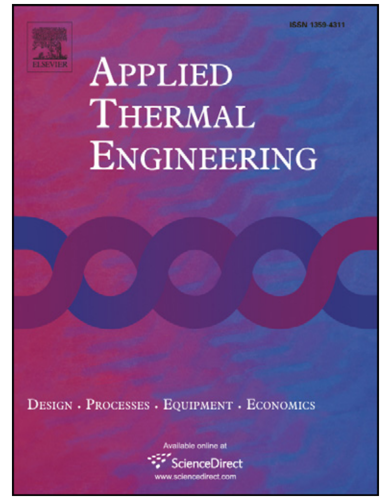

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An energy management method for the food industry

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Abstract

This article presents a method aimed at tracking energy saving opportunities in the food-processing industry through a combination of top-down and bottom-up approaches. On the one hand, the top-down modelling method aims at correlating the measured energy consumptions with the final products and auxiliaries as well as at allocating the energy bills among major consumers. This approach will, therefore, set priorities for energy saving actions. On the other hand, the bottom-up approach, which is based on the thermodynamic requirements of the process operations, is used to define the energy requirements of these consumers. A comparison of the measured consumptions and the energy requirements enables the identification of energy saving opportunities. In the case study presented in this article, these opportunities have been evaluated using thermo-economic modelling tools and range from good housekeeping measures and optimised process operations to energy saving investments.

Key words:
food industry, energy management, top-down, bottom-up, energy efficiency, multiple linear regressions

1 Introduction

The food industry is a non-energy intensive industry where energy is only a small part of the total cost of production (approximately 3%) [1, 2]. However, it is an important energy consumer in the industrial sector due to its size. For example, in 1998, food industry accounted for 4.4% of the energy consumption of the US industry sector. It was the fifth biggest consumer (out of 20 sectors) after petroleum and coal products, chemicals, paper and primary metals [3]. Thus, the potential energy savings achievable through an efficient energy management program can be significant. Furthermore, the fact that most of the saving opportunities can be replicated from one production site to the others provides greater overall opportunities for corporations having a large number of production sites.

Regardless of these potential benefits, multiple barriers have to be overcome in order to put in place an efficient energy management program [4]. Since energy is only a small part of the total cost of production, it is not considered as a *core* business. Thus, it is not regarded as a priority in daily management. 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

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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, energy management needs constant attention. For this reason, top management commitment is a necessary condition for an effective energy management program [5, 6]. Another frequently encountered difficulty is the lack of resources for energy monitoring as well as for implementing energy efficiency projects. Most of the time, resources allocated to energy management are accounted as operating costs, while these should be considered as an investment directed at increasing the factory productivity. Another consequence of the secondary role played by energy is the low level of energy metering and recording frequently done in the factories. The few pieces of information available are often spread all over the factory and are neither centralized nor allocated to business units due to the lack of human resources. The availability of reliable data is usually a bottleneck when implementing an energy management program.

Today, even if the food industry remains a non-energy intensive industry, higher energy prices and the Kyoto Protocol have attached an increased importance to energy efficiency. As a consequence, top management is making resources available to set up energy management programs and to coordinate the agents involved in these programs: factory manager, technical manager, maintenance and project engineers, production and utility operators. These agents have different visions and expectations. According to O'Callaghan [7], the goal of an energy management program is to monitor, record, analyse, critically examine, alter and control energy flows so that energy is always available and utilized with maximum efficiency. The needed knowledge to fulfill these goals includes engineering, economics, management and information technology.

In the field of engineering, a wide range of methods and tools are available to support energy management programs:

- energy monitoring tools;
- process modelling, simulation and optimisation tools;
- process integration;
- energy and exergy analysis; and
- decision support tools: best practices, literature,etc.

The first method can be considered as a top-down approach while the three following ones are considered as bottom-up approach, since they are focused on the process itself. In the industry sector, only one of these two groups is often used for energy management purposes. The last method compiles general conclusions and pieces of advice available in previous studies. This paper presents an energy management method that combines a top-down approach - which offers a holistic vision of the energy consumptions in the factory - with a bottom-up approach - which determines the efficiency gaps between the thermodynamic requirements of the process operations and their technological implementation in production. Together with the best practices, this method will help in defining road maps towards energy efficiency measures.

2 Methodology

A systemic representation of the sub-systems and the mass and energy flows in a factory is given on Figure 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 the distribution systems, the support to production, such as water, solvent or compressed gases and the waste treatment. Horizontal transformations concern transformation of raw materials into products or by-products. They have to be maximised while minimising the vertical flows which include energy usage and waste generation. This figure also clearly reflects the first principle of thermodynamics, expressed in the well known "more in-more out" rule of process integration [8] : the resources that do not leave the system as product, by-product or useful energy will leave the system as waste or emission. Maximising the horizontal flows and minimizing the vertical one (resources) means as well minimising the environmental impact. In conventional process integration approaches, as applied in the chemical industry, the focus is on the process; consequently, the integration potential of the utilities is usually disregarded. Energy and water flows are considered as input for 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 process. This may be mainly due to the fact that most of the processing operation occur at a limited temperature level. This offers opportunities for integrating combined heat and power production or heat pumping. Another characteristic 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.

Two approaches can be considered when it comes to analysing the energy consumption of a factory with the aim of energy efficiency: top-down and bottom-up approaches. Based on energy bills, the top-down approach aims at allocating the consumption among the different users in the factory. It helps identify the main energy drivers. In this framework, multiple linear regressions can be used to define relationships between dependent variables, such as energy consumptions, and independent variables, such as production volumes, ambient temperature, etc. Experience shows that a linear model is accurate enough in most of the cases [9]. A more detailed discussion on the application of the top-down approach can be found in the article of Vogt [9]. Unlike the top-down approach, which is based on the global energy consumption of the factory (i.e. the utility bills), the bottom-up approach aims at thermodynamically modelling the energy consumptions of the different process operations in order to recalculate the global energy consumption by summing up their different contributions. This technique is widely used in the chemical process modelling community and offers an excellent basis for pinch analysis [10, 11], given the large amount of information that is made available. The method suggested by Dalsgard et al. [12] can be used to simplify the process integration analysis in the food industry by identifying the sub-problems, considering the utility system as the tool for the integration and eliminating streams with limited energy saving potential.

Both approaches have been applied to chemical batch plants. The efficiency of each method will mainly depend on the variability of the products as shown by Bieler et al. [13, 14]. From our experience, 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.

Due to its characteristics, the top-down is better adapted for a rapid identification of the main energy drivers of a factory, which can be the basis for a more detailed study in a specific area. 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 difficult to apply it in industries where the resources dedicated to energy management are limited. In our approach, 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 to the whole site, as done when aiming to recompute the energy bill.

3 Top-down approach: fuel modelling

In our methodology, the top-down approach is used to model the different energy bills: fuels and electricity. It is also applied to model the energy distribution flows (e.g. steam or water) within the factory. The main independent variables are production volumes, the heating degree days (HDD) and the cooling degree days (CDD). Degree days are used to characterize the heating and cooling requirements as a function of the ambient temperature $T_{i,j}$ of the day j in the month i [15, 16]. Beside the independent variables, a base load is also considered for the consumption of the utilities. For the sake of demonstration, this technique has been applied in a Nestlé 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. The database built up for this study covers a period of 36 months ($n_{month} = 36$) from January 2000 to December 2002. Assuming that no major process modifications have occurred during this period, the problem is solved using the least square principle and is formulated as follow:

$$\min_{a_p^f,h^f,k^f}[\sum_{i=1}^{n_{month}}(\epsilon_i^f)^2] = \min_{a_p^f,h^f,k^f}[\sum_{i=1}^{n_{month}}(\hat{y}_i^f - y_i^f)^2] \quad (1)$$

with

$$\hat{y}_i^f = \sum_{p=1}^{n_p} a_p^f \cdot v_{i,p} + h^f \sum_{j=1}^{n_{days_i}} HDD(T_{i,j}) + k^f \cdot n_{days_i} \quad (2)$$

where a_p^f (GJ/t of product p) are the production regression coefficients, h^f (GJ/d/°C) is the heating 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. In Switzerland, heating degree days are computed according to a norm [15] and available from a meteorological data base :

$$HDD(T_{i,j}) = \begin{cases} T_{room} - T_{i,j} \text{ if } T_{i,j} \leqslant T_{lim}; \\ 0 \quad \text{ if } T_{i,j} > T_{lim}. \end{cases} \quad (3)$$

T_{room} and T_{lim} are respectively the indoor temperature and the heating temperature limit (set respectively at 20°C and 12°C according to the norm). It has to be mentioned that the norm is built for residential buildings and not for industrial applications. However, since part of the heating requirements is related to office heating, we have kept the initial assumption and made a sensitivity analysis considering the measurements of the temperatures from data bases. 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 coefficients obtained by the least square estimation are presented in Table 2, together with the coefficient of determination R^2. In order to validate the developed correlation, the model is tested against the assumption that, at least, one coefficient of the correlation is significant. The validity of the model is, therefore, tested against the following assumption:

$$H_0\text{: } \beta_j = 0 \; \forall \; j \quad \text{vs.} \quad H_1\text{: at least one } \beta_j \neq 0 \text{ with } \beta_j \in \{h^f, k^f, a_1^f, ..., a_{n_p}^f\}$$

The test is performed using the F statistic:

$$F = \frac{(n_{month} - m - 1)R^2}{m(1 - R^2)} \tag{4}$$

where R^2 is computed by Eq. 5:

$$R^2 = \frac{(\hat{Y}^f)^T \hat{Y}^f - n_{month}(\bar{Y}^f)^2}{(Y^f)^T Y^f - n_{month}(\bar{Y}^f)^2} \tag{5}$$

$$\bar{Y}^f = \frac{1}{n_{month}} \sum_{i=1}^{n_{month}} y_i^f \tag{6}$$

$\bar{Y}^f$ is the mean value of Y^f computed by Eq. 6. $\hat{Y}^f$ and Y^f are respectively the array of the estimate $\hat{y}_i^f$ and the measured consumptions y_i^f, and m is the number of independent variables excluding the constant k^f. In the example, $n_{month} = 36$ and $m = 4$.

The F statistic has a F distribution with m, $n_{month} - m - 1$ degrees of freedom. As shown in Eq. 4, the test is performed by comparing the F statistic with the critical F-value of a table at a given level of significance. As it can be seen on Table 2, the computed F-value (Eq. 4) 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) can be rejected. This result could have been expected given the high value of the coefficient of determination R^2 (Eq. 5), which intervenes in the computation of the F-value.

After testing the relevance of the model, the validity of each of the coefficients of the model is verified by testing the following hypothesis:

$$H_0 : \beta_j = 0 \quad \text{vs.} \quad H_1 : \beta_j \neq 0 \ \forall j$$

According to Freund and Wilson [17], this assumption is tested against the t statistic:

$$t = \frac{\hat{\beta}_j}{\sqrt{c_{jj} \cdot MSE}} \tag{7}$$

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

$$MSE = \frac{\sum_{i=1}^{n_{month}} (\epsilon_i^f)^2}{n_{month} - m - 1} \tag{8}$$

c_{jj} is the jth diagonal element of matrix $C = (X'X)^{-1}$ where X is the n_{month}-by-$(m+1)$ matrix containing all the independent variables including the constant. The constant is represented by a column of 1 in the first column of matrix X.

The t statistic has a Student's t distribution with $(n_{month} - m - 1)$ degrees of freedom. The test involves comparing the computed t-value with the critical t-value of a table at a given level of significance. From the results presented in Table 2, the null hypothesis for coefficient a_3^f cannot be rejected because the computed t-value is lower than the table value of 2.04 at 0.05 level of significance and 31 degrees of freedom. As a consequence, a model without the product 3 variable ($v_{i,3}$) should be used for further analysis. This also means that product 3 does not significantly affect the energy consumption. With the aim of improving the model, the sensitivity of the T_{lim} and T_{room}

values in Eq. 3 has been studied. The resulting coefficients of determination are presented in Table 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 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. The resulting estimated monthly fuel consumptions are then compared with the measured consumptions on Figure 2. The figure shows as well the contribution of the different independent variables on the overall fuel consumption of the period. 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 process stand-by periods.

4 Top-down approach: electricity consumption modelling

A similar model is used to estimate the monthly electricity consumption $\hat{y}_i^e$:

$$\hat{y}_i^e = \sum_{p=1}^{n_p} a_p^e \cdot v_{i,p} + h^e \sum_{j=1}^{n_{days_i}} CDD(T_{i,j}) + k^e \cdot n_{days_i} \tag{9}$$

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). Since all the refrigeration unit uses electricity as the driving energy (mechanical chiller), the hotter the outside temperature is, the bigger electricity consumption will be registered. The commonly used function to model this behaviour is given in Eq. 10 below:

$$CDD(T_{i,j}) = \begin{cases} T_{i,j} - T_{room} \text{ if } T_{i,j} \geqslant T_{room}; \\ 0 \qquad\qquad \text{ if } T_{i,j} < T_{room}. \end{cases} \tag{10}$$

T_{room} is usually taken as 18°C according to ASHRAE [16]. It should be noted that the CDD representation is based on the building air conditioning, which is not necessarily true since part of the cooling load derives from refrigeration. An analysis of the cooling system shows, however, that HVAC equipment and refrigeration are in use in the factory. The refrigeration unit is a water-cooled system. Assuming that the water temperature varies less than the ambient temperature, the CDD model can be considered as a valid approach.

The two types of tests presented for the fuel model are also 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 5. 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 Eq. 10. Indeed, as stated in ASHRAE [16], 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 5 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. However, from the daily measurement made at the factory, we can see that the model predicts quite well the base load consumption as shown in Figure 3. 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 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 monthly electricity consumption predicted by the model as well as the contribution of the independent variables is presented in Figure 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 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 Figure 4 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.

4.1 Top-down approach: breakdown of electricity consumption

The same approach can 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 looked into more details 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 goal 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 on Figure 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 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 directly link the distributed energy Q_{evap} with the consumed electricity W_{in} as shown in Eq. 11:

$$COP = \frac{Q_{evap}}{W_{in}} \tag{11}$$

This parameter is highly influenced by the efficiency of the compressors which has also been identified. These parameters are presented in Table 6 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.

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 7) 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). 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 5).

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 $8.9\% \cdot 8.3\% = 0.7\%$.

5 Top-down approach: discussion

In the proposed methodology, the top-down approach is used to direct the next step of the method (the bottom-up approach) on the major energy drivers in the factory by defining their contributions to the energy bills. Compared to similar analysis [13], the top-down approach appears to be more appropriate 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. Moreover, the models developed in the top-down approach have also been used for consumption forecasting and budgeting exercises. They have allowed for the detection of errors in the production volume records. As mentioned in Table 1, they can also be easily used for targeting-monitoring in order to detect deviations in the process efficiency. It has to be noticed that the availability of reliable data record is essential in the top-down approach. Moreover, the data should also be available for the same periods, for dependent and independent variables. For example, in this study, the electricity consumptions used in the models 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. Indeed production volumes are available weekly and cannot be determined for a given month. Some months presented in Figure 2 and 4 are composed of four weeks while some others of five. It is for this reason that the base loads plotted in this two figures are not constant.

The same approach can be used on a weekly basis if all the needed data (energy consumptions, production volumes, 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 results showed 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. However, the coefficients of determination obtained are lower than for the monthly approach. It was 0.84 for the fuel model and 0.65 for the electricity model. This can be explained by the fact that the data are less accurate and are not always available for the same period, as discussed above.

6 Bottom-up approach

Though the top-down approach has allowed a quick identification of the main energy drivers in the studied facilities, this analysis does not usually lead to direct energy saving opportunities. Another approach, called bottom-up, is used for that purpose. As an example, the significant base load in the two major utilities (electricity and fuel) made them natural priorities in the bottom-up approach. The methodology used has been to compute the thermodynamic requirements of different process units contributing to base load consumptions and to compare them with their technological implementation. In process integration studies, this dual representation of the requirement [18] is important to identify situations where the process requirements are satisfied with the wrong utility or the wrong technology. It will, therefore, highlight opportunities for energy savings by process integration when the process energy supply is changed. In this case, the approach is used to identify malfunctioning units and deduce some correcting actions. To illustrate this concept, let us consider some examples.

6.1 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 requirement of this operation is 16.1 Nm^3/h of 0.5 barg air. Assuming an isentropic compression, the power needed is 0.2 kW. This is to be compared with its technical 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 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.

6.2 Vacuum production in dryers

Another example is the production of vacuum of 25 mbars that is needed in a dryer. Presently , it is performed with a liquid ring vacuum 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 optimise its efficiency. This model has been validated through tests on site. The model shows that the steam ejector was 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 this modification are of approximately 15,000 liters of fuel per year together with the corresponding cooling and demineralised water savings.

6.3 Summary of energy savings

The top down-approach supported with the bottom-up approach presented here the major advantage of putting emphasis on energy efficiency actions. 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 system that contribute to the high base load observed in both fuel and electrical consumption. These measures have been classified in three categories:

- measures that require only changes in process practice;
- modifications that require process operation optimisation; and
- modifications that require investment.

Table 8 presents the main yearly energy savings obtained in this application. These results confirm the results of similar studies [19, 20], which showed that a significant part of the savings can be considered as good housekeeping and require no or few investments.

The proposed approach is however only the first step of the study. The next steps will concern a more in depth analysis of the process requirements, the study of the energy recovery through process integration and the optimal integration of energy conversion technologies.

7 Conclusion

A top-down modelling approach has been applied in an energy management method developed for the food industry. This method is especially appropriate for non-energy intensive industry where the resources for energy management are often limited. However, it could also be applied to other industries. The top-down approach has permitted to model the energy consumptions with multi-linear regression models. Statistical tests were used to include in the models only the variables that have significant impact on energy consumption and to test the validity of the models. The regressions have showed high coefficient of determination (0.954 in the case of fuel consumption and 0.872 for the electricity consumption), which are good quality indicators. The top-down models could be used as reliable tools for forecasting and budgeting energy consumptions and for targeting-monitoring measures.

The method presented has, however, some limitations since it does not represent the process units operation and has, therefore, a limited extrapolation capability. It is used in the beginning of a study to give an overview of the energy use in the factory and to identify immediate energy savings measures. It has to be considered as the first step of a more detailed analysis in which not only unit efficiency but also heat recovery and energy conversion integration should be considered.

In the application, these models have been used to set priorities for more detailed studies performed by applying a computer-aided bottom-up approach and applying best practice measures. The bottom-up approach aims at modelling the thermodynamic requirements of the process operations identified as critical by the top-down analysis. The results have shown that there is, in some process units, a gap between the thermodynamic requirements of a unit and its technological implementation, allowing for energy savings. The study shows that a significant part of the energy savings identified could be obtained with good housekeeping and require limited investment.

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Nomenclature

y_i	Measured consumption during moth 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/℃/d]
CDD	Cooling degree day [℃·d]
HDD	Heating degree day [℃·d]
$T_{i,j}$	Ambient temperature of the day j in month i [℃]
T_{room}	Room temperature [℃]
T_{lim}	Ambient temperature below (resp. above) which the heating (resp. cooling) devices are turn on [℃]
k	Correlation base load coefficient [GJ/d]
n_{month}	Number of months considered
m	Number of independent variables in the regression excluding the base load
R^2	Coefficient of determination
F	F statistic

t	t statistic
MSE	Mean square error
COP	Coefficient of performance [-]
HVAC	Heating, Ventilating, and Air-Conditioning

Superscripts

f	fuel
e	electricity
r	refrigeration

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List of captions

Table 1
Advantages and disadvantages of the top-down and the bottom-up approaches

	Advantages	**Disadvantages**
Top-down	• Low cost • Simple model • Easy monitoring • Easy forecasting • Flexible • Minimal maintenance	• Require statistical expertise • Require data history • No efficiency assessment • High-level modelling • No modelling of efficiency measures
Bottom-up	• Based on equipment thermodynamics • Good accuracy • Clear picture of energy usage • No data history required • Efficiency assessment • Modelling 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

Table 2
Results of the regression ($T_{lim} = 12$°C and $T_{room} = 20$°C)

	k^f	a_1^f	a_2^f	a_3^f	h^f	R^2	Computed F-value
Unit	$\frac{GJ}{d}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{d°C}$		
Coefficients	61.48	1.56	1.71	-0.31	4.18	0.950	147.13
Computed t-value	6.61	3.57	2.64	0.68	19.08		
$t_{0.95}[31]$	2.04				$F_{0.95}[4;31]$		2.68

Table 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
Results of the regression (T_{lim}=10°C and T_{room}=22°C)

	k^f	a_1^f	a_2^f	a_3^f	h^f	R^2	Computed F-value
Unit	$\frac{GJ}{d}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{d°C}$		
Coefficients	56.68	1.42	2.46	-	3.77	0.954	223.61
Computed t-value	8.59	3.50	4.14	-	24.49		
$t_{0.95}[32]$	2.04				$F_{0.95}[3;32]$		2.90

Table 5
Results of the regression for the electricity

	k^e	a_1^e	a_2^e	a_3^e	h^e	R^2	Computed F-value
Unit	$\frac{GJ}{d}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{°C}$		
Coefficients	81.50	1.67	3.03	-	-	0.872	112.63
Computed t-value	13.69	4.19	5.12	-	-		
$t_{0.95}[33]$	2.04				$F_{0.95}[2; 33]$		3.28

Table 6
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

Table 7
Results of the regression for the refrigeration cycle

	k^r	a_1^r	a_2^r	a_3^r	h^r	R^2	Computed F-value
Unit	$\frac{GJ}{d}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{t}$	$\frac{GJ}{HDD}$		
Coefficients	-	-	0.56	0.36	1.39	0.989	236.5
Computed t-value	-	-	6.67	3.95	4.49		
$t_{0.95}[8]$	2.31				$F_{0.95}[2;8]$		4.46

Table 8
Summary of some energy savings identified

Measure	Energy saving [MWh/year]	Estimated payback
Replace compressed air usage by dedicated blowers[a]	166	2
Regulation of HVAC[a]	80	negl.
Removing stand-by of air compressors with a VSD unit[a]	69	23
Fixing compressed air leakage[a]	50	negl.
Insulating pipes of high temperature condensate return[b]	338	1.5
Vacuum production in dryer[b]	150	1
Regulation of steam user[b]	50	negl.

Notes: [a] and [b] denote electricity and fuel savings respectively.

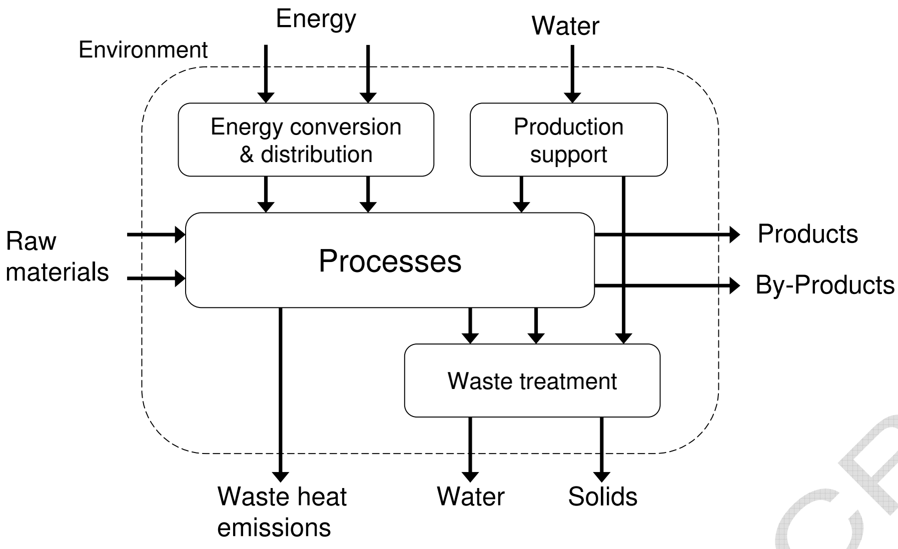

Fig. 1. Typical production setup.

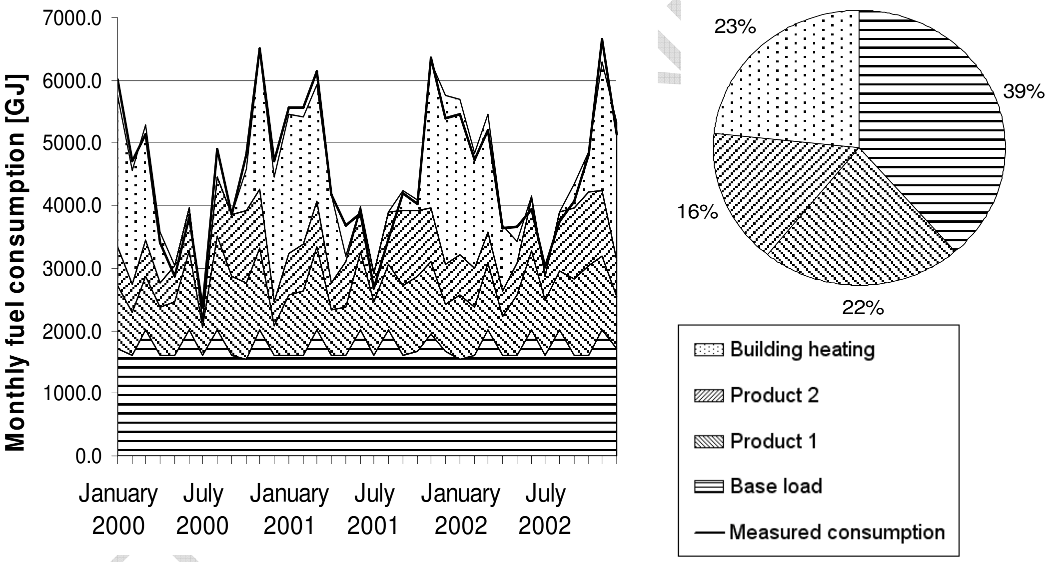

Fig. 2. Comparison between measured fuel consumption and estimation from the model, and contribution of independent variables.

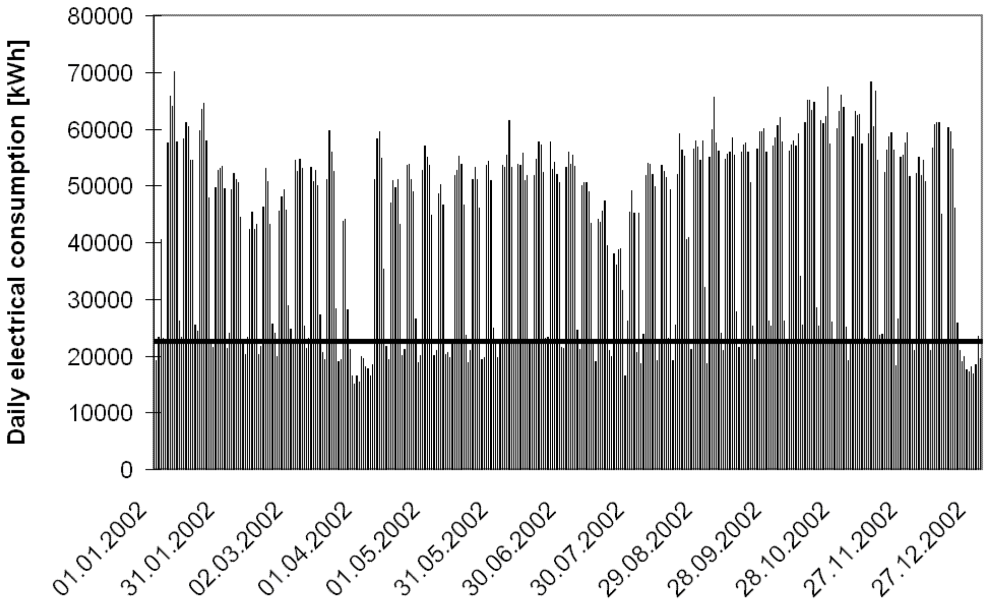

Fig. 3. Measured base load consumption versus model prediction for the year 2002

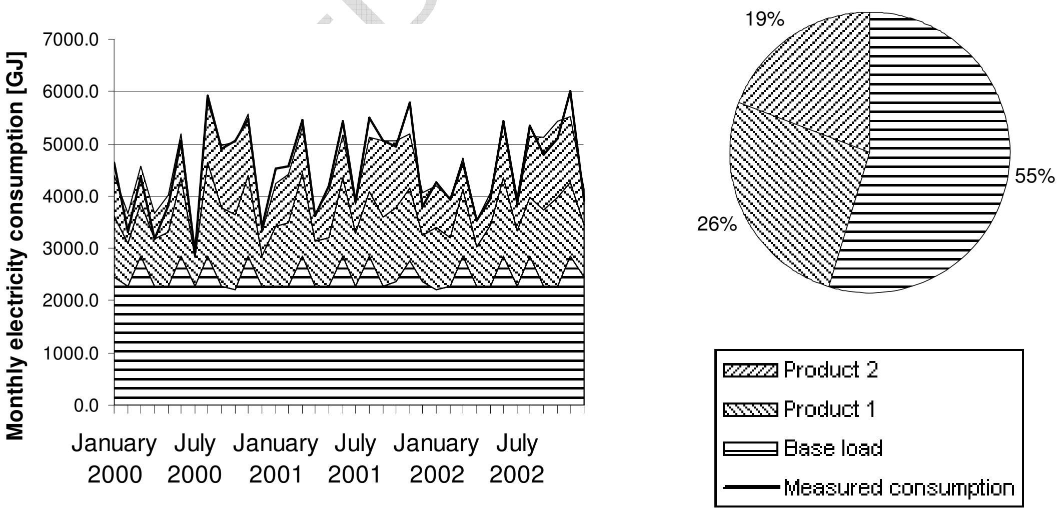

Fig. 4. Comparison between measured electricity consumption and estimation from the model, and contribution of independent variables

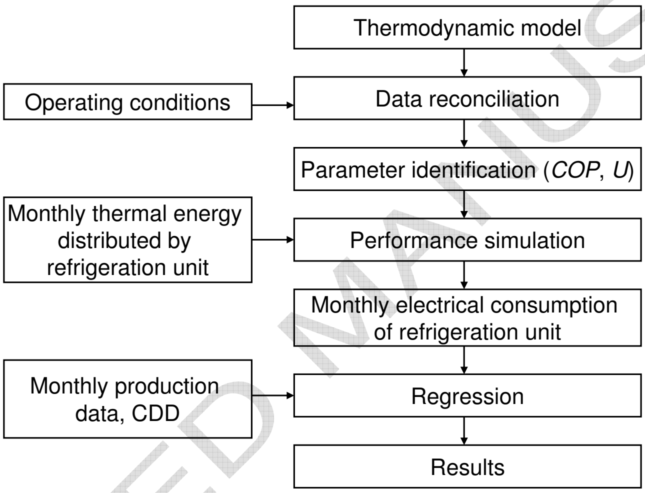

Fig. 5. Procedure applied when using a thermodynamic model