Numerical estimation and sensitivity analysis of the energy demand for 6 industrial buildings in France

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ABSTRACT

When it comes to dealing with energy savings in buildings, studies almost systematically focus on the residential and tertiary building stocks while the industrial building stock is ignored. This study comes as a first step to move forward on this topic and its objectives are threefold: first to develop a simple methodology suitable for various industrial activities, then to analyse the distribution of the energy demand by use for 6 different cases and, finally, to carry out a sensitivity analysis. A first observation was that the energy demands for HVAC and lighting systems and the heat loads were of the same order of magnitude. The energy demand for heating and cooling was normally distributed, and the uncertainty on the results lay between ±20% and ±40% for most cases. The influence of 6 weather conditions was estimated for all of the 6 buildings and found to be significant, yet not uniformly.

KEYWORDS

Industrial building, sensitivity analysis, dynamic thermal simulation, TRNSYS, Monte Carlo Analysis

NOMENCLATURE

A	Area	m²
e	Thickness	m
h	Heat loss coefficient	$W.°C^{-1}$
H	Height	m
p	Perimeter	m
P	Power	kW
Q_V	Volumetric air flow	$m^3.s^{-1}$
r	Pearson's coefficient	-
S	Sensitivity index	-
T	Temperature	°C
U	Thermal transmittance of a wall	$W.m^{-2}.K^{-1}$
X	Input of the model	-
Y	Output of the model	kWh
z	Floor depth below ground level	m

Greek symbols

α	Vertical temperature gradient	$°C.m^{-1}$
λ	Thermal conductivity	$W.m^{-1}.K^{-1}$
μ	Mean value	-
σ	Standard deviation	-

Subscripts

$_{INS}$	Insulating Material
$_{F}$	Floor
$_{G}$	Ground
$_{M}$	Maximum
$_{m}$	minimum
$_{R}$	Reference
$_{SP}$	Set-Point
$_{Sim}$	Used in simulation

Abbreviations

CFD	Computational Fluid Dynamics	
HVAC	Heating, Ventilation and Air Conditioning	
SFP	Specific Fan Power	$kW.(m^3.s^{-1})^{-1}$

1. INTRODUCTION

It is acknowledged that a significant amount of energy is consumed for the operation of buildings, mainly for Heating, Ventilation and Air Conditioning (HVAC) systems and for lighting. As a result, regulations have been modified over recent decades so that buildings are designed to consume as little energy as possible. Because of the low turnover in the construction sector, however, the impact of these regulation changes on the building stock is not expected to be significant in the short term and there is a need to assess the actual energy demand of the building stock and the potential benefits of energy conservation measures. This issue is still a current concern and some recent examples can be found in (Filogamo et al. 2014; Gangolells et al. 2016; Capozzoli et al. 2015), among others. However, these studies are almost systematically focused on the residential and tertiary building stocks, while the industrial building stock is ignored. There may be several reasons for this:

- Energy consumption is highest in residential building stock, which makes it a priority. Moreover, the use of these buildings is fairly standard and well documented, which facilitates studies on the topic;
- Since regulation codes were introduced, energy performance certificates have been issued. These certificates bring useful information for a building statistical database (Gangolells et al. 2016) and are compatible with data mining techniques (Capozzoli et al. 2015). However, the regulation codes do not apply to industrial buildings, at least in France, so there is no equivalent database;
- For residential buildings, it is known that the energy consumption is mostly related to space and water heating, as underlined in (Filogamo et al. 2014). Therefore, there is a strong relationship between the energy bills, the building design and the heating systems. For industrial buildings, the total electricity consumption is easy to obtain and suitable for use with forecasting techniques, such as Artificial Neural Networks as exemplified in (Azadeh, Ghaderi, and Sohrabkhani 2008). However, it is hard to discriminate between the fraction of the electrical energy that is used for the HVAC and lighting systems, and the energy used by the industrial process because the energy demand may vary significantly depending on the industrial activity (from warehouses to factories). For this reason, the information related to the energy consumption of HVAC systems in industry is rather scarce.

Consequently, it is still unclear whether it is worth considering the energy consumption of HVAC systems and lighting for industrial buildings when investigating potential energy savings.

As underlined above, the industrial building stock is heterogeneous, which makes it more difficult to study. However, some examples can be found in the literature. In 1992, a first study was reported (Akbari and Sezgen 1992), in which two industrial buildings in California were considered. In (Dongellini, Marinosci, and Morini 2014), the energy audit of 8 large industrial buildings dedicated to car manufacturing in Italy was presented and analysed. In both cases, the energy analysis was based on knowledge of the on-site energy consumption for HVAC systems. A single manufacturing hall located in Slovakia was monitored in (Katunsky et al. 2013). Temperature and heat flux measurements were used to fit the results obtained with building energy software named ESP-r and thus allow a more in depth analysis. It should be noted that all three of these studies concluded on the significant influence of internal heat loads. Therefore, the energy audit of an industrial building should combine both the physical description of the building and a description of its use, so users should be interviewed on their real habits and practices. However, it also appeared that no standard technique existed (Olivia and Christopher 2015) because of differences in the use of these buildings. Finally, it was pointed out in (Akbari and Sezgen 1992) that it is not rare for the actual current activity to differ from what was originally intended.

Some case studies highlight the potential for energy reduction in this sector. In (Dongellini, Marinosci, and Morini 2014), it is demonstrated that high energy gains could be obtained by modernizing the equipment, using energy recovery systems or simply adapting the control system. Similarly, in (Mirade et al. 2012), the energy consumption of fans was reduced by 50% by adapting the control system. It is also suggested in (Akbari and Sezgen 1992) that improving the efficiency of the lighting system could lead to significant energy savings. This could be achieved by modernizing the equipment or by increasing the use of daylight (X. Wang et al. 2013). However, assessing the influence on the overall energy consumption is not a straightforward affair, as heat loads are reduced at the same time. Another possibility would be to improve the thermal insulation of the envelope, which tends to be lower for industrial buildings than for the tertiary sector. However, the payback period is bound to be much longer than for upgrading the equipment, as mentioned in (Dongellini, Marinosci, and Morini 2014). Several combinations of energy conversion and heat distribution systems are compared in (Chinese, Nardin, and Saro 2011) by using a multi-criteria approach named the Analytical Hierarchy Process. It is highlighted that the basis for a decision on a heating system is different in the industrial sector and the residential sector: capital costs are higher than operational costs for the industrial sector. This should be included in the general reflection on energy reduction policies. Finally, 78 papers are reviewed in (Abdelaziz, Saidur, and Mekhilef 2011), where it is demonstrated that significant energy reduction could be obtained by considering the industrial process itself. However, this falls outside the scope of this paper as we propose to focus on the building and the HVAC systems only.

From a general point of view, it seems that significant energy savings can be obtained by considering the HVAC and lighting systems. However, the papers reviewed rely on case studies only and, to the authors' knowledge, no generalisation has been attempted. This objective is too ambitious to be achieved within a single study, but there is a clear need to move forward on this topic. In this paper, we propose to numerically assess the energy consumption in connection with HVAC and lighting systems for 6 French industrial buildings. The first objective is to develop a simple methodology suitable for a wide range of industrial activities.

Nowadays, many Building Energy Simulation (BES) programs and numerical techniques are available to predict a building's energy consumption, as reviewed in (Zhao and Magoulès 2012). According to this study, the commonly accepted drawback of a BES program is the difficulty of running it in practice due to high complexity and a lack of input information. This is not the case with statistical regression models and artificial intelligence models, which have already been successfully applied to this topic. However, such models require historical data such as the real energy consumption for HVAC systems, which is rarely available for industrial buildings as already mentioned above. Therefore, a BES program was preferred for the needs of this study. The simulated buildings were selected in order to be representative of the heterogeneity of the industrial building stock from an energy demand point of view. The second objective was to analyse the distribution of the energy demand per use (heating, cooling, ventilation and lighting) and to identify the limits of the methodology.

The number of parameters required to model a building grows drastically as the description of the building is refined. It may be necessary to use more than one hundred parameters, even for simple architecture and a simplified model. However, the influence on the output, in this case the energy consumption, is not the same for every parameter. Therefore, it would be interesting to identify which parameters are the most sensitive, so that they can be looked at more carefully for both design and modelling purposes. In our case, the comparison of the results obtained for 6 different buildings would also indicate whether it is possible to find general trends for industrial buildings. This objective can be attained by using sensitivity analysis (Saltelli et al. 2000). This is a general methodology, and it has already been applied to the energy consumption of buildings. Some examples can be found in (Ioannou and Itard 2015; Spitz et al. 2012; Prando 2011; Breesch and Janssens 2010; Lomas and Eppel 1992) and two review papers (Tian 2013; Hamby 1994) have been published on the topic. Therefore, the third objective of this paper is to identify which parameters are sensitive and correlated to energy consumption for heating and cooling, by means of a sensitivity analysis.

The next section explains the methodology, including the selection of the 6 buildings and a brief description of each, their modelling with TRNSYS simulation software and the sensitivity analysis technique. In the last section, the results obtained from the reference cases and the sensitivity analysis will be presented and discussed separately. General trends will be identified and the possibilities of improvements in the modelling of the buildings will be debated. Finally, the influence of the outdoor conditions will be discussed specifically.

2. **Methodology**

2.1 Selection of the buildings

The number and age of European industrial buildings are reported in (Schimschar et al. 2011). These figures are used to calculate the distribution of the stock by floor area, yet no information is provided concerning energy consumption. For the specific case of France, the distribution of the industrial stock was estimated based on the floor surface of the French industrial stock in 2012 (total floor area: 1.5 billion of square meters). More detailed data can be found in (SOeS 2016; MSI Reports 2013). Note that this classification is based on the floor surface but the number of buildings was not provided. Three age ranges and three types of activities (agriculture, manufacturing and warehousing) were distinguished and have been used to plot Figure 1. It can be observed that most of the building stock is related to agriculture, while only 7% is dedicated to warehousing. However, many agricultural buildings are not closed buildings and are used as shelters only. As there is no energy demand for operating this type of building, they fall outside the scope of this study. It should be observed that this classification of the building stock is not universal. In (Pérez-Lombard, Ortiz, and Pout 2008) for example, agricultural buildings are not systematically counted as industrial buildings. Also, buildings are distinguished by their level of energy consumption (high or low) rather than by activity in (Azadeh, Ghaderi, and Sohrabkhani 2008).

Second, more than 75% of the building stock was built more than 20 years ago, before the introduction of the first thermal regulations in France. This statement has to be qualified by considering the activity, as it was observed that the warehouse building stock was the most recent (71% built over the last 20 years).

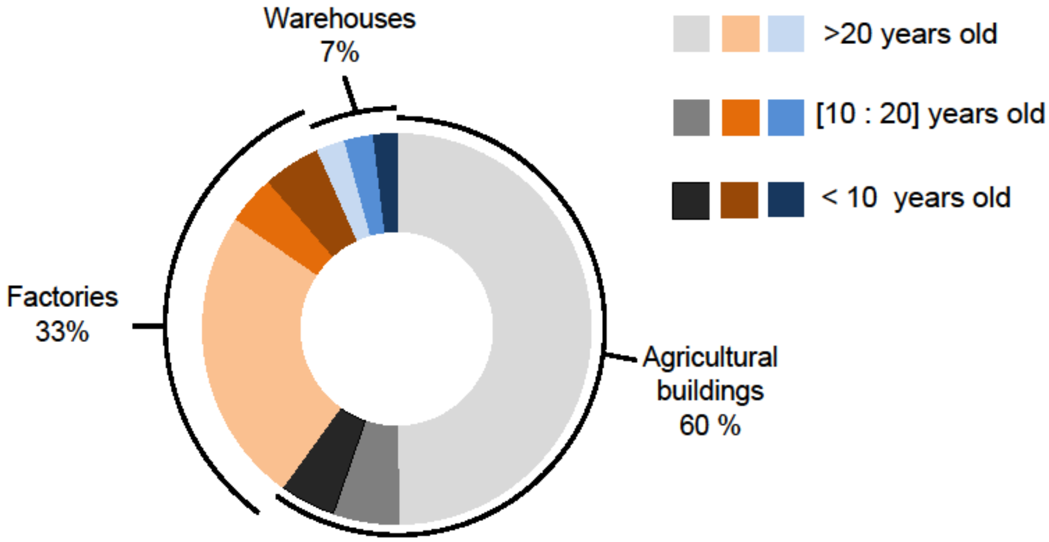

Figure 1. Distribution of the industrial building stock in France based on the activity and age

As no more detailed information was available, it was decided to define and study buildings based on the advice of experienced practitioners. The latter were obtained in the framework of a national project named Batindus, which gathered experts from various fields of civil engineering (namely, CERIB, CTICM and FCBA for the use of precast concrete, steel and wood, respectively, in construction, and CETIAT for HVAC systems). Also, it was presumed that the differences in terms of energy demand were related to the activity rather than to the thermal performance of the envelope, which is generally designed accordingly. Indeed, indoor conditions depend greatly on the industrial activity, as well as the thermal loads. As a consequence, the thermal insulation is not the same for buildings with low heating requirements and for food factories. Also concrete walls may be preferred to steel frame structure for fire safety purposes, etc. First, each case was selected to reflect the variety of industrial activity, for example in terms of indoor temperature and air change rate, so that the energy demand should be different for each building. Second, plans of existing buildings were gathered in order to use realistic data. However, details about the envelope and / or the HVAC system were often lacking or too specific. Therefore, simplified designs were defined based on common practices. Consequently, the description of simulated buildings is rather coarse compared to already published work (Spitz et al. 2012) or to what can be achieved with BES programs. However, it was presumed that the differences in terms of activity and building design would prevail over the simplifying assumptions. The selected buildings are:

- Two warehouses, with different designs because of the nature of the goods;
- Two factories with high heat loads. The first one includes a workshop and offices while a workshop and a storage room are considered in the second one;
- A food industry building with low heat loads and a low temperature set-point.
- An agricultural building for cattle rearing and milking;

2.2 Building modelling with TRNSYS

In this work, the TRNSYS simulation tool (Klein 2010) was selected to determine the energy consumption of the industrial buildings. This environment was first developed to model transient energy systems but it also includes a building model (named Type-56) that relies on an energy balance applied to the indoor air node and takes basic heat transfer (conductive, convective and radiative heat transfer) into account. Walls are modelled with the transfer function technique (or response factor), allowing short computational time. This software was successfully used for modelling a positive energy house in (Krauss et al. 2006), a typical dwelling in Kuwait in (Al-ajmi and Hanby 2008), and to analyse some retrofit strategies applied to a tertiary building (Valdiserri et al. 2015). Finally, several models dedicated to HVAC and heat production systems are available or can be easily integrated, as in (Chargui and Sammouda 2014), for example.

In this paper, the thermal transmittance of the walls, *U*, was estimated by using the built-in material library. The model assumes unidimensional heat transfer, meaning that the thermal bridges inside the walls are neglected. However, in a practical guide on industrial steel claddings, it is mentioned that the real thermal transmittance is underestimated by 40% in such a case (Collectif FFB 2008), because of the structure of the cladding. Therefore, the early value proposed in the software was increased by 40% by modifying the thermal conductivity of the insulating material, when such material was mounted in the walls. Second, the thermal bridges of the structure (e.g. bonds between the floor and the vertical walls) were taken from a general guide (CSTB 2008). Besides, the window model is quite detailed in TRNSYS software: it calculates transmission, reflection and absorption of solar radiation for windows up to six panes, includes shading devices, frame and edge corrections for glazing spacer types and the external solar radiation split into two bands. However, the influence of window's type was not extensively investigated in this paper and two types of windows only were considered here (single glazed and double glazed windows). The latter were taken from the library of the software. One of the reasons for this simplification is that the glazed area of industrial buildings is generally lower than for tertiary buildings (from 1 to 10% and from 15 to 30% respectively). Therefore, it was presumed that the influence of the glazed area would be small in front of other parameters.

Slab-on-ground floor is the most common technique used for industrial buildings, meaning that there is no crawl space or thermal insulation under the floor. However, heat transfer with the ground cannot be modelled by simply considering the thermal resistance of the concrete slab because the soil acts as a semi-infinite thermal collector. This is not explicitly modelled in TRSNYS type 56 and has to be taken into account. Here, it was decided to use the approach proposed in the European standard (NF EN ISO 13370 2008), which is dedicated to this heat transfer problem. The results obtained with the standard were investigated recently by (Simões and Serra 2012) and a simplified method was proposed. It relies on (. 1), where U_{BF} and U_{BW} values are obtained from tables presented in (Simões and Serra 2012). Note that this methodology was developed for residential buildings first. For industrial buildings, the perimeter and surface of the floor are significantly larger than for residential buildings. However, it can be observed that an asymptotic value was reached as the floor surface increased. Therefore, it should still be valid for industrial buildings.

(. 1) $$h_G = A \cdot U_{BF} + z \cdot p \cdot U_{BW}$$

Heat transfer with the ground was modelled by assuming a sinusoidal evolution of the temperature of the ground. The latter was estimated based on the methodology presented in (NF EN ISO 13370 2008) for average soil properties. To be implemented in TRNSYS, the floor was modelled as an insulating material, the thickness of which was adjusted using (. 2), so that the heat transfer coefficient with the ground would be the same as computed with (. 1).

(. 2) $$e_{F,Eq} = \frac{A \cdot \lambda_{Ins}}{h_G}$$

Next, the air change rate results from the combination of air infiltrations and of the use of the ventilation system. In this study, three different cases were distinguished:

1. Absence of mechanical ventilation, so only air infiltrations were active. However, it is rarely measured for industrial buildings and the instantaneous rate may vary significantly because of the activity, e.g. the opening of sectional industrial doors. Some measurements made in industrial buildings are reviewed in (Said 1997) and found to range from 0.08 to 5.74 air change per hour (ach). Therefore, it is hard to generalise to all industrial buildings. In this paper, a fixed value was

estimated for the infiltration rate from the common opinion of practitioners (given as a volumetric rate per square meter of surface area in ($m^3.h^{-1}$).m^{-2}). In the current French regulation code, minimal requirements are 0.6 and 1 ($m^3.h^{-1}$).m^2 for individual and collective housing respectively. In the present work, buildings were assumed leakier and values ranging from 0.5 to 2 ($m^3.h^{-1}$).m^2 were preferred, depending on the activity. By this, we mean that the air-tightness of a refrigerated room was assumed to be more efficient than the one of a storage room at uncontrolled temperature;

2. An exhaust ventilation system was used to maintain a minimum air change rate, typically in a zone with offices. Generally, the airflow removed by the mechanical system was lower than the infiltration rate. The latter was used to compute the heat balance but the electricity consumed by the fan was included in the calculation of the energy consumption of the building. It was assumed that this system remained turned on all year long. Generally, the manufacturer relates the electric power of the fans to the airflow rate by means of (. 3), as presented in a standard (NF EN 13779 2009). Here, it was assumed that SFP equalled one, which is an average value;

(. 3) $$P = Q_V \cdot SFP$$

3. The ventilation system is designed to provide good indoor mixing, which can be obtained if the air flow rate is higher than 1 vol.h^{-1}. Note that most of the air flow is recycled and only a small amount of fresh air is introduced in regard to sanitary conditions. To emphasise the difference in this paper, the airflow exchange between the indoors and the outdoors was expressed in ach, while the airflow rate for indoor mixing was expressed in vol.h^{-1}. For the latter case, there was systematically a small amount of fresh air expressed in ach. One consequence of mixing indoor air is that the heat released by the fan is transferred to the indoor space, so it should be added to the heat loads. In this case, the zone was assumed to be over pressured so that there were no air infiltrations.

Finally, it should be mentioned that the displacement ventilation technique, also known as stratified air conditioning, is effective for cooling (Y. Wang et al. 2014) and is applied to some industrial buildings. Because of its complexity, air movement had to be studied by means of a CFD tool, as exemplified for an airport departure hall in (Gowreesunker, Tassou, and Kolokotroni 2013). In this paper, however, this technique will not be investigated.

One specific issue concerning industrial buildings is the indoor thermal stratification. Because of the high ceilings, the buoyancy forces have significant effects, leading to notable temperature variation with height: the air temperature near the floor would be lower than close to the ceiling. This phenomenon was quantified in eight aircraft hangars in Ottawa (Saïd, Macdonald, and Durrant 1996). It was concluded that two air layers existed as the temperature gradient ranged from +0.8 to +2.6°C.m^{-1} for the lowest air layer (from 0 to 2 m high) and was approximately +0.5°C.m^{-1} above. This result was not influenced by the ceiling height when the latter varied from 9.4 m to 17.1 m. The consequence of thermal stratification is that the indoor boundary conditions are not homogeneous. In TRNSYS however, it can hardly be taken into account because of the one-dimensional heat transfer assumption and the use of a single air node. More realistic results could be obtained with Computational Fluid Dynamics (CFD) simulations. However, a precise description of the indoor space and of the HVAC systems is required, as they significantly impact the temperature field (Y. Wang et al. 2014; Valančius, Motuzienė, and Paulauskaitė 2015). Moreover, the reliability of CFD results also depends on other factors. For example, it was recently demonstrated that the radiative heat transfer should be included in CFD simulations in the context of high temperature fields of industrial buildings (Meng et al. 2016). In the present paper, it was decided to take the thermal stratification into account in a simplified manner, based on the experimental results presented in (Saïd, Macdonald, and Durrant 1996). The temperature set-point was modified by using (. 4) so that it represented the arithmetic mean of the temperature of the air volume. Thermal stratification in the lowest air layer was neglected: it was assumed that the temperature probe would be located in the middle of this layer, so that it would be representative of the average temperature of this fraction of the air volume. Note that no thermal stratification was considered when the ventilation system was designed to provide air mixing. In practice, this is often achieved by using destratifying devices.

(. 4) $$T_{Sim} = \frac{1}{H} \cdot \left(\int_0^2 T_{SP} \cdot dx + \int_2^H T_{SP} + \alpha \cdot (x-2) \cdot dx \right)$$

The schedule for the industrial activity was set so as to represent typical industrial day and night shifts. It was assumed that the artificial lighting was turned on during working hours only, as was the industrial process. The lighting system was modelled roughly by using common proportions of lighting devices expressed in $W.m^{-2}$. Four different cases were assumed, based on the lighting device library included in TRNSYS:

1. Precise workmanship (10 $W.m^{-2}$);
2. Rooms dedicated to the main activity or offices (7 $W.m^{-2}$);
3. Rooms used for a secondary activity, such as storage in a factory (5 $W.m^{-2}$);
4. Lighting sized for safety (1 $W.m^{-2}$);

This value was decreased by 30% for offices to take account of the possibility of some people being out during the day, or simply switching off the lights when natural lighting was sufficient. This is generally not the case in workshops.

The thermal inertia of the air nodes was calculated by adding the inertia of indoor air, the structural elements that were not included in the description of the envelope (posts and beams) and inside walls. The mass of the latter was determined for the purpose of a Life Cycle Analysis, which is not presented in this paper. The heat loads from persons were included according to (NF EN ISO 7730 2006). For offices, it was assumed that every person was using a computer, the heat load of which was 230 W. The weather conditions for twelve French locations were available in the Energy Plus database (Energy Plus 2017). As a first step, it was decided to use the weather file from Lyon because there is a high density of industrial buildings in this part of France. Moreover, two buildings used in this study, namely warehouse 1 and factory 2, were located close to this place. Secondly, the calculation was repeated for 5 other outdoor conditions, so that weather influence can be analysed. This will be presented in section 3.3. Finally, very little information was available on the heat loads of industrial processes. Therefore, the latter were based on expert opinion.

The HVAC system was not modelled. Instead, a system with unlimited power was simulated, so that the energy demand for heating and cooling could be estimated. The energy efficiency of the system (or the coefficient of performance for cooling devices) was assumed to be that of average equipment (see Table 1) so that the energy consumption could be estimated. It was assumed that the efficiency of a heating system would decrease with the intensity of its use. The energy consumption for hot water was also estimated for buildings equipped with recreational rooms and washrooms but was taken to concern factories only. It was assumed that every worker took a shower a day, which required 50L to be heated from 10°C to 35°C per worker per day.

Table 1. Efficiency of the heating and cooling systems

Heating system	Gas heater Low efficiency	Gas heater High efficiency	Electric devices	Refrigerating unit
Efficiency	0.77	0.9	1	3.5

The following subsections describe the 6 buildings; their main characteristics are summarized in Table 2.

2.3 Warehouses

Despite the fact that warehouses represent the lowest floor surface area of the French industrial building stock, it was easier to collect data for this type of building. One possible reason is that this part of the building stock is the most recent. Here, two cases were selected, according to the nature of the goods.

The first warehouse was used solely for the storage of products for supermarket distribution. The floor area was greater than 14.000 m^2 and the building was made up of three smaller, almost identical blocks, reaching a height of 26 m. The indoor temperature had to be maintained between 17 and 25°C throughout the year. The building was modern, so the walls and the roof were well insulated and the infiltration rate was very low compared to that of other industrial buildings. Because of the height of the building and the indoor temperature requirements, the HVAC system was designed to provide a high air flow rate that prevented thermal stratification. Most of the extracted air was recycled and there was only 1000 $m^3.h^{-1}$ of fresh air per block. One specific aspect of this building was its high indoor thermal inertia due to the use of storage racks as structural elements.

The second warehouse was more general as there was no specific requirement for the storage of the goods, except that they must be protected from frost. In practice, this meant that the heating system had to maintain the indoor temperature above 5°C. The floor area was approximately the same as for the first building but the height was only 12.4 m and the thermal insulation was less effective. No ventilation system was installed. Air renewal was achieved mainly by infiltration and door opening and reached 0.6 ach. In these conditions, it was assumed that thermal stratification occurred. For both buildings, the heat loads from the process and human activity were low, which is in line with the storage activity.

2.4 Factories

High heat loads can be found in factories because of the industrial process. Depending on the activity, the indoor temperature may have to be controlled because of excessive heat generation or technical requirements (mechanical adjustment of machine tools for example). Generally, the requirements for the workshop differ from those of the other rooms (offices, storage, etc.). Here, the buildings were simplified and the model considered the workshop and the adjacent rooms only, so that the specific case of a room with high heat loads could be highlighted.

The first factory was typical of a mechanical workshop contiguous with a two-storey office. The total floor area was more than 6100 m^2 (with 93% taken up by the workshop) and the building was 7m high. The building was representative of recent, steel frame, industrial buildings: the envelope was made of steel cladding with an insulating material and was moderately leaky (0.37 ach). On the other hand, the offices were modelled so as to meet the minimum requirements of the thermal regulations in force 10 years ago. The minimum indoor temperature was set to 18°C in the workshop and had to remain in the [20:24]°C range in the office during the day. This meant that the cooling system operated in the office only. Moreover, a 16°C night setback temperature was simulated for both rooms. No ventilation system was used in the workshop, so thermal stratification was taken into account. Finally, the heat loads from the process were set to 150 kW in the workshop.

The second factory building was representative of the plastics industry. The total floor area was 5000 m^2 and the building was split into two parts: one half was reserved for storage and the other half was the workshop. The building was 11.4 m high but the ceiling height was lower in the workshop (9.11 m). The structure of the building was made of concrete that acted as firewalls, which were required for safety reasons. For productivity purposes, the temperature in the workshop had to be maintained between 18 and 25°C during working hours, and higher than 16°C otherwise. As a large amount of heat was released from the process (220 kW), the HVAC system was designed for cooling and a high rate for air recycling (2 ach) was used. Because of air recycling, there was no thermal stratification in the workshop. This was not the case in the storage room, where there was no ventilation and thermal stratification thus existed. The temperature set point was 5°C and the air infiltration rate was estimated to be 1 $vol.h^{-1}$. Because of the presumed high energy demand for cooling, the envelope was designed to be efficient from a thermal point of view. The artificial lighting system was taken to be more intense than usual in the workshop in order to facilitate precise workmanship (10 $W.m^{-2}$).

2.5 Cattle rearing

A cattle rearing building located in the centre of France (Clermont-Ferrand) was selected to represent industrial buildings related to agricultural activity. Its floor area was 2400 m^2 and the ceiling height was above 7 m. This building was divided into two rooms: the main one was a rearing facility for 140 cows while the second one, much smaller (244 m^2), was used for the milking activity four hours a day. There was no heating device in the rearing room, as cows can tolerate a wide range of temperatures. Therefore, a simple electric heater was installed in the room dedicated to milking. As cows are significant sources of heat (800 W per cow on average (Brühlmeier et al. 1996)), the rearing room was considered in the simulation work. The envelope was mostly wood based and there was no thermal insulation, except for the roof of the milking room. All the air renewal was achieved by infiltration, and the building was assumed to be very leaky because of large openings in the rearing room. Consequently, the air change rate reached 1 ach in the milking room and as much as 2.5 ach for the rearing room. Additionally, it was assumed that the artificial lighting system in the rearing room was significantly less powerful than systems used for most other professional activities.

2.6 Food industry

Low temperatures (generally 4°C or even lower) are required for industrial buildings dedicated to food preparation, in order to prevent contamination. Because of this low temperature, the thermal insulation of the envelope is almost systematically very good; otherwise the energy consumption would increase dramatically. In addition, the ceiling height is generally lower than for other industrial buildings in order to minimize the indoor volume to be cooled and the surface of the vertical walls exposed to outdoor conditions. The building selected in this study was rather small (2400 m²) and divided into 4 rooms: including the workshop, storage, three-storey offices and an attic. The structure of the building was made of concrete walls. Thus the thermal inertia of the walls was high and the indoor air had a low value of thermal inertia as there were no apparent structural elements. The vertical walls were not homogeneous: the lower layer was made of 0.2 m thick concrete walls whereas steel cladding was placed above. An additional layer of insulation was added for the rooms where a temperature of 4°C was required, namely the workshop and the storage. The partition walls with offices and the attic were also insulated (this technique may be referred to as "box within the box"). The ventilation system was designed to provide an airflow rate of 3 vol.h^{-1} in the workshop and in the storage, but only an exhaust fan was used in the offices. The scenario for the offices was the same as for the ones simulated in the mechanical workshop. The attic was not ventilated or temperature controlled but air infiltrations were significant (1 ach). It was assumed that the heat loads from the process were low, meaning that there was no baking in this process. Finally, the artificial lighting in the workshop was stronger than usual in order to facilitate precise workmanship.

Table 2. Main characteristics of the six industrial buildings

		Warehouse 1	Warehouse 2	Factory 1	Factory 2	Food industry	Cattle rearing
Geometry	Floor (m^2)	14524	14773	6904	5000	2400	2347
	Height (m)	26	12.4	7	11.4	12	7.3
Thermal zones		5800 m² (Zone 1) 5410 m² (Zone 2) 3230 m² (Zone 3)	1	5760 m^2 (Workshop) 768m^2 (Offices)	2500 m^2 (Workshop) 2500 m^2 (Storage)	1650 m^2 (Workshop) 500 m^2 (Storage) 750 m^2 (Office)	2103 m^2 (Rearing) 244 m^2 (Milking)
U values (W/m^2K)	Walls	0.27	0.38 (heavy wall) 0.46 (light wall)	0.45 (workshop) 0.34 (office)	0.54	0.27; 0.44 (Workshop) 0.6; 3.6 (Office)	3.73
	Roof	0.27	0.46	0.36	0.52	0.44 (Workshop) 0.84 (Office)	3.94 (Rearing) 0.72 (Milking)
	Floor	0.15	0.15	0.15	0.16	0.21	0.16
Indoor capacity (MJ/K)		4442	720	119 (Workshop) 51 (Office)	107 (Workshop) 174 (Storage)	10 (Workshop) 7 (Storage) 3 (Office)	130 (Breeding) 2 (Milking)
Windows	Area (m^2)	2%	5%	10% (Workshop) 35% (Office)	7% (Workshop) 7% (Storage)	18% (offices)	< 1% (Rearing) 2% (Milking)
	U values (W/m^2K)	2.85	5.22	5.22 (Workshop) 2.85 (Office)	2.85	2.85	5.22 (Rearing) 2.85 (Milking)
Indoor temperature T_{Sim} (°C)		[17: 25]	> 7.2°C	>16.9; 18.9°C (Workshop) >16; [20: 24] (Office)	[16: 25] (Workshop) > 6.9°C (Storage)	< 4°C (Workshop, Storage) >16°C ; [20: 24] (Office)	None (Rearing) > 5°C (Milking)
Efficiency	Heating	77%	90%	77%	100%	100%	100%
	Cooling	3.5	x	3.5	3.5	3.5	x
Artificial lighting (W/m²)		7	7	7 (Workshop) 7 (Office)	10 (Workshop) 5 (Storage)	10 (Workshop) 5 (Storage) 7 (Office)	1 (Rearing) 5 (Milking)
Air infiltration (ach)		x	0.2 ; 0.6	0.37; 1; 2.26 (Workshop) 0.26 (Office)	0.6 (Storage)	0.42 (Office)	1 (Rearing) 5 (Milking)
Ventilation system		1 $vol.h^{-1}$ per zone, including 0.07 ach	x	0.12 ach (Office)	2 $vol.h^{-1}$, 0.13 ach (Workshop)	3 $vol.h^{-1}$, 0.11ach (Worksop) 3 $vol.h^{-1}$, 0.05 ach (Storage) 0.24 ach (Office)	no
Working hours		8am-8pm 5 days a week	7am-11pm 6 days a week	6am-10pm (Workshop) 8am-6pm (Office) 5 days a week	24 h/day (Workshop) 7am-11 pm (Storage) 5 days a week	6am-10pm (Workshop) 8am-6pm (Offices) 5 days a week	8am-3pm Every day
Heat loads for process (kW)		20	10	150 (Workshop)	220 kW (Workshop) 5 kW (Storage)	10 (Workshop) 5 (Storage)	112 (Rearing) 5 (Milking)
Comments		Minor differences exist between the three thermal zones	Infiltration increases when doors are opened Thermal stratification	Infiltration increases when doors are opened Thermal stratification	An attic was modelled	An attic was modelled Additional thermal insulation for the workshop and the storage	Permanent heat loads for rearing

2.7 Sensitivity analysis

To perform the sensitivity analysis, TRNSYS software was combined with GenOpt and Matlab. GenOpt was first developed to deal with optimisation problems (Wetter 2009) and was successfully combined with TRNSYS in (Asadi et al. 2012; Prando 2011). Here, it was used to automate TRNSYS runs only, meaning that none of the algorithm dedicated to optimisation was used. In this paper, we propose to use a technique similar to the one presented in (Spitz et al. 2012), which can be broken down into five steps:

1. For all parameters, a probability density function (pdf) has to be defined. Here, only normal and uniform pdf will be considered. Both are defined by their mean value (the one used in the first simulation, which will be referred as the “reference” later) and standard deviation. Note that the normal pdf was restrained to a ±2σ interval, so the parameter had a probability of 95% of being included in this interval. A uniform distribution exists on a ±√3σ interval, by definition.

2. A One-parameter-At-a-Time (OAT) technique was used to identify the most sensitive parameters. This means that each parameter used in TRNSYS was varied twice while all the other parameters remained identical. For each run, the extremal values used to define the pdf in step 1 were taken. Finally, the parameters were ranked by computing the sensitivity index S defined in (. 5). The parameters with an S value higher than 0.01 (or at least the first ten) were finally kept for step 3.

(. 5)

$$S_i = \frac{\left|Y_{X_i,M} - Y_R\right| + \left|Y_{X_i,m} - Y_R\right|}{2 \cdot Y_R}$$

3. The simulation was repeated with all the chosen parameters varying at the same time. This technique is also known as Monte Carlo Analysis (MCA) and allows the interaction between the parameters to be taken into account, meaning that the influence of one parameter on the output can be counterbalanced by that of another parameter. A sampling technique had to be used in order to obtain numerous sets of inputs. This step relied both on the sampling technique and on the pdf defined in step 1. Latin Hypercube Sampling (LHS) is very popular in building energy analysis according to (Tian 2013). A comparison with simple random sampling was proposed in (Macdonald 2009) and it was found that the sampling technique had no great influence on the results for 100 samples or more. This value is also in agreement with the results obtained in (Lomas and Eppel 1992) for a single-room building. Here, the *lhsdesign* function implemented in Matlab was used to obtain 100 samples.

4. The model was run for each set of values defined in step 3. The results, namely the annual energy demands for heating and cooling, were finally analysed. Here, the analysis relies on the Pearson product-moment correlation coefficient (Hamby 1994), given as follows:

(. 6)

$$r = \frac{\sum_{j=1}^{n}\left(X_{ij} - \overline{X_i}\right)\cdot\left(Y_j - \overline{Y}\right)}{\left[\sum_{j=1}^{n}\left(X_{ij} - \overline{X_i}^2\right)\cdot\sum_{j=1}^{n}\left(Y_j - \overline{Y}^2\right)\right]^{1/2}}$$

By definition, r lies in the interval [-1:1]; a negative value being representative of an inverse correlation. The higher the absolute value of r, the more strongly the input X_i and the output Y are correlated. Note that this index relies on the assumption of linear dependence between X_i and Y so it is worth verifying that no other dependence (quadratic, square root …) exists. This was automatically done by testing usual regression functions (polynomial, exponential, logarithmic and power law). Several other techniques exist: the Standard Ranked Regression Coefficient (SRRC) technique is also popular (Ioannou and Itard 2015; Breesch and Janssens 2010; Tian 2013) and also relies on linear regression. The Sobol technique, as exemplified in (Spitz et al. 2012), takes the combined influence of two or more parameters into account, with no limitation on the regression type. However, it also requires additional computational efforts (Tian 2013). As this study did not focus specifically on sensitivity analysis, the Pearson coefficient was preferred because of its simplicity.

5. Finally, the distribution of the energy demand obtained with 100 samples was analysed. A similar analysis was achieved (Lomas and Eppel 1992) for a single-room building, and it was found that the results were normally distributed. In the present study, the assumption of normal distribution was tested by using the Kolmogorov-Smirnov test. If the assumption is validated, this means that the probability of the real value lying in the interval [μ - 2σ: μ + 2σ] is 95%.

Here, normal distributions with a 5% relative standard deviation were assumed for parameters that could be accurately evaluated, such as the material properties or the building geometry. A similar assumption was made in (Ioannou and Itard 2015; Tian 2013). On the other hand, design variables can be regarded as being equally probable according to (Tian 2013). Consequently, parameters related to the occupancy (schedules, heat loads) were assumed uniformly distributed on a ±10% interval as in (Spitz et al. 2012). A higher interval (20%) was chosen for the infiltration rate because its uncertainty was higher. The same assumption was made for the ventilation rate: as there is no standard for the ventilation of the industrial buildings, the actual air change rate of the building may vary strongly from one building to another. The set-point temperature was assumed to be uniformly distributed with a 1°C standard deviation, which corresponds to the value of the throttle range used in (Ioannou and Itard 2015) and also to the assumption used in (Lomas and Eppel 1992). The standard deviation for the schedules was assumed to equal 30 min. Finally, some general coefficients are used in TRNSYS (convective heat transfer coefficient, heat capacity of air, etc.) and their default values were used here. A normal distribution with a 5% relative standard deviation was used in this case. These figures are summarized in Table 3.

Table 3. Pdf types and standard deviations used for the sensitivity analysis

Parameters	Pdf Type	Interval
Material properties (densities, thermal conductivities, heat capacities)	Normal	10%
Geometrical parameters (lengths, heights, thicknesses)	Normal	10%
Set-point temperature	Uniform	1°C
Schedules	Uniform	30 minutes
Heat loads	Uniform	10%
Infiltration rate, ventilation rate	Uniform	20%
Default values (convective coefficients, emissivity, air properties)	Normal	10%

Of course, the results depend strongly on the assumed pdf of the input parameters, and other assumptions can be found in the literature. For example, normal distributions were assumed for all the parameters in (Lomas and Eppel 1992). In the latter work, the relative standard deviation for the thermophysical properties of the materials were estimated from published literature. The values depend strongly on the material and could exceed 10% in some cases, e.g. for the thermal conductivity of polystyrene. On the other hand, it was assumed that the geometry of the real building was likely to be very close to those proposed by the designer, which resulted in a relative standard deviation of only 0.2%.

3. RESULTS AND DISCUSSION

3.1 Energy consumption for the six buildings under the same climate

It would not be relevant to make a comparison of the six buildings based on the raw values of energy consumption, because the size of the buildings and their use differed significantly. However, the difference can be offset by normalising the energy demand to the floor area of the building or to its volume. It is also interesting to compare the energy demand for the building use (HVAC and lighting) against the internal heat loads, as the latter give a rough estimation of the energy demand for the industrial process. Finally, the energy distribution is broken down per use in Table 4 and in Figure 2.

Table 4 : Energy consumption and distribution for the six buildings

		Warehouse 1	Warehouse 2	Factory 1	Factory 2	Food industry	Cattle Rearing
Energy consumption	MWh/y	1297	892	786	579	474	14
	Ratio Heat loads	17.3	17.8	1.2	0.5	6.4	6.5
	kWh/m²/y	89	25	128	93	163	6

	$kWh/m^3/y$	3	2	18	10	29	1
Energy distribution	Heating system	Gas	Gas	Gas	Electric	Electric	Electric
	Heating	10%	42%	73%	6%	15%	56%
	Cooling	7%	X	1%	41%	40%	X
	Lighting	12%	58%	24%	36%	20%	44%
	Ventilation	71%	X	0%	15%	22%	X
	Hot water	X	X	2%	2%	3%	X
	Main	Ventilation	Lighting	Heating	Cooling	Cooling	Heating

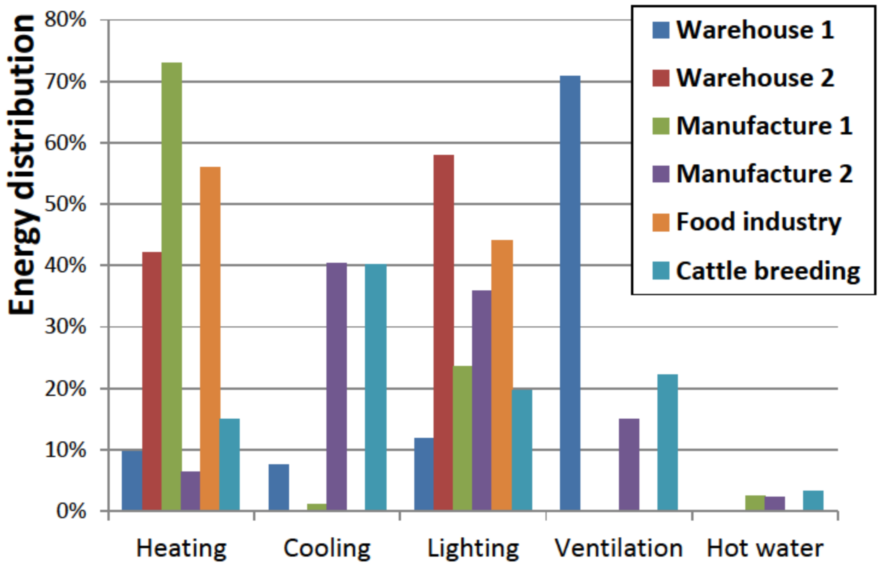

Figure 2. Energy distribution for the 6 industrial buildings

The energy demand for the warehouses was the highest and reached as much as 1297 MWh per year for warehouse no. 1. However, if the ratio between the energy consumption and the indoor volume was considered, low values were obtained for the warehouses. This high energy consumption value has to be set against the substantial size of the building (14500 m^2 and 26 m high) combined with the need for permanent ventilation. Therefore, the energy demand was mostly related to the ventilation system (71% of the total consumption). Even though the indoor temperature had to be maintained between 17°C and 25°C, the energy demand for heating and cooling was moderate. This was related to the efficient thermal insulation, the absence of significant heat loads and the low airflow rate for fresh air. For warehouse no. 2, the energy distribution was very different yet the consumption was also one of the highest. It was mostly related to the lighting system (58%), which remained turned on throughout the working hours. As the floor area was more than 14.000 m^2, the energy consumption for the latter was automatically significant. This illustrates one of the limits of this study: the lighting system was simulated roughly although it can be a major energy consumer. In reality, the owner of the building may try to favour daylight, which could significantly reduce the use of the artificial lighting system (up to 70% as exemplified in (X. Wang et al. 2013)). However, this approach implies that software using a 3D description of the building has to be combined with TRNSYS. Note that this is already done in some other simulation tools, as exemplified with PLEIADES-COMFIE in (Tsoka 2015). Finally, the energy consumption for the building use was approximately 17 times higher than the heat loads from the process in both cases.

The energy consumption of the first factory was mostly related to the heating demand in spite of significant heat loads (195 kW altogether for the workshop). The heating demand was the highest for this building, even though the thermal insulation of the envelope did not differ significantly from that of the other buildings. On the other hand, it was assumed that some of the sectional doors remained open during industrial activity. A seasonal scenario was proposed, so that only one third of the doors were open from October to April and all of them for the rest of the year. Consequently, the infiltration rate ranged from 1 to 2.26 ach during periods of activity. This is a high value compared to the other cases presented here, yet it remains within the range observed for industrial buildings (Said 1997). For this building, it can also be observed that the energy consumption for the offices was only 4.5% of the total energy consumption, while the offices made up 13% of the indoor volume. The energy demand for the second factory was mainly related to cooling (41%) because of the high heat loads in the workshop and the need to maintain the indoor temperature below 25°C. However, the energy consumption for lighting was also sizeable (36%). The energy demand for the ventilation system was moderate because of the small air volume to be treated, compared to the first warehouse. The heating system was used to maintain 16°C in the workshop during the weekend, when there was no activity. During workdays, the minimum temperature was systematically exceeded because of the heat loads of the process. The energy demand for the food industry building was rather homogeneously distributed among all the uses. Even though a low indoor temperature was required (4°C), the envelope was designed accordingly, which resulted in moderate energy consumption for cooling (40%). This explains why the energy demand for the other uses remained significant. For these three buildings, the energy demand per cubic meter was the highest (from 11 to 30 $kWh.m^{-3}.y^{-1}$). However, the energy consumption for the building use and the heat loads were of the same magnitude, except for the food industry where heat loads were low. Finally, the energy consumption for hot water was estimated in all the three cases, but remained negligible (approximately 2%).

The energy demand for the building dedicated to cattle rearing was significantly lower than for the other cases (92 times lower than for the first warehouse), even when the ratio was calculated with the floor area or the indoor volume. This can be easily explained as most of the building was neither heated nor ventilated. Also, it was observed that the heat loads from the cattle did not significantly influence the heating demand for the milking room, which was a consequence of the high air infiltration rate in the rearing room.

Some general comments can be made on the results obtained with the 6 case studies:

1. The energy consumption for the building dedicated to cattle rearing was significantly lower than for all the others. This result has to be set against the distribution of the industrial building stock, as most of the buildings are used for agricultural activities.
2. The floor area and the ceiling height varied significantly from one building to another. Therefore, the energy consumption should be normalised by the floor area or the indoor volume. In the authors' opinion, the latter value is the most relevant as significant variations in ceiling height were observed in this study (from 7 to 26 meters).
3. Most of the time, the highest demands were for heating and cooling. However, it should be observed that the energy consumption for lighting was often significant (more than 20%, except for the first warehouse where only one third of the floor area was illuminated). Note that a similar value is expected for tertiary buildings (15% according to (Pérez-Lombard, Ortiz, and Pout 2008)). When there was a need for ventilation, the energy consumption was also sizeable. However, it depended strongly on the industrial process, while the lighting systems considered here were more homogeneous.
4. Except for the second factory, the energy consumption for the HVAC and lighting systems was higher than the heat loads, meaning that it would be relevant to focus on the these systems in the framework of an energy reduction approach. For comparison purposes, note that the energy demand for building uses makes up 70% of the total energy use for US and UK offices according to (Pérez-Lombard, Ortiz, and Pout 2008).

These statements are based on the results obtained for only 6 buildings, and additional cases should be studied to better assess their overall applicability. This will be achieved in the near future and the final number of buildings should reach 16. In this paper, we relied on a sensitivity analysis to strengthen the analysis of the energy demand for heating and cooling.

3.2 Sensitivity analysis

The local sensitivity analysis was carried out in order to identify the input parameters that could influence the energy demand for heating and cooling by at least 1%. The latter will be referred to as sensitive parameters below and are listed in Table 7 (in the Appendix, Section 7) and a summary is presented in Table 5. It was observed that the number and nature of such parameters differed from one case to another but some general trends were observed.

First, from 12 to 19% of the input parameters were found to be sensitive. The food industry is noteworthy, as the energy demand was found to be sensitive to only 4% of the input parameters (i.e. 4 input parameters). At the same time, the description of this building required the largest number of input parameters (114) as the envelope was more complex than for other buildings. Also, there were four thermal zones for this building, each with its own scenario, while there were only two for most of the other cases. We presume that these two statements are related: as the complexity of the envelope increases, the influence of a single parameter on the global performance decreases. The same argument is valid when considering the activity: if the heat loads, start time, temperature set-point, etc. vary from one room to another within the same building, the influence of a single parameter decreases. However, some sensitive parameters could be grouped as they are related to the same phenomenon. For example, both the thickness of the insulating material and its thermal conductivity are necessary to compute the thermal resistance of the layer. As a result, both parameters were identified when the energy demand was found to be influenced by the thermal resistance. Thus, the number of sensitive parameters provides only a partial analysis. For this reason, the parameters identified as sensitive were analysed in more detail (not presented in the paper). They were grouped into three categories as follows:

1. Parameters related to the geometry of the building (area, thickness, volume);
2. Parameters related to the material properties and to default values;
3. Parameters related to the scenario (heat loads, set-points, schedules, air flow rates).

It was found that these three groups were balanced for the warehouses and the cattle rearing building, meaning that there was approximately the same number of sensitive parameters in each category (although the sensitivity index differed strongly). For the other cases, namely the factories, a significantly higher number of parameters were related to the scenario (approximately two thirds of the sensitive parameters). This suggests that the definition of the activity carried more weight than the description of the building itself for factories. As the envelope was more sophisticated for these buildings, this strengthens the first conclusion. On the other hand, it should be observed that few seasonal variations were used in the description of the activity (for example, no breaks or peaks in the industrial activity were taken into account), meaning that the description of activity could be refined. In the same way, it was observed that the variation of the energy demand for the industrial sector over the years has been strongly non-linear, as exemplified in (Azadeh, Ghaderi, and Sohrabkhani 2008). It is presumed that, in contrast with the residential sector, the industrial process takes precedence over the envelope and the HVAC system. Generally, the industrial process has to adapt to economic conditions, the time scale of which is significantly shorter than that of energy policies, the long-term purpose of this study. This is another reason why more attention should be paid to the HVAC and lighting system rather than to the envelope, as soon as the latter meets minimum thermal insulation requirements. Note that this was the case for the buildings studied here, except for the one dedicated to cattle rearing.

Finally, from a very practical point of view, it was observed that performing a local sensitivity analysis provided the opportunity to step back from the software as the practitioner checks the parameters one by one, thus probably identifying typing errors or incomplete data entries. The same is true when it comes to the analysis of the results, where such errors may lead to unexpected values. This aspect should be taken seriously; it is acknowledged that a significant variation in simulation results can be related to the practitioner, because of variations in expertise and/or typing errors.

Table 5. Results from the sensitivity analysis for the 6 buildings

Building	Nb of input parameters	% of sensitive parameters	Heating and cooling demand MWh/y	kWh/m^3/y	Uncertainty
Warehouse 1	83	19%	397	1.1	20%
Warehouse 2	69	16%	379	2.1	33%
Factory 1	93	18%	556	12.7	25%
Factory 2	92	12%	843	37.0	20%
Food industry	114	4%	694	43.1	6%
Cattle rearing	94	19%	7	4.2	36%

The results obtained with the global sensitivity analysis can be analysed. The values of the Pearson number are reported in Table 7. For convenience, the inputs and outputs were reduced to a dimensionless value by normalising by the mean value. When the absolute value of Pearson's number narrows to 1 or 0, the interpretation is straightforward, but this is not the case for intermediate values. In this paper, it was arbitrarily considered that the input was not correlated to the heating and cooling demand when its value was lower than 0.4. The use of such a threshold value can be debated but it facilitates the analysis of the results. For illustration purposes, Figure 3 was plotted by using some of the results of the global sensitivity analysis for three different cases, namely:

- The temperature set point for heating for warehouse no. 2 (r=0.88);
- The night setback temperature set point for factory no.1 (r=0.57);
- The thickness of wood panels for cattle rearing (r=0.01).

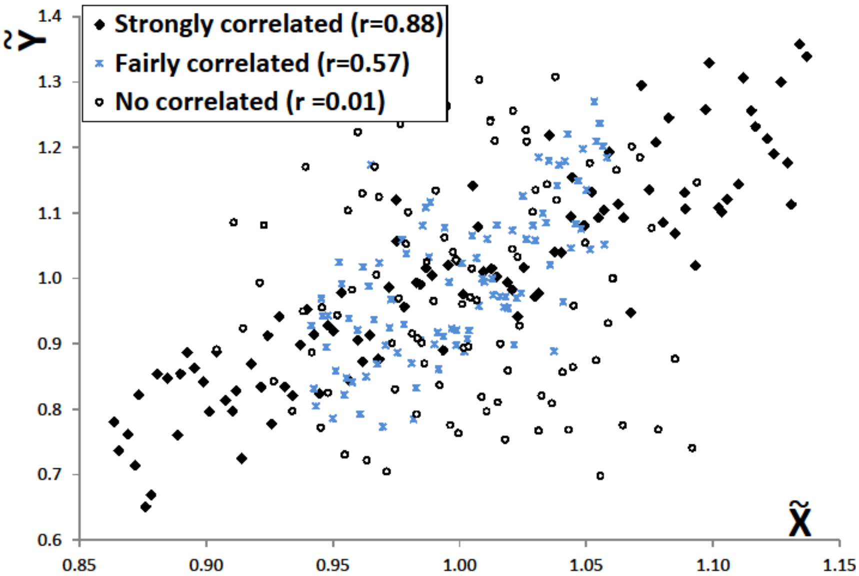

Figure 3 : Examples of strong, fair and no correlation between dimensionless energy demand (Y) and input parameters (X)

First, very few parameters were found to be linearly correlated with the energy demand (from 1 to 3 depending on the case). Second, all these parameters were related with the scenario and none were related to the materials' properties or with the building geometry. Finally, the parameters correlated with the energy demand were also those identified previously as the most sensitive. Most of the time, this concerned the temperature set-point, but heat loads and air infiltration rate also stood out from the rest in some cases (notably for factory no. 1 and the food industry).

Second, the distribution of the outputs obtained from 100 runs was found to be normal for every building. Consequently, 95% of the values lay in the interval [μ - 2σ: μ + 2σ], which represents the uncertainty on the estimated energy demand. This uncertainty is given in the last column of Table 5 and ranges from ±20 to ±36% for five of the buildings, while it reaches only 6% for the food industry building. This result is in line with the local sensitivity analysis, as it had already been observed that the output was sensitive to fewer parameters and with a lower magnitude. For all the other cases, the uncertainty was significant: for comparison, it remained in the [6: 11]% range in (Lomas and Eppel 1992) for a single-room tertiary building, but the uncertainty on the inputs was within the same range. Therefore, it can be assumed that the high uncertainty on the energy demand results from the building type and its use rather than from the methodology used in this paper.

From a more general point of view, several points were highlighted by the sensitivity analysis:

1. The computed value of the energy demand for heating and cooling was sensitive to input parameters related to the use of the building rather than to the ones describing the envelope.
2. Higher uncertainties were obtained for simple buildings, i.e. when the levels of detail of the envelope and the activity were the same and involved few parameters.
3. The annual energy demand was linearly correlated with very few parameters: almost exclusively the indoor temperature set-point. It can be concluded that fine tuning of temperature set-point (and its control system) would certainly decrease the energy consumption for most industrial buildings.

Therefore, it sounds reasonable to assert that more accurate predictions would be obtained with a more precise description of the activity. This is hardly compatible with the long-term purpose of this study, as a more specific description of a building would be representative of a smaller fraction of the industrial stock.

3.3 Influence of the weather condition

It should be observed that the sensitivity analysis presented above did not take into account the influence of the outdoor conditions. For this reason, the global sensitivity analysis was repeated for 5 other climates and for each building, leading to a total of 3600 simulation runs. The locations were selected to achieve a compromise between the places of origin of the buildings, the availability of the weather files and the diversity of the French climates. Compared to other countries, the French climate may seem homogeneous, but the current French regulation code enforces the distinction of 8 climatic zones. In this paper, the selected climatic conditions were the ones from:

- Lyon, Clermont-Ferrand and Strasbourg, where a continental climate can be found (hot summer, cold winter)
- Paris Orly and Brest, were milder conditions are generally obtained ;
- Nice is located on the Mediterranean coast, where temperatures and sun radiations are slightly higher.

The average weather conditions are roughly compared in Table 6. The temperature amplitude is a parameter computed by approximating the real yearly outdoor conditions by a sinusoidal curve. This parameter was required to compute heat transfer through the ground, and gives an idea on the seasonal temperature variation.

Table 6. Average weather conditions for the six locations used in this study

City	Type of climate	Mean temperature (°C)	Temperature amplitude (°C)	Sun radiation ($MWh.m^{-2}.y^{-1}$)	Mean RH (%)	Mean wind speed ($m.s^{-1}$)
Lyon	Continental	11.9	9.2	2.80	76	3.2
Clermont	Continental	11.4	8.4	2.78	72	2.8
Paris Orly	Oceanic	11.1	7.9	2.79	77	4.0
Brest	Oceanic	11.2	5.0	2.83	84	4.7
Nice	Mediterranean	15.5	7.6	2.92	71	3.9
Strasbourg	Continental	10.3	8.7	2.76	79	3.1

The mean energy demands for heating and cooling are plotted in Figure 4. Values were compared with the ones obtained for the climate of Lyon, which were presented in section 3.1. The energy consumption of ventilation, lighting and hot water were not considered here as their design and calculation does not depend on the outdoor condition. As the values for the energy demand were found to be normally distributed in all the cases, the uncertainty was computed just in the same way as before (see 3.2) and normalised with the value obtained for the climate of Lyon. The results are presented in Figure 5.

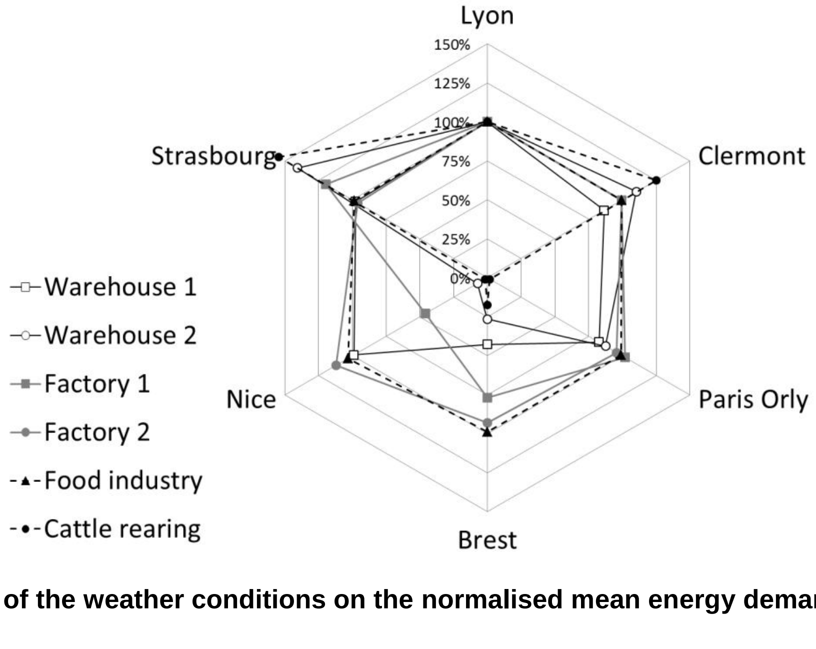

Figure 4. Influence of the weather conditions on the normalised mean energy demand of the six buildings

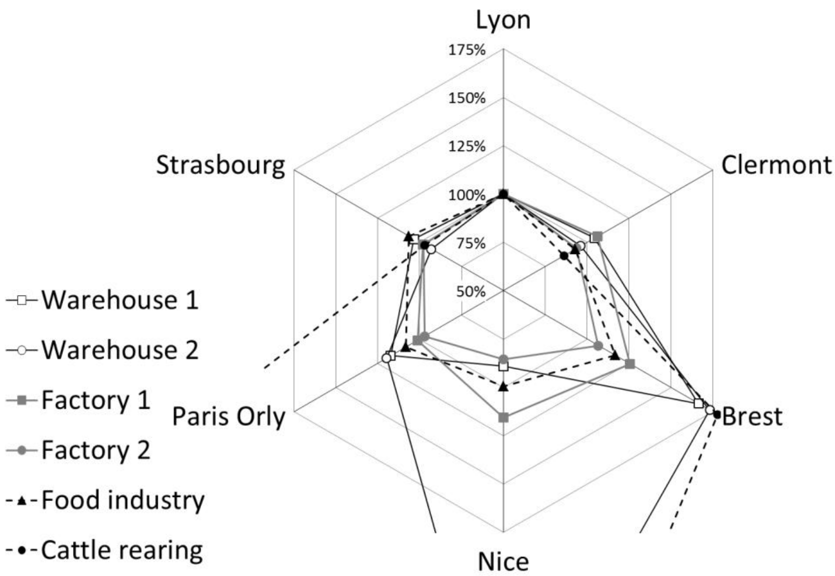

Figure 5. Influence of the weather conditions on the normalised uncertainty on the estimated energy demand of the six buildings

It can be observed that the climate as a significant effect on the yearly heating and cooling demand, yet it is not homogeneous. One can distinguish two groups:

- Changing the weather conditions may result in more than ±40% variation for two buildings (warehouse no.2 and cattle rearing) or for two climates (the ones of Nice and Brest);
- In all the other cases, the energy demand variation remains lower than ±20%.

It should be observed that the heating system for warehouse no.2 and cattle rearing were designed to prevent from frost, meaning that the temperature set point T_{SP} was set to 5°C. Considering the values given in Table 6, it can be observed that the outdoor temperature should remain higher than this value most of the time for the climates of Brest and Nice, unlike for the other climates. Consequently, a lower temperature should be observed only punctually, which explains why the energy demand for heating drops down. Significant variations (up to ±60%) were also observed for warehouse no.1 and factory no. 1, but for the climates of Brest and Nice only. As the energy consumption for heating was significant for these buildings, milder outdoor conditions result in a significant variation. For food industry and factory no.2 finally, most of the energy demand was related to cooling, either to maintain a very low indoor temperature or to remove the heat loads of the process. In these cases, the climate was found to be of little influence.

The same trends were obtained for the normalised uncertainty: it remained between ±20% for most cases, except for the climate of Brest and Nice. Very high differences were observed for cattle rearing, because the energy demand for heating was very low under some climatic conditions (<2 MWh/y). As the relative value was used to express the uncertainty, it could overreach 350%. For readability purposes, the scale of Figure 5 was modified so that these points do not appear.

From this short study, it can be concluded that the outdoor conditions have a significant influence on the results, yet it strongly depends on the industrial activity. Therefore, no generalisation should be attempted and a case-by-case study should be foreseen.

3.4 Toward the estimation of the energy consumption of the industrial building stock

The primary objective of this paper was to propose a methodology to simulate the energy demand of industrial buildings. However, this study is in the framework of a larger project which long term objective is to give an estimation of the energy consumption of the industrial building stock. Given the results presented in this paper, the outlook is threefold.

First, one could try to increase the confidence in the simulation results. Indeed, several limits were identified during this study, from the modelling of the physical phenomena to the reliability of the input parameters. One key improvement would be to better assess the energy demand for artificial lighting, which means that daylight would have to be taken into account, even in a simplified way. More broadly, the reliability of the estimation of the energy demand would be strengthened by a more precise definition of the building use, meaning that it it would be more relevant to go into details of the industrial activity rather than of the parameters of the envelope. This could be achieved by using a seasonal scenario, taking account of the use of natural lighting and considering field surveys to define various scenarios for the same industrial activity.

Second, the building stock heterogeneity is insufficiently represented by 6 buildings. This methodology should be applied to additional buildings (up to 14) in the near future for a broader view of the real industrial building stock. To this end, more detailed statistical data are required, so that the selected building would be representative of most of the building stock. Given the results presented in this paper, the influence of the weather conditions is significant and should also be taken into account.

Finally, it is still unclear how to move from a limited number of simulations to the scale of the whole building stock. The methodology proposed here and the selected simulation tool lead to relatively short computational time (it took approximately 1 hour to run 100 simulation on a regular laptop). Therefore, it sounds reasonable to consider data learning techniques, as already used for the tertiary building stock (see section 1). To this end, a high number of simulations should be realised with varying the main characteristics of the buildings (i.e., a combination of the ones identified during the sensitivity analysis with the ones available for the building stock). This would allow building a database which would be used to train an algorithm, such as Artificial Neural Networks (ANN) for example (Ascione et al. 2017; Khayatian, Sarto, and Dall'O' 2016; Melo et al. 2014).

4. CONCLUSION

In this paper, the energy consumption for the HVAC and lighting systems of six industrial buildings was estimated by using TRNSYS simulation software. A methodology was proposed for simply modelling the main physical phenomena and evaluating energy consumption at the building scale. This methodology was found to be general enough to be applicable to the whole industrial building stock. It is acknowledged that more complex phenomena would require a significant computational effort, which is not in line with the purpose of this study. Still, some encouraging trends appeared. First of all, the magnitude of the energy demands for the HVAC and lighting systems and the heat loads are the same. As the heat loads are representative of the energy consumption of the industrial process, it is relevant to consider the energy uses of the HVAC and the lighting system for future energy policies. Second, even though there are similarities between tertiary and industrial buildings, the energy demand differs significantly. Therefore, this building stock has to be considered separately. This was more particularly highlighted by the sensitivity analysis, as it appeared that the estimated energy demand was mostly sensitive and correlated to the parameters used to describe the building use. Also, it was found that the distribution of the energy use varied significantly from case to case. This distribution was also connected to the industrial activity considered, although it is noticeable that the energy demand for lighting was more uniform. Finally, a Monte Carlo Analysis was carried out and the distribution of the energy demand for heating and cooling was obtained. The distribution was normal and the uncertainty was estimated to lay between ±20% and ±40% for most cases. The influence of 6 weather conditions was estimated for all of the 6 buildings and found to be significant, yet not uniformly. Further work is needed to move from the simulation of few buildings to the scale of the whole building stock. To do so, the use of data learning techniques such as ANN seems to be an interesting possibility, if combined with a sufficiently described statistical database.

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7. APPENDIX

Table 7 : Parameters, sensitivity index and Pearson's coefficient obtained from the local sensitivity analysis for the 6 buildings (weather: Lyon)

Warehouse 1			Cattle breeding			Manufacture 1		
Parameter	S_i (%)	r	Parameter	S_i (%)	r	Parameter	S_i (%)	r
Temperature set point for heating	14.2	-0.70	Temperature set point	29.8	0.91	Night temperature set-point (Workshop)	13.1	0.57
Temperature set point for cooling	11.1	0.63	Infiltration rate (milking room)	9.5	0.17	Indoor volume (Workshop)	9.4	0.28
Thickness of the insulating material	6.3	-0.14	Indoor volume (milking)	4.8	0.04	Daytime temperature set-point (Workshop)	6.1	0.17
Insulating material thermal conductivity (wall)	6.1	0.36	Start time	2.5	0.17	Infiltration rate (door open)	5.2	0.34
Short wave emissivity	2.1	0.23	Air density	2.3	0.17	Heat loads (process)	4.3	-0.21
Floor thickness	1.4	0.22	Infiltration rate (breeding)	2.1	0.08	Infiltration rate (permanent)	4.3	0.47
Thermal resistance floor	1.4	0.02	Indoor convective coefficient	2.0	0.19	Air density	3.9	0.26
Outdoor convective coefficient	1.4	-0.18	Long wave emissivity	1.9	0.05	Start time (workshop)	2.5	0.27
heat gain ventilation 8	1.3	-0.03	Heat loads (cows)	1.7	0.17	Insulating material thermal conductivity	2.5	0.13
Roof area windows 6	1.3	0.12	Thickness of wood panels	1.7	0.01	Insulating material thickness (roof)	2.4	-0.12
Roof area 6	1.2	0.10	Thermal conductivity of wood panels	1.5	-0.09	End time (workshop)	2.0	-0.09
Roof area windows 7	1.2	0.08	Roof area (milking)	1.3	0.03	Heat capacity of air	1.9	0.09
Vertical wall area east 8	1.2	-0.03	Stop time	1.3	0.08	Daytime temperature set-point (office)	1.9	-0.01
air renewal 8	1.1	0.16	Western wall area (milking)	1.2	0.10	Temperature set point for cooling (office)	1.5	-0.31
Roof area 7	1.0	-0.10	Heat capacity of air	1.1	-0.02	Indoor convective coefficient	1.4	0.08
Roof area 8	1.0	0.15	Sky factor (vertical)	1.1	0.05	Roof area (Workshop)	1.3	-0.04
			Indoor volume (breeding)	1.0	-0.04	Night temperature set-point (Office)	1.1	0.09
			Northern wall area (milking)	1.0	-0.02			

Warehouse 2			Manufacture 2			Food industry		
Parameter	S_i (%)	r	Parameter	S_i (%)	r	Parameter	S_i (%)	r
Temperature set point	25.0	0.88	Heat loads (Process)	14.5	0.89	Heat loads (HVAC - workshop)	3.1	0.68
Infiltration rate (permanent)	7.9	0.36	Temperature set point for cooling	6.4	-0.42	Temperature set point for cooling	3.0	-0.47
Indoor volume	7.7	0.24	Heat loads (lighting, workshop)	2.4	0.07	Heat loads (HVAC - storage)	2.3	0.42
Infiltration rate (door opened)	7.5	0.19	Indoor convective coefficient	2.0	0.10	Night-time temperature set point (office)	1.5	0.16
Air density	3.1	0.03	Area of separating wall (attic and workshop)	2.0	-0.09	Thermal conductivity of insulation material	0.9	0.27
Thermal conductivity of insulating material	2.6	0.11	Air renewal by ventilation	1.7	-0.04	Heat loads (lighting - workshop)	0.9	0.06
Thickness of insulating material	2.6	-0.06	Night-time temperature set point (workshop)	1.7	0.03	Set point temperature (office)	0.7	-0.01
Heat loads (lighting)	1.9	-0.21	Area of separating wall (storage and workshop)	1.6	-0.10	Start time (workshop)	0.6	0.14
Roof area	1.7	-0.01	Thermal conductivity of concrete	1.2	-0.04	Stop time (workshop)	0.6	-0.08
Heat capacity of air	1.5	0.17	Temperature set point (storage)	1.1	0.20	Indoor convective coefficient	0.6	0.13
Soil temperature	1.2	0.20	Heat loads (HVAC system)	1.0	0.05			