro != 'NULL'",
                              :order => "date_rate DESC",
                              :limit => 1)
  if latest_rate[0].date_rate < yesterday
      wsdl_url = "http://www.newyorkfed.org/markets/fxrates/WebService/v1_0/FXWS.wsdl"
      soap = SOAP::WSDLDriverFactory.new(wsdl_url).create_rpc_driver
      # Exchange rate CHF <-> $
      response = soap.getLatestNoonRate('CHF')
      xml = REXML::Document.new(response)
      @usd= xml.elements["//frbny:OBS_VALUE"].text.to_f
      @currency_date= xml.elements["//frbny:TIME_PERIOD"].text
      # Exchange rate EUR <-> $
      response_euro = soap.getLatestNoonRate('EUR')
      xml_euro = REXML::Document.new(response_euro)
      @euro= xml_euro.elements["//frbny:OBS_VALUE"].text.to_f
      ws_date_get =ParseDate.parsedate(@currency_date)
      ws_date = Date.new(ws_date_get[0], ws_date_get[1], ws_date_get[2] )
      #Information is saved in the database
      unless ws_date <= latest_rate[0].date_rate
            @db_currency = Currency.new
            @db_currency.date_rate = @currency_date
            @db_currency.rate_usd = @usd
            @db_currency.rate_euro = 1/@euro
            @db_currency.save
      end
  else #Latest value of the database is the actual one. Avoid a web service request.
  @currency_date = latest_rate[0].date_rate.to_s
  @usd = latest_rate[0].rate_usd
  @euro = 1/latest_rate[0].rate_euro
  end
  rescue #In the case where the web service is not available
  @currency_date = latest_rate[0].date_rate.to_s
  @usd = latest_rate[0].rate_usd
  @euro = 1/latest_rate[0].rate_euro
end
```

Figure 7.11: Source code of the function that obtains the latest exchange rate from the web service of the Federal Reserve Bank of New York

parsed using REXML, a XML processing library available in ruby. The exchange rate and the corresponding date are obtained by matching their element names in the XML structure (see lines 972, 973 and 977). If necessary, the values are then saved in the database (see lines 982-986).

7.5 Conclusion

In this chapter, we have shown how recent web technologies can be used to rapidly develop a reliable and user-friendly simulation platform. The structure of the platform, including the server and the database, is described and the means used to improve the user-friendliness are also presented. Among these means, we can mention the usage of Ajax to display a waiting screen during a simulation or the use of SVG to present the simulated value in a graphical representation of a boiler.

The means to interact with the simulation platform are also presented. They include a classical Graphical User Interface accessible through a web browser for "human" users and a web service that allows other web applications to interact in batch mode with the simulation functions implemented. In the future, the simulation platform will thus serve as a calculation engine for "what if?" scenarios implemented in the web application developed by the industrial partner of this project. Even when this solution may be slightly less reliable than one where the simulation functions are coded directly in the web application, it offers the possibility of using the modeling know-how available in research centers, such as LENI.

Chapter 8

Conclusion and future work

8.1 Conclusion

Increasing environmental concerns as well as the rise in energy prices make energy management more and more important in the industry even in non energy-intensive sectors such as the food industry. While SMEs have limited resources for energy management, large companies have the opportunity to make an efficient use of the know-how available both in head offices and across their subsidiaries worldwide. Besides top management commitment, the success and the sustainability of an energy management program on a long-term basis will also rely on tools and methods and, particularly, on computer-aided tools. In this context, this work has introduced a methodology and presented its implementation through web-enabled tools, aimed at helping engineers and managers perform an efficient and sustainable energy management. The developed web application is the outcome of a fruitful collaboration between an industrial partner and the Laboratory for Industrial Energy Systems (LENI) of the Swiss Federal Institute Technology of Lausanne (EPFL). By combining the complementary knowledge and expertise of both the academic and the industrial world, the developed application has a strong theoretical background while being adapted to industrial requirements. In this sense, this thesis has consisted in developing prototypes and concepts, which have then been implemented by the industrial partner.

As illustrated in figure 8.1, the developed web application is a "knowledge & expertise repository" used and fed by the three types of users identified (managers, engineers in factories and energy experts). Compared to commercially available solutions for energy management, the application has the advantage of being aimed at all the agents involved in energy management in large companies. It provides managers with a means of monitoring factories and

rationally allocating resources available for energy management. For engineers in the factories, it permits to assess the performance of their factories according to standards set by the experts and by comparison with other factories worldwide through benchmarking. They can thus easily identify specific areas with important improvement potentials. In addition, they have the possibility to quantify energy saving options in energy conversion units through "what if?" scenarios, which have been validated by experts in the fields. By encapsulating complex thermodynamic models in a user-friendly interface, the web application allows for overcoming some of the barriers often encountered when using simulation software. From the perspective of the experts, the developed application helps them efficiently disseminate their knowledge across the factories worldwide and acts as filter for the requests engineers in factories may have in relation to energy efficiency projects. In this context, the application permits the different users to work more efficiently.
As regards the practical implementation, the web application makes an efficient use of the existing IT structure (the company Intranet), which permits a rapid and efficient dissemination worldwide as well as a facilitated update and maintenance.

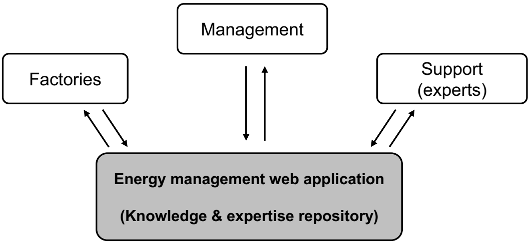


Figure 8.1: Sharing knowledge and expertise

The web application builds on a methodology based on two fundamentals approaches: the top-down approach and the bottom-up approach. Starting from the energy bill of a factory, the top-down approach permits the identification of the main energy drivers in the factory. Its implementation in the web application is based on a modular factory model, which enables each factory to define its energy usage, allocate costs among the different energy consumers and compute key performance indicators. The assessment of energy conversion units is performed by encapsulated thermodynamic models. Once defined, the factory models are available to users worldwide in the web application through standardized representations. Since the amount of information potentially available to users in the web application is extremely large (the industrial partner has over 500 factories), strategies such as a mechanism to rate performance indicators and benchmarking have been implemented to facilitate the extraction of relevant information and to identify factories and specific areas within these factories with important improvement potentials.

The bottom-up approach is used to identify and quantify energy saving potentials in the process by analysing the process requirements. For that purpose, a triple representation of a process requirements has been introduced and applied to a whole factory in a case study. This example has demonstrated the relevance of the 80/20 rule as regards energy usage in production setups. In a further step, the triple representation and the 80/20 rule have been combined to evaluate heat recovery potentials in the process under study. The combination of these two concepts has permitted to overcome some of the barriers frequently encountered when applying process integration in the food industry. The results of the analysis has shown a potential of reduction of the operating cost ranging from 0.8% to 16.1%, depending on the representation considered. In a further step, the possibility to integrate combined heat and power or heat pumping solutions has been explored using multi-objective optimization. A wide variety of solutions including these technologies have been obtained, ranging from low investment and low saving solutions to high investment and high saving ones. A maximum saving potential of 37.7% has been identified.

The concept of "what if?" scenarios has been demonstrated in this thesis by the development of a web-based simulation platform prototype. This platform can be used by human users through a graphical user interface. It acts as a decision support tool by providing graphical representations of profitability and risk analysis related to energy efficiency actions. In addition, the use of web services will also make the platform available in the future to the web application, as a calculation engine for "what if?" scenarios.

Even if it is too early to evaluate the efficiency on a long-term basis of the web application developed, it has to be mentioned that, so far, there has been a high degree of acceptance of the application by engineers worldwide. The availability of "what-if?" scenarios in a near future will increase the added-value of the tool as well as its popularity among users.

In the methodology proposed, statistical methods aimed at identifying the main energy drivers in a factory have been proposed to support the definition of the factory model. In contrast to the factory model based on annual data, statistical methods require greater observation to produce reliable results. Chapter 4 has highlighted that monthly or even weekly obtained data should be considered. While the extra effort required to gather these data is small (they are directly available from utility bills and production records), the benefits of statistical methods in the day to day energy management are substantial. Firstly, they provide a good framework for targeting-monitoring and for detecting variations in energy consumption. Secondly, they can be used to forecast energy consumption in the perspective of negotiating future energy supply contracts, or simply for budgeting exercises.

In the case study presented in this work, these methods showed that a significant part of the consumption of utilities was not directly correlated to production volumes.

8.2 Future work

The factory model included in the web application developed in this work has been designed to be highly modular. Consequently, new blocks could be easily added to the application without modifying its global structure. For this work, it was decided to focus essentially on well-established energy conversion units. However, other modules could be implemented in the factory model and in "what if?" scenarios. They include waste treatment units, which have been touched upon very briefly in this work and which could present an interesting potential to produce energy from process wastes (for instance, biomass-based cogeneration). The work of Witschi (2005) also showed that some emergent energy conversion technologies, such as wind turbines, could be useful to reduce CO_2 emissions. Implementing these models in "what if?" scenarios could permit to assess the impact that such technologies would have in existing factories. Although food process are very diverse, cross-cutting technologies, such as vacuum production units, are encountered in many processes. Developing models of such technologies and implementing them in the application could be relevant to extend the scope of the application.

The increased need of reporting in large companies has been shown in the introduction of this work. Although necessary, reporting is a time-consuming and tedious task for engineers in factories, which requires the manipulation of the same data for various purposes. Consequently, all the synergies that could be found between the developed application and existing tools or procedures to decrease data entry and manipulation for engineers in factory would be an added-value. In that context, the use of the web application for environmental reporting purposes could be an interesting option. In addition, the automatic integration of data (mainly financial) from business software applications, such as SAP, in the web application would also result in a more efficient use of the time by engineers in factories.

As regards the bottom-up approach, it has been mentioned in Chapter 5 that, although promising, the savings associated with process integration and the integration of heat pumps and CHP units need to be validated by properly estimating the investments required to implement the heat recovery potentials identified in the process and the new energy conversion units. This requires the synthesis of the heat exchanger network for the multi-period problem that will allow to meet the computed targets at minimum cost.

The developed methodology and web application is based on concepts (benchmarking, simulation, cost allocation) that are broad enough to be applied to other areas than factories in a large company. Particularly, in the food industry, maintaining the cold chain of products from production facilities to the consumption stage requires large amounts of energy in cold stores. Energy management of such facilities, as well as administrative buildings for instance, could be perfectly performed with the developed application by implementing new models similar to the factory model. As regards cold stores, a preliminary work has been carried out in the framework of this thesis by developing advanced thermodynamic models of these facilities (Dalla Piazza, 2007). Finally, it would be interesting to test the developed methodology and web application in other sectors of the process industry (chemical, pulp and paper). Although some adjustments would be required, in the opinion of the author, the web application could be rapidly operational and it could be even more profitable than in non energy-intensive industries.

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Appendix A

Properties of fuels

A.1 Composition

Table A.1: Typical composition of solid and liquid fuels

	Mass fraction						
Fuel	C	H	N	O	S	H_2O	$Ashes$
HFO	84.9	10.6	0	1	3.5	0	0
LFO	85.7	13.1	0	0.2	1	0	0
Diesel	86	13.2	0	0.2	0.6	0	0
Coal	69.2	3.7	1.1	8.7	0.2	2.1	15
Wood	48.5	6.5	0	41.4	0	2.8	0.8
Coffee ground (dry)	59.5	7.3	2.5	30.7	0	0	0

Table A.2: Typical composition of gaseous fuels

	Molar fraction						
Fuel	CH_4	C_2H_6	C_3H_8	$n-butane$	$n-pentane$	$others$	N_2
Natural gas	97.45	0.88	0.26	0.04	0.02	0.05	1.3
LPG(propane)	0	2	96	2	0	0	0
LPG(butane)	0	0	1	98	1	0	0

Equivalence between between air excess, O_2 content and CO_2 content in flue gases for LFO, HFO, LPG and natural gas for the composition of tables A.1 and A.2 are presented in figure A.1.

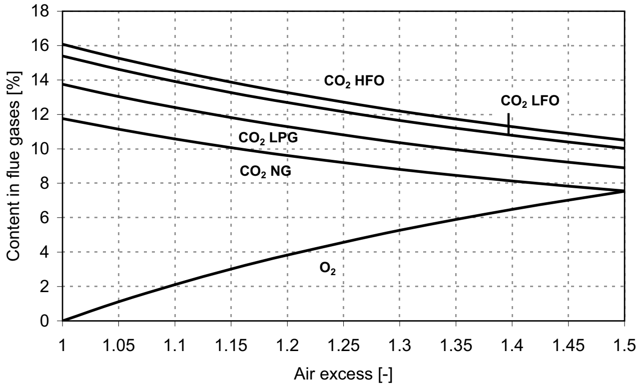


Figure A.1: Air excess

A.2 Coffee ground

A large amount of coffee ground is generated during the production of soluble coffee (0.91 kg of coffee ground per kg of soluble coffee). The use of this biomass as a fuel instead of disposal can supply a large amount of energy (as high as 75% of the thermal energy of a typical process of production of soluble coffee). After the extraction process, coffee ground have a humidity of 80% (w. b.). They are then pressed to obtain a humidity of approximately 50%. They can then be burned in a boiler at that humidity level or they can be processed into a dryer to reduce the humidity to 30% before the combustion (Silva et al., 1998). Coffee ground have heating values that might vary depending on the blends of coffee and the extraction process. However, the heat value is higher than that of wood as it can be seen in table 2.2. LHV as well as HHV have been computed with Vali using a bomb calorimeter model. The results are presented in figure A.2. It can be seen that the higher and the lower heating value are highly influenced by the humidity of the coffee grounds. This explains the effort that is usually make to dry the coffee ground with the exhaust gases for example. This figure also points out the fact that the ratio of the higher heating value to the lower heating value is increasing with humidity as more water is available in the combustion gases.

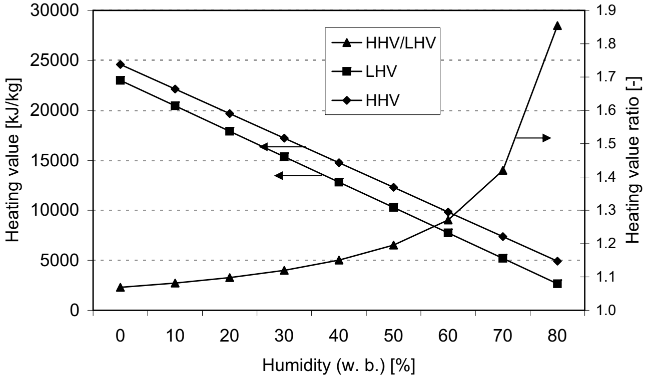


Figure A.2: Coffee ground lower heating value and higher heating value

Appendix B

Exergy losses in the cascade refrigeration unit

Table B.1: Share of exergy losses in the cascade refrigeration unit of figure 3.9 (T_a=25°C)

Unit	**Exergy [kW]**	[%]	[%]
Exergy delivered at -52°C	64.85	23.73	42.34
Exergy delivered at -47°C	59.09	21.62	38.58
Exergy delivered at -17°C	29.21	10.69	19.07
Total of exergy delivered	153.15	56.04	100
Condenser	19.12	7.00	15.91
Compressor NH_3 up	17.91	6.55	14.91
Heat exchanger cascade	14.46	5.29	12.04
Compressor NH_3 down	14.3	5.23	11.90
Compressor CO_2 -52°C	10.19	3.73	8.48
Compressor CO_2 -47°C	8.35	3.06	6.95
Flash vessel CO_2 -52°C	6.26	2.29	5.21
CO_2 gas mixer	5.25	1.92	4.37
Flash vessel CO_2 -47°C	4.68	1.71	3.90
Economiser	4.53	1.66	3.77
Evaporator -52°C	4.46	1.63	3.71
Evaporator -47°C	4.23	1.55	3.52
Evaporator -17°C	3.15	1.15	2.62
Flash vessel NH_3 -20°C	3.07	1.12	2.56
NH_3 gas mixer	0.18	0.07	0.15
Total of losses	120.14	43.96	100
Total of exergy	273.29	100	

Appendix C

Heat transfer in a boiler and an economizer

C.1 Heat transfer in a boiler at part load operation

Two heat transfer mechanisms are present in the boiler: radiative heat transfer, which occurs mostly in the furnace, and convective heat transfer in the tube assembly. Part load operation of the boiler principally influences the convective heat transfer. As a consequence, the latter has to be well characterized which is not possible with the model of figure 3.2. The furnace and the tube assembly have to be modeled separately. The furnace is modeled with an HEXVAL unit in Vali which is used to represent heat exchangers. This unit is based on the following equation:

$$\dot{Q} = U \cdot A \cdot F \cdot \Delta T_{lm} + G \cdot A \cdot \sigma \cdot (T_{h,o}^4 - T_{c,o}^4) \tag{C.1}$$

where

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{ln\frac{\Delta T_2}{\Delta T_1}} \tag{C.2}$$

For a co-current exchanger:

$$\begin{aligned} \Delta T_1 &= T_{h,i} - T_{c,i} \\ \Delta T_2 &= T_{h,o} - T_{c,o} \end{aligned} \tag{C.3}$$

For a counter-current exchanger:

$$\begin{aligned} \Delta T_1 &= T_{h,i} - T_{c,o} \\ \Delta T_2 &= T_{h,o} - T_{c,i} \end{aligned} \tag{C.4}$$

$T_{h,i}$ and $T_{h,o}$ are respectively the inlet and outlet temperature of the hot stream while $T_{c,i}$ and $T_{c,o}$ are the equivalents for the cold stream.
The first term of equation (C.1) models the convection while the second is used for the radiative heat transfer. U is the global heat transfer coefficient, A is the heat transfer area, F is a correction factor for multi-pass heat exchanger accounting for the deviation from the counter-flow configuration, G is a geometric factor for radiation and σ is the constant of Boltzmann. U is computed from:

$$\frac{1}{U} = \frac{1}{U_1} + R_t + \frac{1}{U_2} \tag{C.5}$$

where U_1 is the film heat transfer coefficient on shell side R_t is the thermal resistance of the tubes, U_2 is the film heat transfer coefficient on tubes side. For part load operation, the heat transfer coefficients U_1 and U_2 are computed as follows:

$$U_i = U_{i,ref} \cdot (\frac{\dot{m}_i}{\dot{m}_{i,ref}})^{0.7} \quad i = 1, 2 \tag{C.6}$$

where $U_{i,ref}$ is the film heat transfer coefficient at nominal conditions, $\dot{m}_i$ is the actual flow rate, $\dot{m}_{i,ref}$ is the flowrate at nominal conditions.

As only radiative heat exchange is considered in the furnace, the first term of equation (C.1) is not taken into account. This assumption is based on data from Warga Boiler (2006) that emphasize that more than 65% of the heat exchange in the furnace come from radiation phenomenon. Modeling of both radiative and convective heat exchanges is possible in a HEXVAL unit, however, convergence is much more difficult when both phenomena occur simultaneously. The tube assembly principally contributes to the global heat exchange in the boiler through convective phenomena (radiation represents less than 4% of the heat transfer in the tube assembly according to Warga Boiler (2006)). It is also modeled with a HEXVAL unit will considers only convective heat exchange (only first term of equation (C.1) is used). The global heat coefficient is computed according to equations (C.5) and (C.6). Since the heat transfer coefficient of the boiling water and the thermal resistance can be neglected compared to the heat transfer of the flue gas U_1 , the global heat transfer coefficient U is equal to U_1. The determination of this coefficient is presented here for a fire-tube boiler.

U_1 varies in function of the Nusselt number Nu (Incropera and DeWitt, 1996):

$$U_1 = Nu \cdot \frac{k}{D} \tag{C.7}$$

where k is the thermal conductivity of the tubes and D their inner diameter. In a fire-tube boiler, the flue gas flows through the tube assembly of the boiler. The characteristics of this internal flow depends on the Reynolds number:

$$Re = \frac{\rho \cdot u_m \cdot D}{\mu} \tag{C.8}$$

where ρ is the fluid density, u_m is its mean velocity and μ is its dynamic viscosity. For turbulent flows in tube ($Re > 2300$), the Nusselt number can be computed according to the Colburn equation (Incropera and DeWitt, 1996):

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.33} \tag{C.9}$$

Since ρ, D, μ, Pr and k can be considered constant in the range of our application, the heat transfer will vary like $Re^{0.8}$ and consequently like $u_m^{0.8}$. Since we have also:

$$\dot{m} = \rho u_m S \tag{C.10}$$

where S is the cross section area of the tubes which is constant, equation (C.6) in Vali has to be changed to

$$U_i = U_{i,ref} \cdot (\frac{\dot{m}_i}{\dot{m}_{i,ref}})^{0.8} \quad i = 1, 2 \tag{C.11}$$

To validate this new exponent, it has been used to compute the part load efficiency curve of the *Warga* boiler (Warga Boiler, 2006). The heat transfer coefficient of flue gas identified with Vali for this boiler at nominal load is $U_1 = 74.6$ [W/m^2/K] [1]. This result has been obtained assuming that the temperature at the outlet of the radiative section is constant (753°C) as well as the share of radiation losses in the boiler losses. Since part load efficiencies are not available from *Warga*, data from the technical sheets of the VITOMAX 200 HS boiler from Viessmann (Viessmann, 2003) which is in the same range of thermal power and pressure are used for the comparison. Figure C.1 presents the part load efficiency curves for the VITOMAX 200 HS as well as those obtained for the *Warga* boiler with equations (C.6) and (C.11). This figure clearly shows that the slope of the data of the VITOMAX boiler is almost the same as the one obtained by simulation for the *Warga* boilers with equation (C.11), which validates the use of the exponent 0.8 in equation (C.11). The offset in efficiency between

[1] the heat transfer computed for the *Warga* boiler according to equations (C.7), (C.8), (C.9) is $U_1 = 52.3$ [W/m^2/K]. The difference can be explained by the fact that the effect of the coiled-wire turbulators is not taken into account in the calculations.

these two curves points out that the losses by radiation are bigger for the *Warga* boiler than for the VITOMAX boiler.

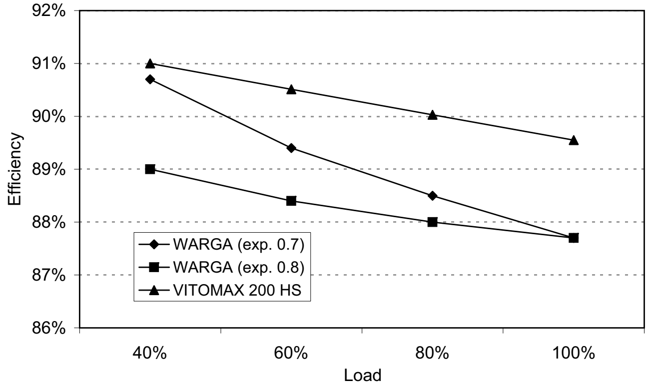


Figure C.1: Part load efficiency curves for VITOMAX 200 HS and *Warga* boilers

C.2 Heat transfer in economizer

The global heat transfer coefficient between two fluids separated by a tube (neglecting fouling) is given by equation (C.5). This equation can be rearranged as follows ($R_t = \frac{\delta_t}{k}$):

$$U = \frac{1}{\frac{1}{U_1} + \frac{\delta_t}{k} + \frac{1}{U_2}} \tag{C.12}$$

where U_1 and U_2 are the heat transfer coefficients of the two fluids. δ_t and k are the tube thickness and thermal conductivity. For economizers, since the conductivity of metal is very high, the term $\frac{\delta_t}{k}$ in equation (C.12) is negligible. In addition, since the heat transfer coefficient of water U_2 is much greater than that of flue gas U_1, the term $\frac{1}{U_2}$ in equation (C.12) can also be neglected. Thus, the global heat transfer in the economizer can be expressed as

$$U = U_1 \tag{C.13}$$

The heat transfer coefficient resulting of the flue gas flows across a banks of finned-tubes can be computed as follows:

$$U_1 = h \cdot \eta_0 = Nu \cdot \frac{k}{D} \cdot \eta_0 \tag{C.14}$$

where η_0 is the overall surface efficiency, h the convective heat transfer coefficient, Nu is the Nusselt number and D the outer diameter of a tube. According to Basu et al. (2000), the Nusselt number can be approximated using the following formula for cross-flow over an in-line bank of tubes:

$$Nu = 0.2 \cdot C_z \cdot C_s \cdot Re^{0.65} \cdot Pr^{0.33} \tag{C.15}$$

for cross-flow staggered tubes, the Nusselt number is given by

$$Nu = C_z \cdot C_s \cdot Re^{0.6} \cdot Pr^{0.33} \tag{C.16}$$

where C_z and C_s are correction factors for the bank configuration (staggered or in-line, number of rows, transverse pitch, longitudinal pitch)(Basu et al., 2000). Re and Pr are the Reynolds and Prandtl numbers defined as

$$Re = \frac{V \cdot D}{\nu} \tag{C.17}$$

$$Pr = \frac{\nu \cdot c_p \cdot \rho}{k} \tag{C.18}$$

V is the flow velocity, ν the flue gas kinematic viscosity, ρ the density of the flue gas and c_p the specific heat of the flue gas.

These equations have been used to estimate the global heat transfer coefficient of an existing economizer based on data available from the supplier (Warga Boiler, 2006). The economizer is composed of 10 rows of 10 finned-tubes in aluminium alloy. The fins are circular. The characteristics of the arrangement is presented in table C.1.

As proposed by Incropera and DeWitt (1996), the flue gas properties can be taken as having properties of air at corresponding temperature (180°C in average in our case). Consequently we have $Pr = 0.686$, $\nu = 32.39 \cdot 10^{-6}$ and $k = 37.3 \cdot 10^{-3}$. The velocity to be used to compute Re (equation (C.17)) is the maximum velocity in the flow which occurs within the tube bank and is compute as follows assuming an incompressible fluid

$$V = \frac{S_T}{S_T - D} \cdot v = 14.3 \quad [\frac{m}{s}] \tag{C.19}$$

Given the values of D, S_T, S_L, the correction factor values are $C_z = C_s = 1$ (Basu et al.,

Table C.1: Data of economizer on *Warga* boiler

Tube length		0.8m
Number of rows	N_L	10
Tube total length	L	80m
Tube diameter	D	0.03m
Distance between tubes in row	S_T	0.055m
Distance between tubes-rows	S_L	0.07m
Fin height above tube	H	0.015m
Fin thickness	t	0.0003m
Distance between fins	f	0.015m
Flue gas velocity at inlet of economizer	v	6.5 m/s
Flue gas temperature at inlet of economizer	T_i	255.2 °C
Flue gas temperature at outlet of economizer	T_o	126.6 °C

2000). Using the numerical values in equation (C.15) gives $Nu = 84.4$ and h=105 [W/m2·K].

The overall surface efficiency η_0 is computed as follows

$$\eta_0 = 1 - \frac{N \cdot A_f}{A_t}(1 - \eta_f) \tag{C.20}$$

where η_f is the fin efficiency, N the number of fins, A_f the area of one fin and A_t is the total heat transfer area including the fins. In our case, we have N=5333, A_f=0.0043 m2, A_t=29.8 m2. The fin efficiency can be determined as a function of $H_c^{3/2} \cdot (h/k \cdot A_p)$ where $H_c = H + t/2$, $A_p = H_c \cdot t$ and k is the thermal conductivity (Incropera and DeWitt, 1996). Thus, we have $\eta_f = 0.76$ and $\eta_0 = 0.81$. Finally, we have

$$U = U_1 = h \cdot \eta_0 = 85 \quad [\frac{W}{m^2 \cdot K}] \tag{C.21}$$

To check the validity of this value, we can use Vali to compute U from equation (C.1) by considering only the convective term:

$$U = \frac{\dot{Q}}{A \cdot F \cdot \Delta T_{lm}} \tag{C.22}$$

Data available in Warga Boiler (2006) are $\dot{Q}$=274.1 kW, $A = A_t$=29.8 m^2 and ΔT_{lm}=106.2°C. With a counter-current heat exchanger ($F = 1$) [2], U is identified as 86.6 [W/m2·K] thus validating the approach. Using a similar methodology for a staggered bank of bare tubes, Che et al. (2004) have computed a value of 52 [W/m2·K] using a flue gas speed v of 2.5 [m/s].

[2]It has to be noticed that the assumption of pure counter-flow heat exchange is acceptable since for typical cross-flow economizers, the F would be between 0.92 and 1.

Appendix D

Heating degree-days

D.1 Approximating heating degree-days

Formula for approximating degree-days from monthly mean temperature are available (Badescu and Zamfir, 1999; ASHRAE, 2005). In a first step, the standard deviation of the monthly average temperatures $\overline{T}_0$ about the annual average $\overline{T}_{0,\ yr}$ is computed:

$$\sigma_{yr} = \sqrt{\frac{1}{12}\sum_{1}^{12}(\overline{T}_0 - \overline{T}_{0,\ yr})^2} \tag{D.1}$$

Then, the standard deviations for each month are estimated from the relationship:

$$\sigma_m = 1.45 - 0.029\overline{T}_0 + 0.0664\sigma_{yr} \tag{D.2}$$

A normalized temperature variable θ is defined as

$$\theta = \frac{T_{bal} - \overline{T}_0}{\sigma_m\sqrt{N}} \tag{D.3}$$

where N is the number of days in the month. Finally, the monthly degree days can be approximated by

$$HDD = \sigma_m N^{3/2}[\frac{\theta}{2} + \frac{ln(e^{-a\theta} + e^{a\theta})}{2a}] \tag{D.4}$$

where a= 1.698.

Another way of approximating the HDD is to use the monthly average temperatures $\overline{T}_0$ and the number of days in the month N:

$$HDD = N(max[0,\ T_{bal} - \overline{T}_0]) \tag{D.5}$$

It can be seen on table D.1 where the HDD have been approximated for Bulle (Switzerland) with T_{bal} = 18.3°C that both approximation methods give results close to the measured HDD (1.1% of error with equation (D.5) for the annual HDD and 2.1% of error with equation (D.4)). It can be also observed that the second method which is much simpler gives the exact value of the monthly HDD as long as there is no daily temperature above T_{bal} in the month. A similar approximation for T_{bal} =15°C (see table D.2) shows that the second method gives better results than the first one that is much more sophisticated.

Heating degree-day 12/20 can be approximated using the monthly average temperatures $\overline{T}_0$ and the number of days in the month N:

$$HDD = \begin{cases} N \cdot (20 - \overline{T}_0) & \text{if } \overline{T}_0 \leqslant 12; \\ 0 & \text{else.} \end{cases} \tag{D.6}$$

Table D.3 shows that estimating the HDD with equation (D.6) gives an error of 7% for the whole year. This error that is higher than for the two previous cases is mainly due to the months of spring and autumn when $\overline{T}_0$ is close to 12°C.

Table D.1: Approximating 2002 US degree days (T_{bal} = 18.3°C) for Bulle, Switzerland.

Month	**N** [d/m]	$\overline{T}_0$ [°C]	**HDD** [°C·day]	**HDD*** [°C·day]	**Diff.** [°C·day]	**HDD**** [°C·day]	**Diff.** [°C·day]
January	31	-1.0	599	599	0	599	0
February	28	4.3	393	393	0	393	0
March	31	6.4	369	371	2	369	0
April	30	9.0	280	282	2	280	0
May	31	12.8	173	177	4	169	-4
June	30	20.5	36	19	-17	0	-36
July	31	19.0	25	37	12	0	-25
August	31	16.6	57	80	23	53	-4
September	30	12.7	168	175	7	168	0
October	31	9.8	263	266	3	263	0
November	30	5.3	389	390	1	389	0
December	31	2.3	495	495	0	495	0
	365	9.8	3247	3284	37	3178	-69
$\overline{T}_{0,\ yr}$	9.8						
σ_{yr}	6.44						

* Computed according to equ. (D.4), ** Computed according to equ. (D.5)

Table D.2: Approximating 2002 UK degree days ($T_{bal} = 15.5°C$) for Bulle, Switzerland.

Month	**N** [d/m]	$\overline{T}_0$ [°C]	**HDD** [°C·day]	**HDD*** [°C·day]	**Diff.** [°C·day]	**HDD**** [°C·day]	**Diff.** [°C·day]
January	31	-1.0	512	512	0	512	0
February	28	4.3	314	316	2	314	0
March	31	6.4	283	286	3	283	0
April	30	9.0	196	202	6	196	0
May	31	12.8	102	105	3	82	-20
June	30	20.5	12	5	-7	0	-12
July	31	19.0	1	12	11	0	-1
August	31	16.6	10	34	24	0	-10
September	30	12.7	94	104	10	84	-10
October	31	9.8	176	185	9	176	0
November	30	5.3	305	307	2	305	0
December	31	2.3	408	409	1	408	0
	365	9.8	2413	2477	64	2360	-53
$\overline{T}_{0,\ yr}$	9.8						
σ_{yr}	6.44						

* Computed according to equ. (D.4), ** Computed according to equ. (D.5)

Table D.3: Approximating 2002 degree days 20/12 for Bulle, Switzerland.

Month	**N** [day/mo.]	$\overline{T}_0$ [°C]	**HDD** [°C·day]	**HDD est.*** [°C·day]	**Difference** [°C·day]
January	31	-1.0	651	651	0
February	28	4.3	440	440	0
March	31	6.4	422	422	0
April	30	9.0	306	331	25
May	31	12.8	150	0	-150
June	30	20.5	0	0	0
July	31	19.0	0	0	0
August	31	16.6	17	0	-17
September	30	12.7	136	0	-136
October	31	9.8	274	316	42
November	30	5.3	440	440	0
December	31	2.3	548	548	0
	365	9.8	3384	3148	-236

* Computed according to equ. (D.6)

Appendix E

Weekly regression models

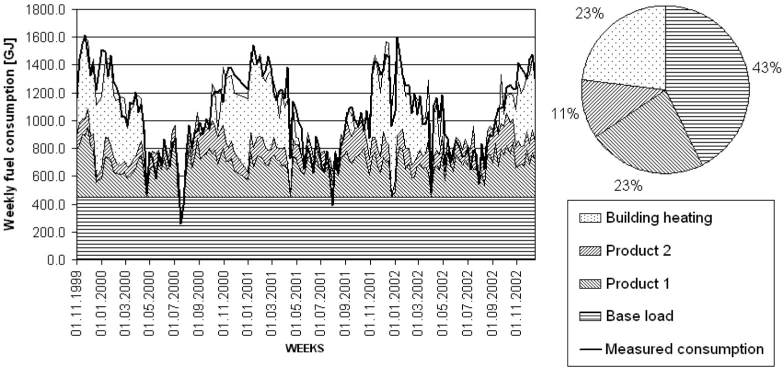


Figure E.1: Comparison between weekly measured fuel consumption and estimation from the model, and contribution of independent variables.

Table E.1: Results of the regression for the weekly fuel consumption (T_{lim}=10°C and T_{room}=22°C)

Analysis of Variance

	DF	SS	MS	F value	Prob > F
Model	3	11'204'970	3'734'990	318.6	0
Error	155	1'816'838	11'721		
Total	158	13'021'808			

R^2	0.860
$F_{0.95}[3; 155]$	2.66
$t_{0.95}[155]$	1.975

Parameter estimates

	Unit	DF	Estimate	Std err.	t value	Prob > |t|
k^{fw}	$[\frac{GJ}{w}]$	1	452.3	27.0	16.77	0
a_1^{fw}	$[\frac{GJ}{T}]$	1	1.39	0.158	8.74	0
a_2^{fw}	$[\frac{GJ}{T}]$	1	1.71	0.322	5.31	3.65E-7
h^{fw}	$[\frac{GJ}{°C \cdot d}]$	1	3.82	0.142	26.9	0

DF: degrees of freedom, SS: sum of square, MS: mean square.

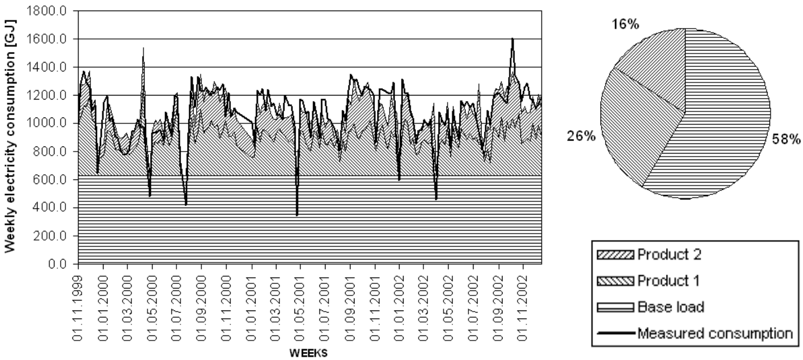


Figure E.2: Comparison between weekly measured electricity consumption and estimation from the model, and contribution of independent variables.

Table E.2: Results of the regression for the weekly electricity consumption

Analysis of Variance

	DF	SS	MS	F value	Prob > F
Model	2	4'037'798	2'018'899	145.4	0
Error	156	2'166'140	13'885.5		
Total	158	6'203'938			
R^2	0.651				
$F_{0.95}[2;156]$	3.95				
$t_{0.95}[156]$	1.975				

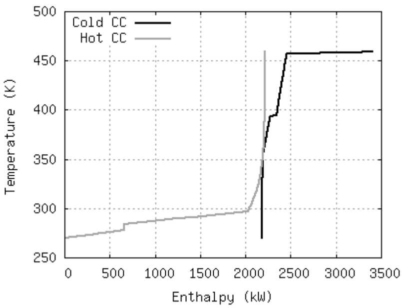
Parameter estimates

	Unit	DF	Estimate	Std err.	t value	Prob > |t|
k^{ew}	$[\frac{GJ}{w}]$	1	627.04	27.59	22.7	0
a_1^{ew}	$[\frac{GJ}{T}]$	1	1.56	0.166	9.39	0
a_2^{ew}	$[\frac{GJ}{T}]$	1	2.38	0.348	6.83	0

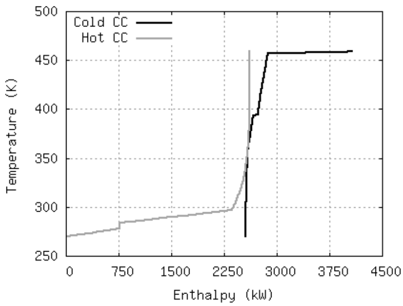
DF: degrees of freedom, SS: sum of square, MS: mean square.

Appendix F

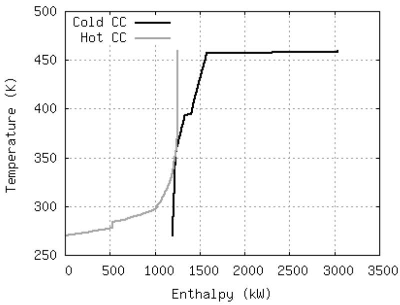
Composite curves



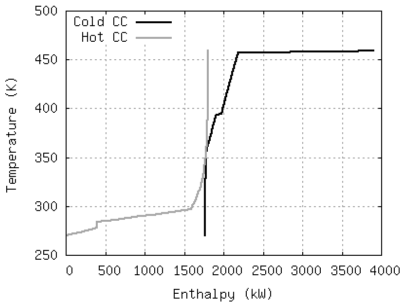
(a) Period 1 (840 hours)



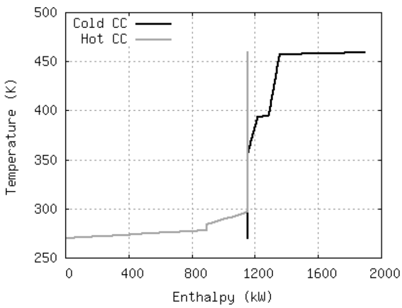
(b) Period 2 (3864 hours)



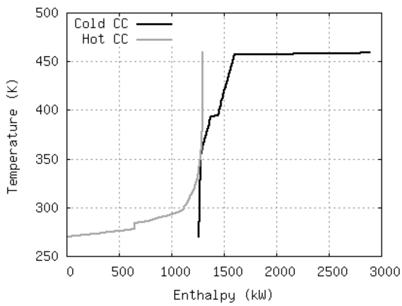
(c) Period 3 (2184 hours)



(d) Period 4 (504 hours)

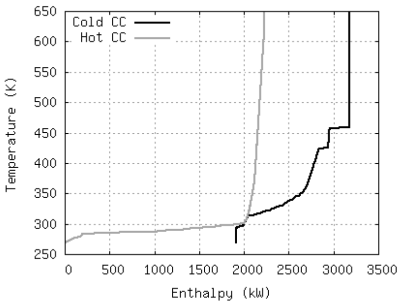


(e) Period 5 (336 hours)

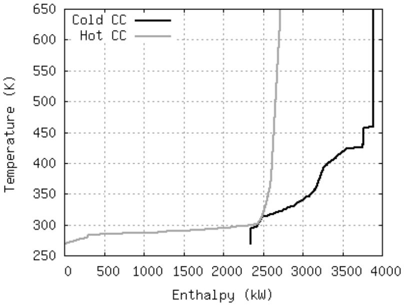


(f) Period 6 (1008 hours)

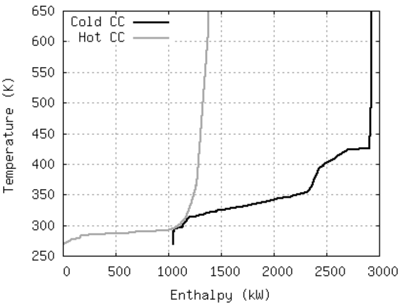
Figure F.1: Hot and cold composite curves for the 6 periods using the utility representation



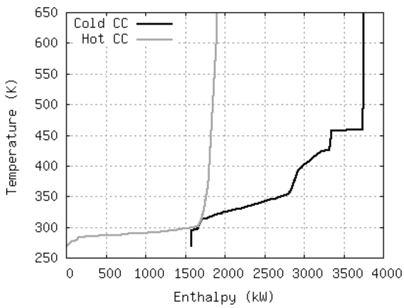
(a) Period 1 (840 hours)



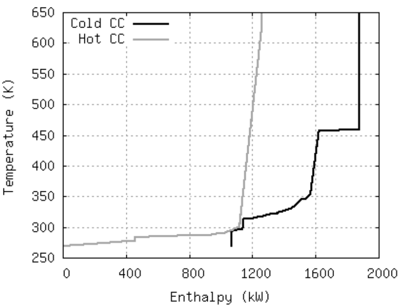
(b) Period 2 (3864 hours)



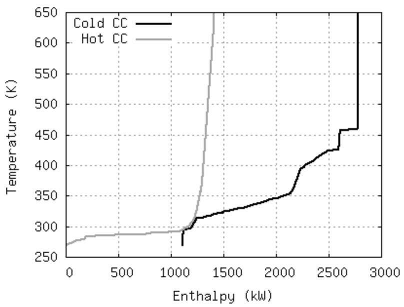
(c) Period 3 (2184 hours)



(d) Period 4 (504 hours)

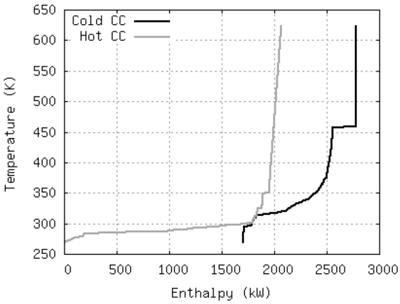


(e) Period 5 (336 hours)

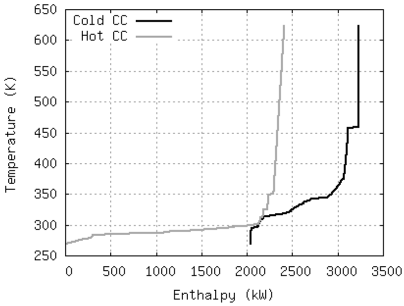


(f) Period 6 (1008 hours)

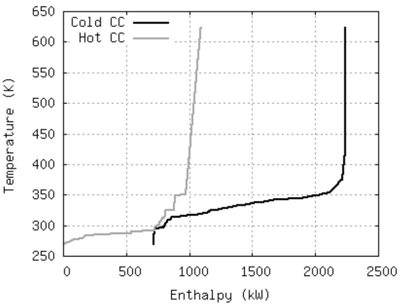
Figure F.2: Hot and cold composite curves for the 6 periods using the technological representation



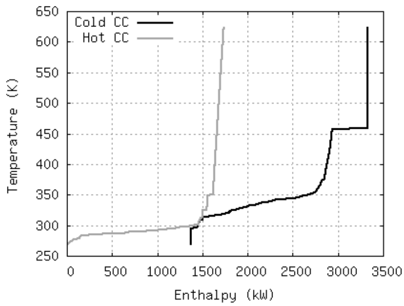
(a) Period 1 (840 hours)



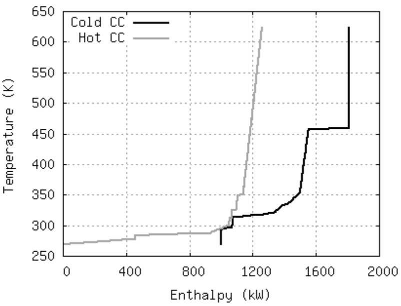
(b) Period 2 (3864 hours)



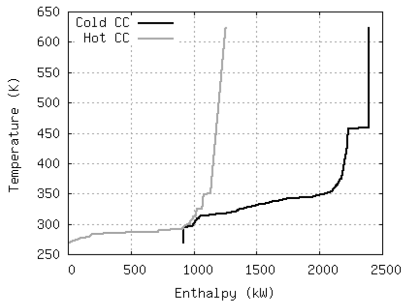
(c) Period 3 (2184 hours)



(d) Period 4 (504 hours)



(e) Period 5 (336 hours)



(f) Period 6 (1008 hours)

Figure F.3: Hot and cold composite curves for the 6 periods using the thermodynamic representation

Appendix G

Simulation models for blowdown heat recovery

The model used in the "what if?" scenarios for the blowdown heat recovery (see section 6.3.4.4). The system of equation corresponding to the first configuration is:

$$\begin{cases} \dot{m}_8 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 - \dot{m}_5 = 0 \\ \dot{m}_8(h_5 - h_8) + \dot{m}_2(h_5 - h_2) + \dot{m}_3(h_5 - h_3) + \dot{m}_4(h_5 - h_4) = 0 \\ \dot{m}_a + \dot{m}_6 - \dot{m}_5 = 0 \\ \dot{m}_a - \dot{m}_b - \dot{m}_4 = 0 \\ \dot{m}_a(h_4 - h_5) - \dot{m}_7 LHV_f \eta = 0 \\ \dot{m}_6(h_6 - h_9) - \dot{m}_1(h_8 - h_1) = 0 \\ \dot{m}_2 - \dot{m}_b cr = 0 \\ \dot{m}_6 - \dot{m}_5 br = 0 \\ \dot{m}_8 - \dot{m}_1 = 0 \\ \dot{m}_9 - \dot{m}_6 = 0 \end{cases} \tag{G.1}$$

The unknowns are $\dot{m}_1$, $\dot{m}_2$, $\dot{m}_4$, $\dot{m}_5$, $\dot{m}_6$, $\dot{m}_7$, $\dot{m}_8$, $\dot{m}_9$, $\dot{m}_a$, h_8.

As regards the second configuration, the problem to solve is the following 12 x 12 nonlinear system of equations:

$$\begin{cases} \dot{m}_8 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 - \dot{m}_5 = 0 \\ \dot{m}_8(h_5 - h_8) + \dot{m}_2(h_5 - h_2) + \dot{m}_3(h_5 - h_3) + \dot{m}_4(h_5 - h_4) = 0 \\ \dot{m}_a + \dot{m}_6 - \dot{m}_5 = 0 \\ \dot{m}_a - \dot{m}_b - \dot{m}_4 = 0 \\ \dot{m}_a(h_4 - h_5) - \dot{m}_7 LHV_f \eta = 0 \\ \dot{m}_6(h_{10} - h_6) - \dot{m}_1(h_8 - h_1) = 0 \\ \dot{m}_6 - \dot{m}_{10} - \dot{m}_{11} = 0 \\ \dot{m}_{10}(h_{10} - h_6) - \dot{m}_{11}(h_{11} - h_6) = 0 \\ \dot{m}_2 - \dot{m}_b cr = 0 \\ \dot{m}_6 - \dot{m}_5 br = 0 \\ \dot{m}_8 - \dot{m}_1 = 0 \\ \dot{m}_9 - \dot{m}_6 = 0 \end{cases} \tag{G.2}$$

The unknowns are $\dot{m}_1$, $\dot{m}_2$, $\dot{m}_4$, $\dot{m}_5$, $\dot{m}_6$, $\dot{m}_7$, $\dot{m}_8$, $\dot{m}_9$, $\dot{m}_{10}$, $\dot{m}_{11}$, $\dot{m}_a$, h_8.

Damien MULLER

Swiss citizen
Born March 7, 1980
damien.muller@a3.epfl.ch

Education

Since June 2003	**PhD student at the Industrial Energy Systems Laboratory.** Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland
1998-2003	**Master of Science in Mechanical Engineering.** Swiss Federal Institute of Technology, Lausanne (EPFL), Switzerland
2000-2001	Exchange programme (3rd year) at Université Laval, Quebec, Canada

Work experience

Since June 2003 — **Researcher at the Industrial Energy Systems Laboratory (EPFL)**

- Development of energy management tools and methods.
- Energy audits (Morocco, India, Switzerland)
- Supervision of 4 master projects

10/2002 - 02/2003 — **Trainee-Engineer at Process Systems Enterprise (PSE), London**
Implemented, using C++ language, a hybrid optimisation algorithm in the process modelling, simulation and optimisation gPROMS software.

Publications

An energy management method for the food industry
Muller, D and Marechal, F and Wolewinski, T and Roux, P.
Proceedings of PRES'05, volume 7, pages 471-476, Giardini di Naxos, 2005.

Languages

French :	Native speaker.
English :	Advanced level. (Courses taken at Université Laval, Quebec, Canada).
Spanish :	Advanced level. (Courses taken at Universidad de Alcala, Madrid, Spain).
German :	Intermediate level, both written and oral.

Computer skills

General :	Windows, MS Office, MS Outlook, MS Project, Endnote, LaTeX.
Engineering :	Matlab, Belsim-Vali, gPROMS, I-Deas, Pro-engineer.
Programming :	C++, Ruby, MySQL, XML, HTML.