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THÈSE

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"Analysis of Heating Expenditure in Social Housing – Application of Economic Provisional Models"

Shaker ZABADA

Thèse dirigée par

Pr. Isam Shahrour et Dr. Marwan Sadek

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Jury:

Pr. Didier Defer	**Président**
Pr. Yacoub Najjar	**Rapporteur**
Pr. Mahmoud Eljafari	**Rapporteur**
Pr. Hani Azzedine	**Examinateur**
Mr. Afif Benyahya	**Invitée**
Pr. Isam Shahrour	**Directeur de thèse**
Dr. Marwan Sadek	**Co-directeur de thèse**

"Education is the most powerful weapon

which you can use to change the world."

Nelson Mandela

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Abstract:

The research conducted in this doctoral thesis concerns a major socio-economic issue, that of the heating consumption in social housing. It aims at understanding the influence of both building characteristics as well as socio-economic indicators on the heating consumption in this sector and the development of numerical models for the prediction of this consumption. The research is based on data provided by Lille Métropole Habitat, who is in charge of the management of a large social housing stock in Lille Metropolis.

The thesis includes four parts. The first part presents a literature review which covers the social housing in Europe, in particular in France, the factors affecting the energy consumption in social housing, and policies proposed for the energy saving in this sector. The second part presents the data used in this work that are provided by LMH. The data concern a large social housing stock in Lille Metropolis (North of France). They include heating expenses as well as the buildings characteristics and some socio-economic indicators on the tenants. The third part presents analysis of the influence of both building characteristics (age, DPE, dwellings' area, number of floors) and socio-economic parameters (tenants' age, marital status and income) on the heating consumption. The last part presents the elaboration of prediction models for the heating expenses in the LMH housing stock and the use of these models to analyze the investment policy in the renovation of this stock. Two methods are used: the classical Ordinary Least Squares method (OLS) and the Artificial Neural Networks (ANN).

Résumé

Le travail mené dans cette thèse porte sur la consommation d'énergie, et plus particulièrement le chauffage dans le logement social. Il vise à (i) analyser l'influence des caractéristiques de bâtiments des indicateurs socio-économiques des occupants sur la consommation de chauffage et (ii) à développer des modèles numériques pour la prédiction de cette consommation. La recherche est basée sur des données fournies par le Lille Métropole Habitat, qui est en charge de la gestion d'un grand parc de logement social à Lille Métropole.

La thèse comprend quatre parties. La première présente une analyse bibliographique, qui couvre le logement social en Europe, notamment en France, les facteurs qui affectent la consommation d'énergie dans le logement social et les politiques proposées pour les économies d'énergie dans ce secteur. La deuxième partie présente les données utilisées dans ce travail, qui ont été fournies par LMH. Ces données concernent un grand parc de logement social à Lille Métropole (Nord de la France). Elles comprennent les dépenses de chauffage, des caractéristiques des bâtiments et des indicateurs socio-économiques sur les occupants. La troisième partie présente une analyse de l'influence des caractéristiques des bâtiments (âge, DPE, superficie et nombre d'étages) et des paramètres socio-économiques des occupants (âge, situation matrimonial et revenues) sur la consommation de chauffage. La dernière partie présente l'élaboration des modèles de prévision des dépenses de chauffage dans le parc de LMH et l'utilisation de ces modèles pour la politique de rénovation. Deux méthodes sont utilisées: La Méthode des Moindres Carrés (OLS) et les Réseaux de Neurones Artificiels (ANN).

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General Introduction

The social housing is deeply embedded in the European history. It played a key role in reinforcing the social cohesion as well as in the economic development. The issue of social housing became crucial in non-European developing countries such as China, Maghreb, Latin America, and South Africa, who have experienced powerful economic development and mass migration to cities, which led to explosive urban growth.

The public policy in the field of social housing constitutes a significant issue in the global policy against poverty and social exclusion. In Europe, housing expenses represent around 40% of the household expenditure of low-income families; consequently actions should be taken for the reduction of this expenditure together with improving the quality of life in this sector. The weight of the social housing varies largely in Europe. In the Netherlands, the social housing stands for 35% of the housing stock, while in Hungary it represents only 4% of this stock.

The expenses of social housing constitute a major social and economic issue. In France, these expenses reached 6400 € in 2011. The part of the running costs in these expenses is equal to 36%. They increased by about 60% during the period 1991-2011 (Commissariat Général au Développement Durable, 2012). The heating expenses constitute an important part of the running costs; they stand for more than 80% of the energy expenses (Association des Responsables de Copropriété, 2012). In the North of France, the heating in social housing reached 7.57 Euro/m^2/year A study on energy saving in social housing in France showed that the reduce of the internal temperature to 18°C could result in a benefit margin of 15.7% (Energy and Environment Report, 2008).

Due to the crucial role of the social housing in the life quality for a significant part of the population as well as the local and national economy, national and local authorities have to invest in the social infrastructure, similar to the investments in other public infrastructures (Like: transportation, water, health, education, energy). Nowadays, this task is yet more critical because of the increasing demand for decent housing..

The development of this sector should be a part of a global economic and social policy, such as the employment policy, which should promote local jobs in order to improve the employment in districts concerned by social housing. It also should integrate both technical and non-technical innovations in order to improve the buildings quality, equipment and management; and, consequently, to reduce the energy and water consumption as well as the greenhouse emission.

This sector of social housing faces large challenges, which result from the economic crisis, the increase in the social and economic difficulties of low-income population, the high increase in the energy price, the aging of the social housing buildings, the non-adaptation of these buildings to sustainability requirement and the planet protection, and the lack of public funding for the renovation of existing buildings, as well as for the construction of new ones. In this context, we do need to conduct innovative research that combines both (i) a deep understanding and diagnostic of the existing social housing sector, and (ii) the development of new materials, appliance and smart systems, which allow to optimize the investments and maintenance expenses devoted to energy saving as well as improvement of the life quality in the social housing.

This work concerns the understanding and diagnostic of the existing social housing sector and the energy consumption in this sector. It aims at understanding the energy expenses and its relationship with both the physical characteristics of buildings and the socio-economic indicators of the tenants. The study is based on the analysis of the data provided by one of the largest social housing managers in the Lille Metropolis (Lille Métropole Habitat – LMH), who is in charge of about 30 000 social housing dwellings.

The thesis includes four parts.

The first part presents a literature review, which covers the social housing in Europe, in particular in France, the factors affecting the energy consumption in social housing and policies proposed for the energy saving in this sector.

The second part presents the data used in this work, which is provided by LMH. The data concern a large social housing stock in Lille Metropolis (North of France). It includes heating expenses as well as the buildings characteristics and some socio-economic indicators on the tenants.

The third part presents analysis of the influence of both building characteristics (age, DPE, dwellings' area, number of floors) and socio-economic parameters (tenants' age, marital status and income) on the heating consumption.

The last part presents the elaboration of prediction models for the heating expenses in the LMH housing stock and the use of these models to analyze the investment policy in the renovation of this stock. Two methods are used: the classical Ordinary Least Squares method (OLS) and the Artificial Neural Networks (ANN).

CHAPTER 1: Literature Review

1.1 Introduction

Social housing aims at making housing accessible, decent and affordable for citizens. It concerns the day-to-day lives and living environments (employment, housing, education, health) of a significant part of the population living under heavy social and economic stresses. The purpose of the housing may affect the social housing definition. For example, social housing is formally available to all households in Austria and Sweden, while in the majority of other countries it is directed to those who cannot serve their own housing needs (e.g. the Netherlands and the UK).

The public policy in the field of social housing constitutes a significant issue in the global policy against poverty and social exclusion. In Europe, housing represents around 40% of household expenditure of low-income families; consequently actions should be taken urgently for the reduction of this expenditure together with improving the life quality in this sector. In some countries, social housing constitutes an important part of the GDP. In Austria, Denmark, England, France, Germany, Hungary, Ireland, the Netherlands, and Sweden — social housing as a percentage of the housing stock ranged from a high of 35% in the Netherlands to a low of 4% in Hungary. In most countries, this percentage had fallen over the last ten years as the provision of social housing had not kept pace with overall building, and social units were privatized or demolished) (Whitehead and Scanlon, 2008).

Due to the crucial role of the social housing in supporting the life quality for a significant part of the population as well as the local and national economy, national and local authorities have to invest in the social infrastructure, similar to the investments in other public infrastructure (transportation, water, health, education, energy). Nowadays, this task is yet more critical, because of the increasing demand for decent housing. This increasing demand results from the urban expansion, urban renewable, economic crisis, social housing aging and augmentation of the energy price. The social housing sector constitutes also a major environmental issue, because of the role of this sector in the energy consumption and in the greenhouse emission.

The development of this sector should be a part of a global economic and social policy, such as the employment policy that should promote local jobs in order to improve the employment in districts concerned by social housing. It should also integrate both technical and non-technical innovations in order to improve the buildings quality, equipment and management and, consequently, to reduce the energy and water consumption as well as the greenhouse emission.

The social housing sector constitutes a major social and economic concern in Europe and becoming a crucial issue in developing countries. Its development is strongly related to the social, economic and political context and history. In order to well understand the challenges of this sector, we present first a brief history of its development in Europe, which will be followed by a detailed presentation of this sector in France. The energy consumption in social housing will be also presented as well as the role of innovation in the improvement of the social housing performances.

1.2 History of the social housing

The history of social housing began in Europe in the 19th century as a key element of welfare policies. It started when the industrialization attracted job-seeking people to urban areas (cities), which were not prepared for hosting large flows of “migrants”. In these areas, poverty, overcrowding, poor hygienic conditions, disease and other misery became more and more evident. Factory owners and investors built high-density buildings with poor heating and sanitary equipment for this flow of migrants. For example, the population of Paris reached one million in the middle of the 19th century, and had grown to more than 2.9 million in 1914. During this period of rapid urbanization, the private actors such as companies and factory owners took the ‘social’ housing initiatives. At the same time private foundations emerged, in particular in countries with a strong tradition of religious social commitment. These foundations considered housing as the core of the inhabitant’s life. Their aim was to settle conditions between workforce and capital in a profitable way for the latter. Although, the number of dwellings in this new form of ‘social housing’ was negligible, the concept of social housing was initiated.
At the end of the 19th century, a combination of social, economic and public health drivers led to establishing housing acts in European countries. Belgium, with the 1889 Act, was the first in the world. In France different laws were established for supporting social housing such as Siegfried

(1894), Ribot (1908) and Bonnevay (1912). The latter created the Public Offices of Habitations à moderate rent (HLM). By 1914 national policies emerged by combining different tools such as use of savings in housing construction, tenants' protection, creation of housing institutions and the adoption of regulations to combat housing misery (Lévy-Vroelant et al. 2008).

The fundamental concept of the social housing was established by the eve of the First World War. Its implementation was conditioned by specific national contexts such as the degree of urbanization, social or cultural characteristics, and the political system. Social housing became a key element of the social welfare system in European countries. After the First World War, France created the "Public Offices" to collect funds, build and manage houses for low-income citizens. By 1920, 38 public offices, 452 private societies and 82 societies for real-estate loans were created for the development of the social housing sector.

With the increase in the municipal commitments, social housing became a key tool for combating housing misery and stimulating mass educational and moral reform. However, just before the Second World War, the public involvement in France in the social housing construction was still modest: the capacity of houses provided by employers was double of that built with the public funding.

Decades following the Second World War are considered as the golden period of social housing. In this period the largest numbers of social were built. They were well designed and equipped and attractive to working-class people as well as to middle-class employees. The construction of the social housing was guided by accessibility, functionality and uniformity.

The period after the mid-1970 was characterized by a gradual withdrawal of public actors from social housing, which ceased to be a major government concern. Public funding was oriented towards personal subsidies, like housing allowances and tax deductions. In France, after a construction peak in 1971, the social housing stagnated at the lowest levels as a result of policy changes. In addition, the structure of the social housing changed: more was provided for medium and upper-income households. At the end of the 1990s, the problem of 'sensitive urban areas' led to urban renewal programs including demolition of big social housing estates. In France, the current situation is paradoxical: the housing sector is active and profitable, but about 3 million households are poorly housed or homeless. The sector of social housing faces major challenges, such as their location in old industrial areas and cities suburbs, which become dilapidated. In addition, it should host households with increasing social and economic difficulties in aging buildings (Lévy-Vroelant et al., 2008).

1.3 Overview of social housing in Europe

There is a significant role of social housing in European countries; Figure 1.1 shows the part of social housing in some European countries. With about 140 residences per 1,000 habitants, the Netherlands has the first position, followed by Austria, Denmark, Sweden, the United Kingdom, France (around 62 residences per 1,000 habitants), Germany, Italy, and Spain. In January 2010, about 6.9% of the French population lived in social housing (Les Échos, 2008).

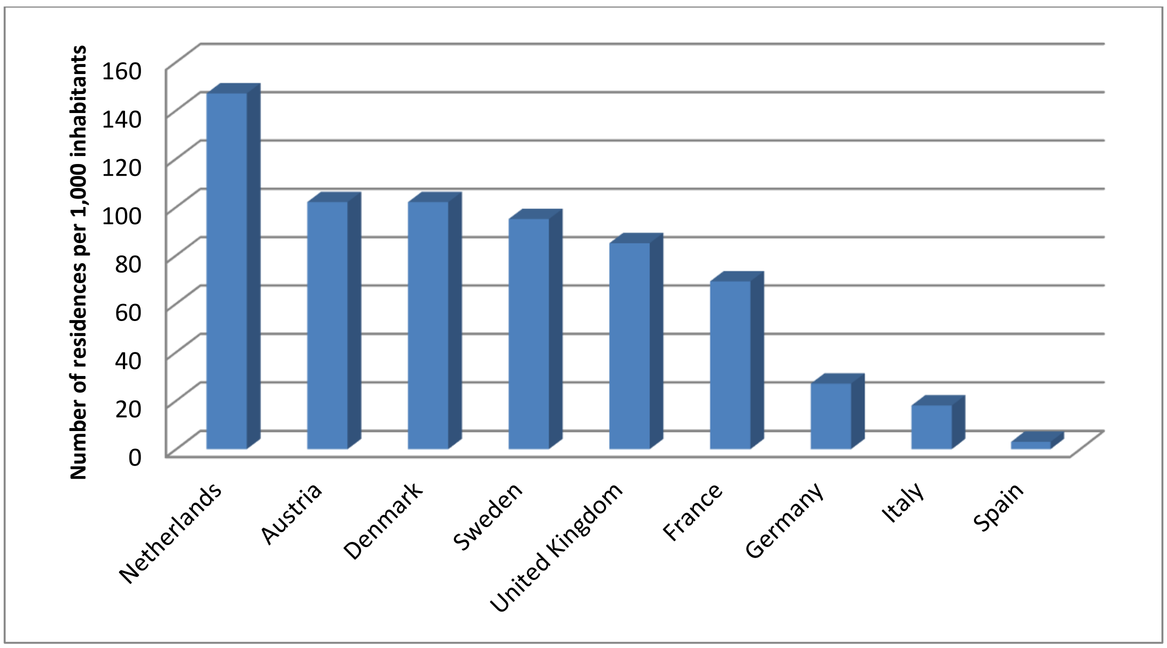

Figure 1.1: The public and social housing in Europe 2008 (per 1,000 inhabitants) (*INSEE, Les Échos, 2008*).

Figure 1.2 shows a general view of the energy use in building in the European countries. It shows that space heating constitutes the major part of the buildings' energy consumption (Energy and Environment Report, 2008)[1].

[1] The tonne of oil equivalent (toe) is a unit of energy consumption used in the reference.

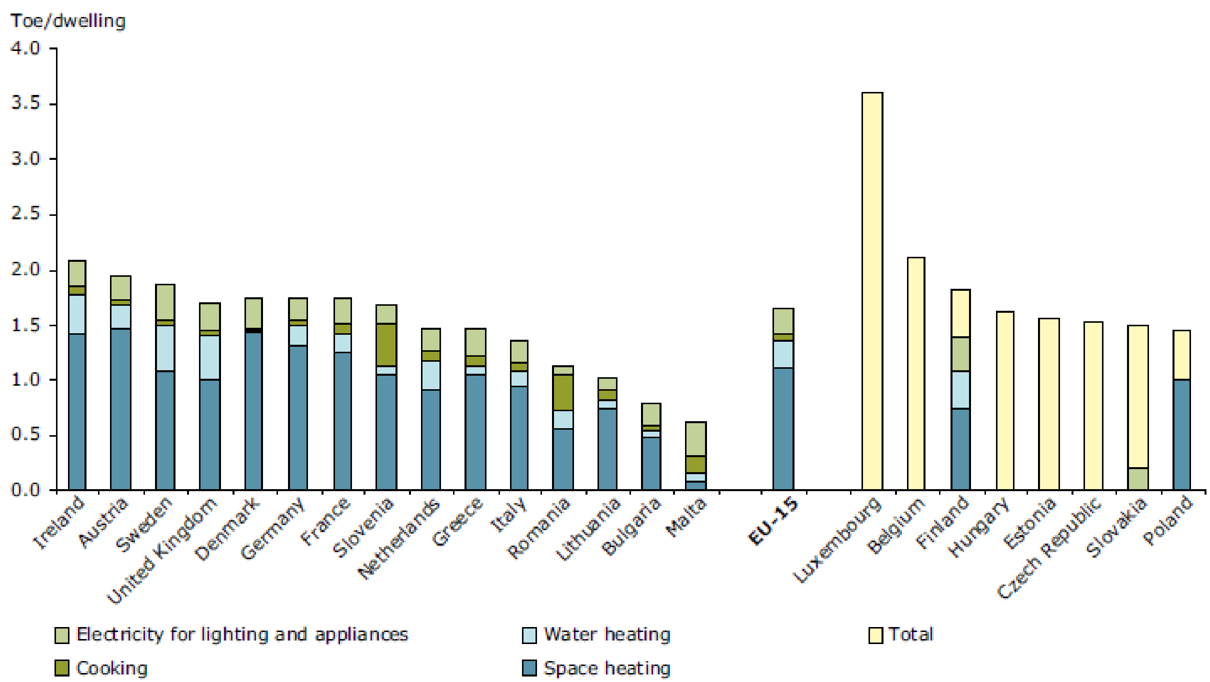

Figure 1.2: Energy consumption by end use per dwelling in residential households in EU countries, 2005

(Energy and environment report 2008)

The social housing in European countries encounters similar pressure: migration, particularly specially after the Second World War, demographic trends, European regulation, increased aspirations, and the rise of owner-occupation.

The 1980s and 1990s were the years of growing doubts and uncertainties about the role of the social rental sector in Europe. In most European countries, the social rented sector has not disappeared, but it has become more and more selective (or targeted) and less and less supported by state subsidies. Britain and Germany have experienced the most drastic changes. However, even in Austria, France, the Netherlands, and Sweden important changes affected the funding and management, if not the scope and ownership of the sector (Whitehead and Scanlon, 2008). Germany, the Netherlands, and the United Kingdom built up significant social rented sectors in the 20th century, especially in the decades following 1945. Each country developed its own model of social housing. Almost all social rented housing in the UK were provided by local authorities, who owned and managed the social housing stock. In the Netherlands housing associations became the major providers of social rented housing rather than local government.

In Germany a rather different concept of social housing led to a much more diverse range of providers, that included municipal housing companies, co-operatives and private landlords. Since the 1980s in the UK, and the 1990s in Germany and the Netherlands, measures have been adopted for the privatization of social rented housing. Privatization emerged in the UK in the 1980s as the government sold state owned companies to the private sector. While the sale of public assets to the private sector is an important (and probably also the most robust) characteristic of privatization, the term is also applied more widely to include any process that reduces government influence over socially-orientated activities or aims to make greater use of the market to achieve social ends (Whitehead and Scanlon, 2008).

Table 1.1 summarizes the social and private rents in some European countries.

Table 1.1: Description of social and private rent in European countries

	Social	Private
Austria	Cost-based.	Also cost based; private < 10% higher (in post-1953 buildings there is de facto no regulation)
Denmark	Cost-based. 3.4% of building cost + bank charges. Average 2005 €6.67/m^2/month	Private rents also regulated. Average €6.83/ m^2/month
Germany	In some regions rents vary with household income. €4-7/ m^2/month	Rent on new leases free, but rises regulated
France	Central government decrees maximum rents (vary by region). Cost based related to estate or owner	Rent on new leases free, but rises regulated. 30-40% higher than social rents
Sweden	Set by annual negotiation between landlords and tenants.	Private rents limited by social rents; private slightly higher.
Netherlands	Rent based on utility value of dwelling and target household income level. Average €353/month.	Also controlled; average rent €419/month.
Hungary	Set by local authorities	Market based
Ireland	Tenants pay % of income in rent. Average rent €155/month.	Rent control abolished 1981 now market determined.
England	Rent restructuring regime based on local earnings and the dwelling price; increases RPI plus 0.5/1%. HAs and LAs must cover outgoings.	Market determined for properties let since 1988

(Whitehead and Scanlon, 2008).

1.4 Social housing in France

This section presents a general overview of the social housing in France. Data and figures are obtained from the National Institute of Statistics and Economic Studies (INSEE).

1.4.1 Social housing repartition

There are about 4.6 million units of social housing in France, which account for 17% of the total housing (www.developpement-durable.gouv.fr, 2013).

Figures 1.3 and 1.4 show the geographic reparation of the social housing in France. We observe that the Seine-Saint-Denis department has the highest level (around 1,380 social housing per 10,000 inhabitants), followed by Vale-de-Marne, Marne, Seine-Maritime, Pas de Calais (around 1,030 social housing per 10,000 inhabitants) and Paris. The department Eure-et-Loir has the lowest social housing (700 per 10,000 inhabitants).

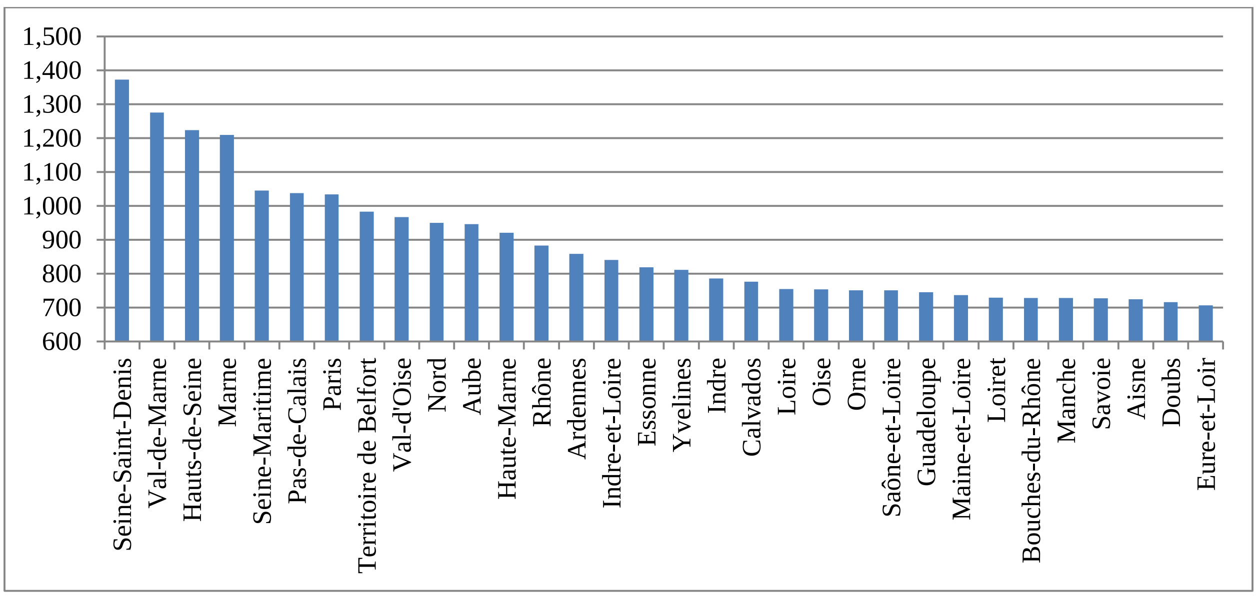

Figure 1.3: Repartition of social housing in France - 2010 (per 10 000 habitants)

(http://www.developpement-durable.gouv.fr,2012)

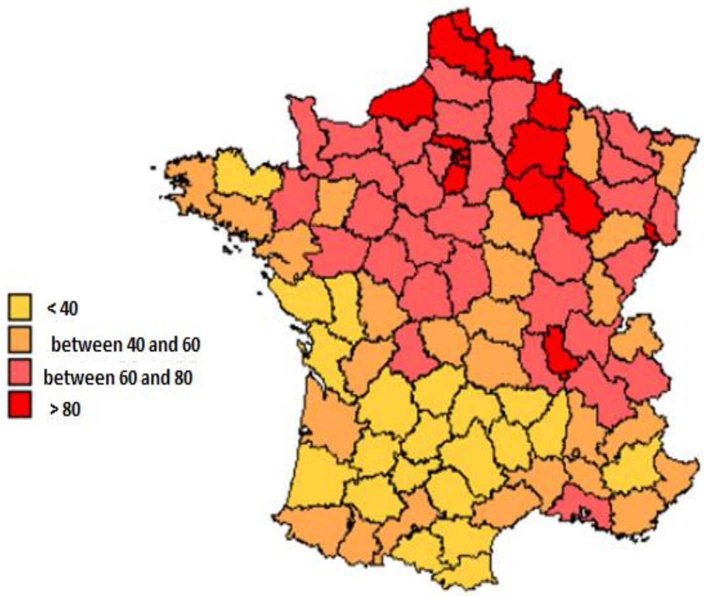

Figure 1.4: Repartition of social housing in France on (January 1, 2011) (per 1000 habitants)

(http://www.developpement-durable.gouv.fr, 2012)

Figure 1.5 shows the variation of the density of the social housing in the Nord-Pas-de-Calais Region as well in its two departments during the period 1990–2009. Four periods could be distinguished:

- The period 1990–2004 with a regular, but moderate increase in the social housing
- The period 2005–2007 with a significant decrease in the social housing
- The period 2007–2008 with a very important increase in the social housing
- The period 2008–2009 with a decrease in the social housing in the Pas-de-Calais Department, an increase in the Nord Department and a stabilization in the Region Nord-Pas-de-Calais.

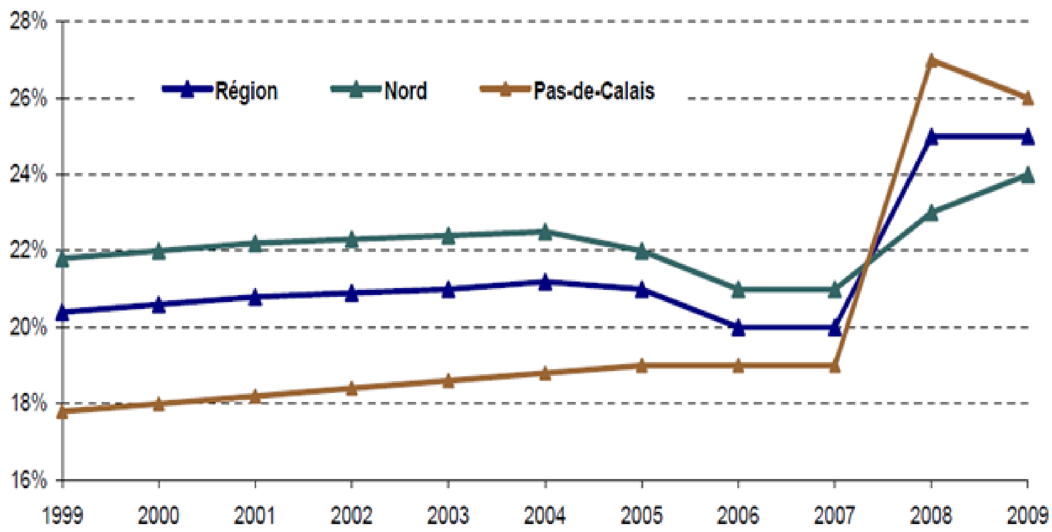

Figure 1.5: Social housing density in Nord-Pas-de-Calais

(http://www.developpement-durable.gouv.fr, 2012).

1.4.2 Social housing expenditure

Figure 1.6 shows the average expenditure in the housing sector in France in 2011. We observe that the average of the housing expenditure per dwelling reached around 9800 €. About 72% of this expenditure concerned the rent, followed by the energy and other current expenses. The average expenditure in social housing (HLM) per dwelling reached 6400 Euro. The part of the energy and other running costs is equal to about 36% of the total expenses, which is very high comparing to other categories of housing. The high percentage of the energy and other running costs in the housing expenses causes a high stress on the social housing tenants, as most of them live with low income. Furthermore, Figure 1.7 shows these expenses increased by more than 100% from 1991 to 2011.

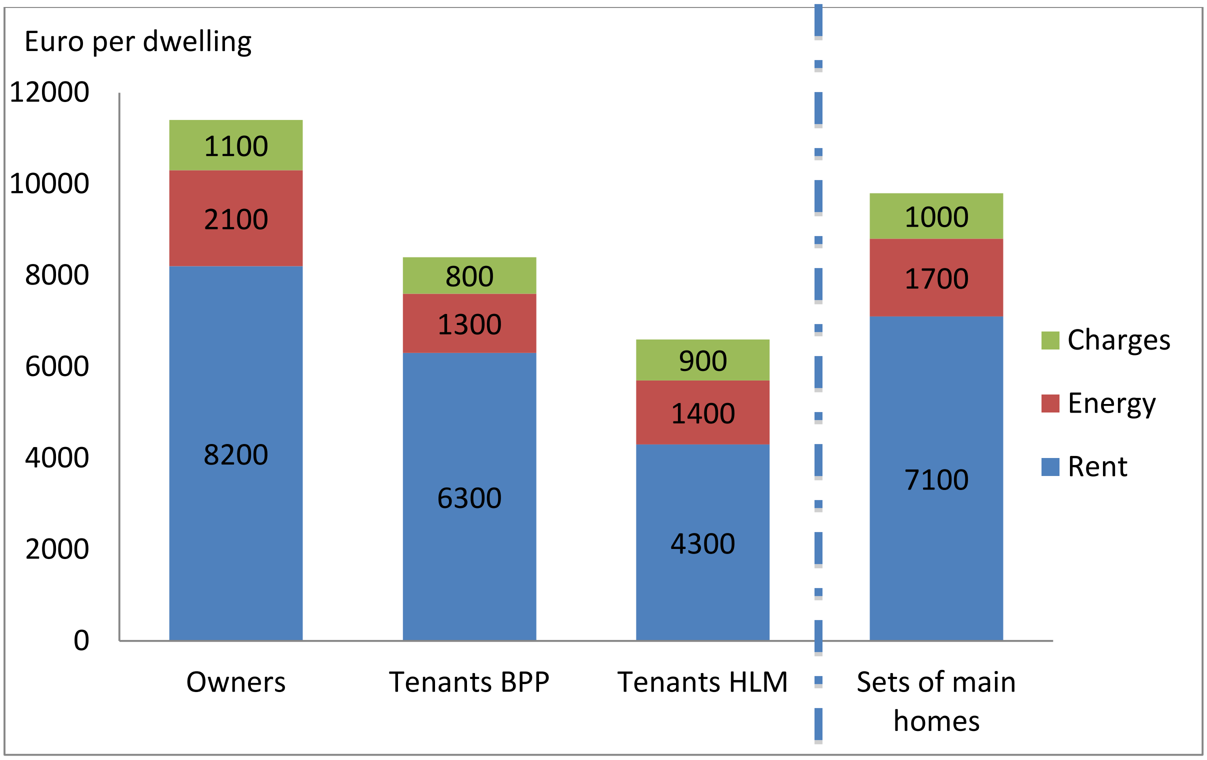

Figure 1.6: Repartition of housing expenses in France in 2011

(Commissariat Général au Développement Durable, 2012)

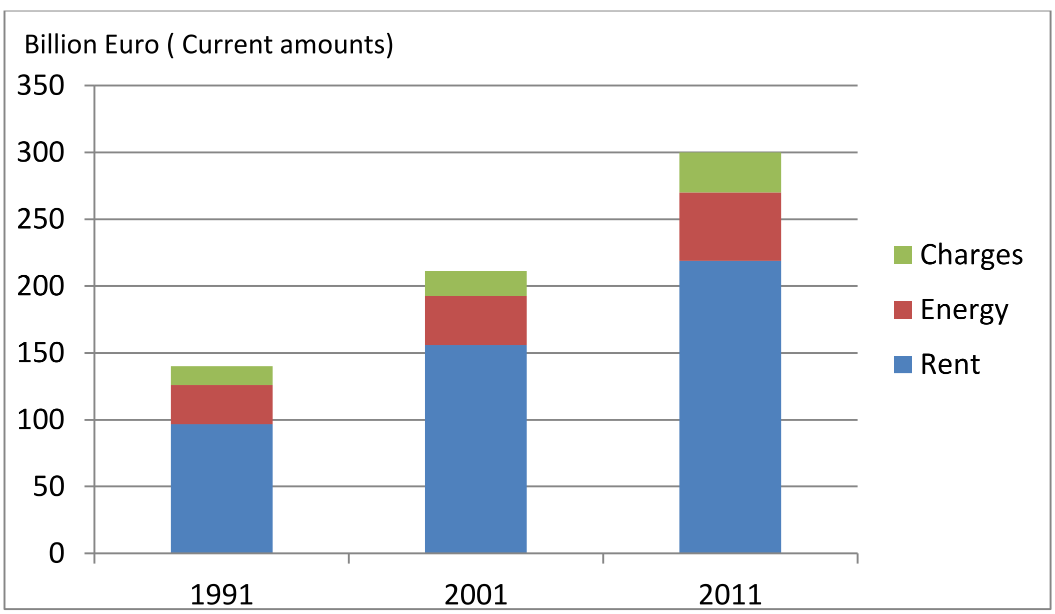

Figure 1.7: Variation of the public housing expenditures between 1991 and 2011

(Commissariat Général au Développement Durable, 2012)

Table 1.2 shows the variation of the components of the social housing expenditures between 1984 and 2010. They increased from 84.8 billion € in 1984 to 303.4 billion € in 2010, with a yearly average increase around 5.0%. Over this period, the yearly average increase in the rent was equal to 5.8%, while that of the energy was equal to 3.0% and that of the other running cost was equal to 4.4%.

Figure 1.8 shows two periods of variation of the indices value in social housing:

- Period 1984–1996: the indices value is characterized by a regular increase for all expenses
- Period 1996–2010: the indices value is characterized by a regular increase for all expenses; however the rate of the increase in the rent indices is lower than that of the first period, while that of the energy and other current expenses is higher than that of the first period.

Table 1.2: Variation of housing expenditure in France

	Amounts in billion Euro					Average yearly evolution (%)			
	1984	**2000**	**2008**	**2009**	**2010**	**2010/1984**	**2010/2000**	**2009/2008**	**2010/2009**
Current housing expenditure	84.8	203.7	290.4	294.1	303.4	5.0	4.3	1.3	3.2
Rent	52.1	149.9	213.8	219.7	225.0	5.8	4.4	2.8	2.4
Energy	23.5	34.9	48.4	46.7	50.4	3.0	3.3	-3.6	8.1
Charges	9.2	18.9	28.2	27.7	28.1	4.4	4.8	-1.8	1.4

(Commissariat Général au Développement Durable, and INSEE 2012)

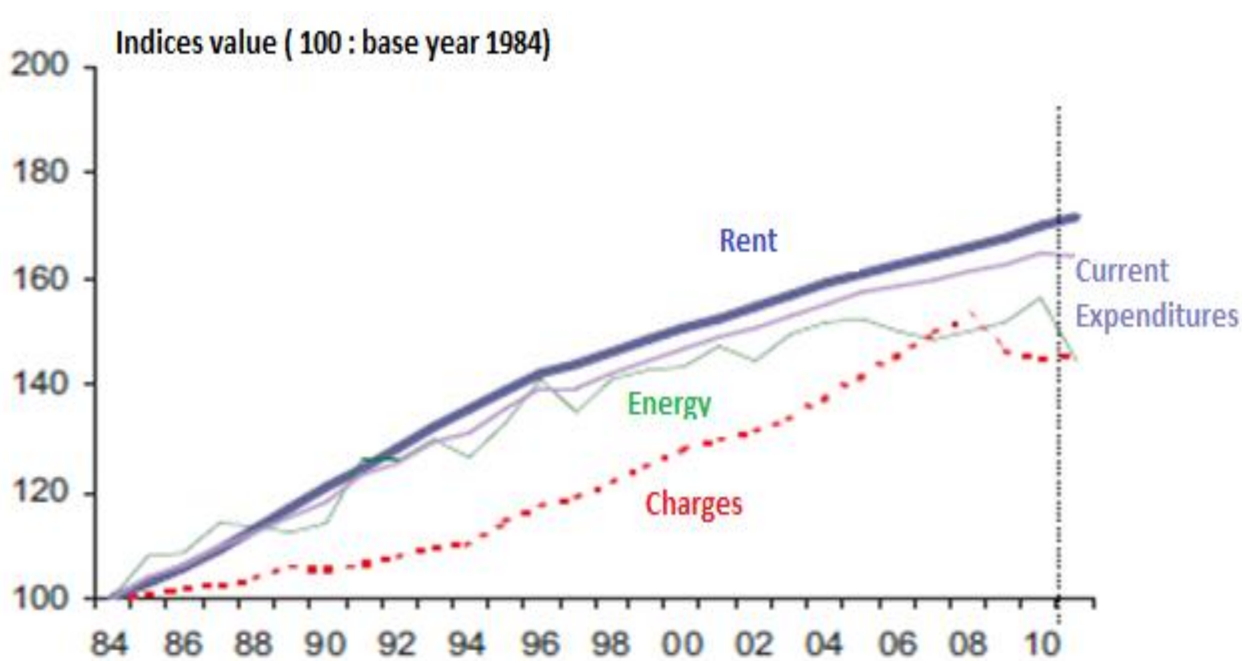

Figure 1.8: The evolution of current expenditure in housing sector in France (1984 to 2010)

(Commissariat Général au Développement Durable, 2012)

1.4.3 Public aid in social housing sector

Figure 1.9 shows the variation of the public aid for social housing between 1984 and 2010. It can be observed that this aid increased from 4.5 billion € in 1984 to 16 billion € in 2010 (256%). It includes three types of aid:

- "L'aide personnalisée au logement (APL)": an individual aid for housing. This type covers the biggest amount since it is personalized and individual. Every person can apply for this aid. But the benefit amounts depend on the income and the amount of the rent. The total amount of this aid in France reached 7 billion € in 2010.
- "L'allocation de logement familiale (ALF)": a family aid for housing. This aid concerns families with at least one child. The total amount of this aid reached nearly 5 billion € in 2010.
- "L'allocation de logement sociale (ALS)": the aid concerns tenants in social housing. The value of this aid reached about 4 billion € in 2010.

Figure 1.10 shows the repartition of the housing public in 2010. With about 47%, the aid for the individual tenants presents the first category of aid, followed by the HLM tents (35%), resident home (7%) and the owners (6%).

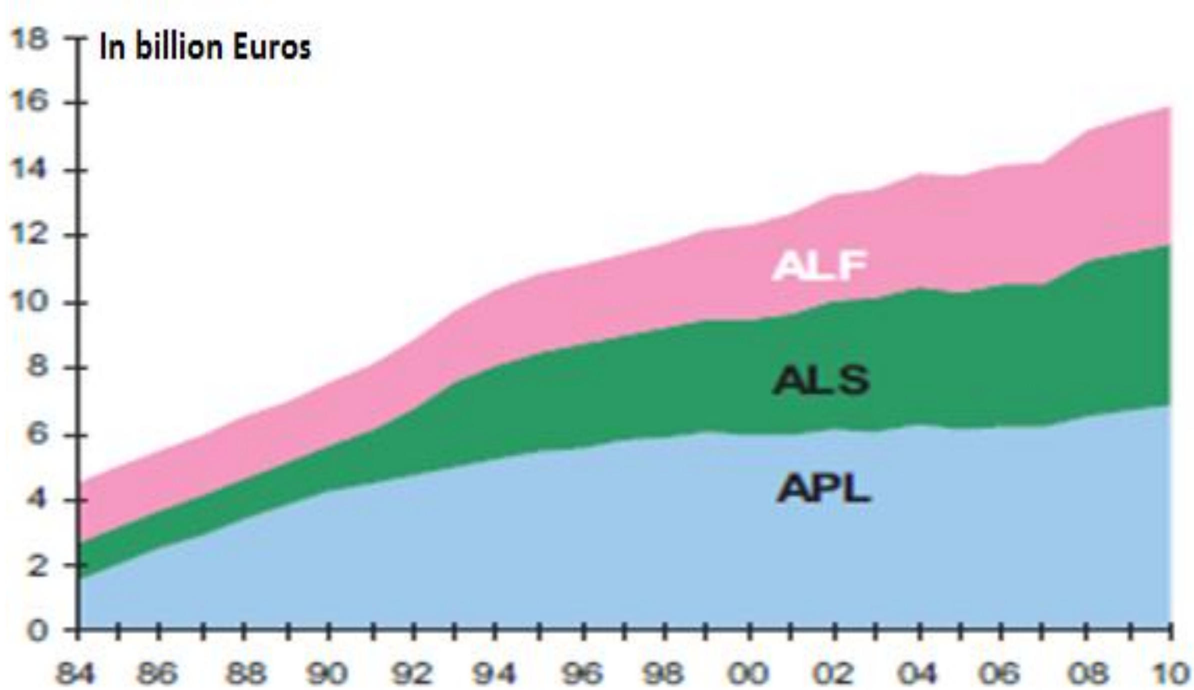

Figure 1.9: The evolution for types of Aid for the housing sector in France

(Commissariat Général au Développement Durable, 2012)

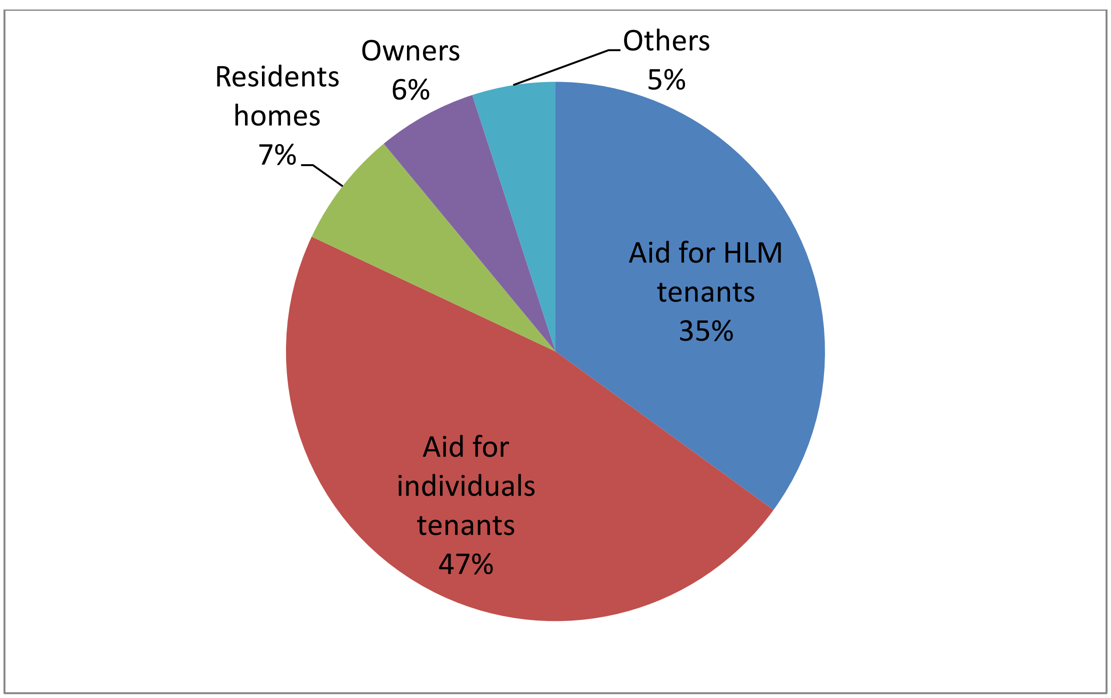

Figure 1.10: The public aid for personal housing sector

(Commissariat Général au Développement Durable, 2012)

1.4.4 Energy use in social housing

Figure 1.11 shows the energy use in social housing in France. For 600 000 single family dwellings, about 350 000 (58 %) use fossil energy, while 250 000 dwellings (42 %) use electric energy. For 3 600 000 multifamily dwellings, about 3 200 000 (89 %) use fossil energy, while 400 000 dwellings (11 %) use electric energy. Gas energy is used in about 2 200 000 dwellings (about 61 % of the multifamily housing dwellings), while district heating is used in 800 000 dwellings (about 22 % of the multifamily housing dwellings). In the totality of the social housing, the electrical energy is used in about 15% of dwellings.

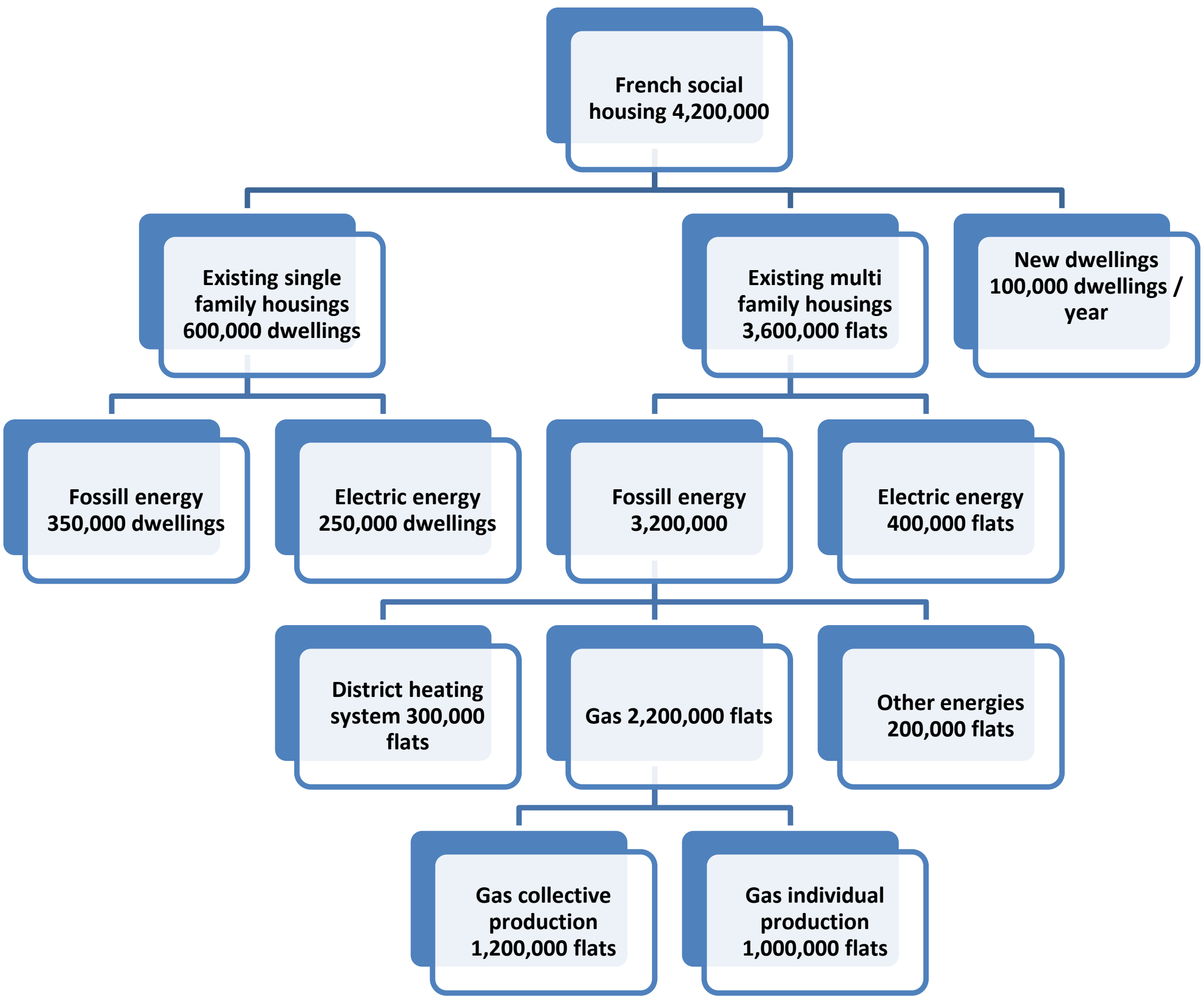

Figure 1.11: Energy use in social housing

(*SAVE@Work4Homes, 2009*)

1.5 Factors influencing the energy consumption in social housing

Santin (2011) classified the factors that affect the energy consumption in buildings into two groups (Figure 1.12):

- The behavior group, which concerns the motivation, background, lifestyle and household characteristics, that influences the use of spaces, appliances, ventilation and heating system.
- The building characteristics group, which refers to the building energy efficiency and the control and interaction system.

The following sections discuss with more details these factors.

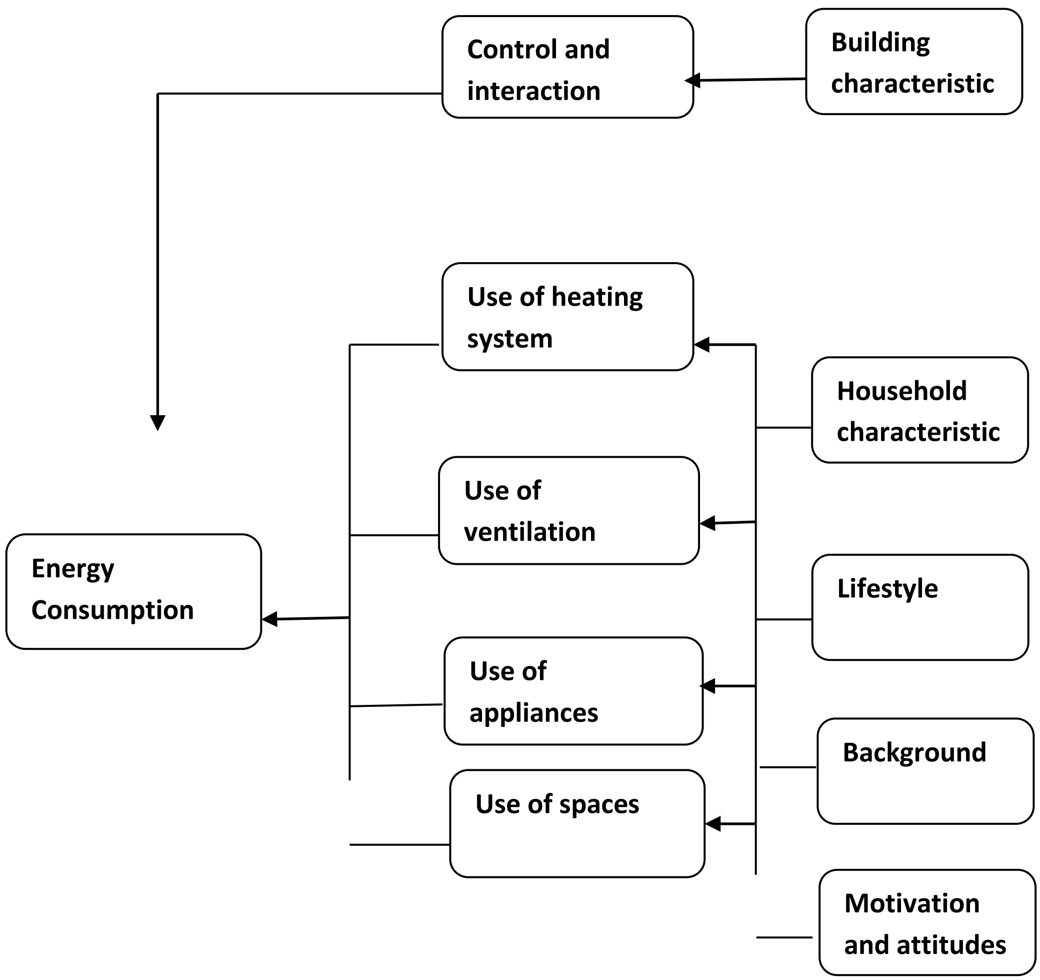

Figure 1.12: The framework of energy consumption in the residential buildings

(Santin, 2011)

1.5.1 Behavior factors

A recently study conducted in the Netherlands showed that the social-demographic characters such as knowledge, motivation and context play an important role in energy-saving behavior (Han et al., 2013). The authors identified five factors in the energy saving behavior of users that. In the next sections we focus on three of these five factors are summarized in Table 1.3.

The first factor is related to the opportunity context, which concerns the energy saving opportunities due to technology and government regulation.

The second factor concerns users' motivation. It is considered as one of the most important factors in energy saving. The motivation could be enhanced by the reduction of expenses related to energy consumption and the improvement of the life quality. Raaij and Verhallen (1983) analyzed the types of household's behavior in the Netherlands. They identified five "household profiles" of energy consumers: conservers, spenders, cool, warm, and average. They showed that the energy consumption difference between conservers and spenders is about 31%.

Groot et al. (2008) identified four households' profiles:

- Ease: mainly interested by comfort with no care in energy saving neither in environment protection.
- Conscious: interested by comfort, but with care for energy saving and environment protection.
- Costs: aware of energy save and expenses reduction.
- Environment: mainly interested by environment protection.

The third factor is related to the knowledge of the energy issue, such as the impact of the energy consumption on the climate change and on environment, as well as the preservation of natural resources, which means that a right understanding of the global energy issue resulted in a more rational saving behavior.

Table 1.4 shows the main behavioral factors that affects heating consumption in social housing. The age of tenants is an important factor in energy use. It largely influences the use of appliances and awareness of energy saving. For example, the use of appliances and technology by people of older age is lower than that used by young people. The energy saving awareness increases with age.

The tenants' incomes is also an important factor in energy saving. Most of tenants in social housing have limited incomes, consequently they should pay more attention to energy saving.

The behavior of tenants in energy consumption is influenced by both the education level and culture. The energy saving increases with the increase in the education level, which improves the tenants awareness about the energy issue and facilitates the use of technology for energy saving.

Table 1.3: List of self-evaluation aspects for energy-saving behavior

Category	**Aspects**	**Related questions**
Context opportunity	Energy-saving possibilities	Money budget, technological possibilities, etc.
	Public opinion, regulation	Opinion of acquanntances, governmental regulation, etc.
Motivation	To invest (or not)	House quality, save energy bill, environmental concern, etc.
	To change (or not)	Effort, comfort, importance, use appliances efficiently, experience in energy saving behavior, etc.
Knowledge	Energy problems	Climate change, environmental problems, depletion of fossil fuels, future uncertainties, etc.
	Measures, advatages	Measures to save energy, advantages for society and/or for individual household, etc.

(Han et al. 2012)

Table 1.4: Behavior factors of energy use in social housing

Behavior Factors
Income
Age
Education level
Nationality
Working type
The location of residence
Family characters
Income

1.5.2 Quality of buildings

The energy consumption of buildings largely depends on their quality, which results from a combination of several factors such as the date of construction, the building architecture design, the building envelope, and the building equipment (Table 1.5).

The date of construction indicates the building age as well as the type of construction materials, the insulation technology, the construction procedure and the building technical equipment and control. These parameters are determinant in the energy efficiency of buildings.

The architecture design of building is a key parameter in energy efficiency. For example, the design of building vertically or horizontally, the shape of building, the external design and the direction of building strongly affect the building energy efficiency.

The building envelope plays an important role in their energy efficiency. The thermal performance of the envelope results from the quality of the construction material and insulation, the quality and surface of windows and the presence of thermal bridges. Nowadays, technology allows the construction of highly isolated building, by using adequate material and envelopes thicknesses. In building renovation, excellent isolation could be achieved by the construction of external envelope.

The building equipment used in both heating/cooling and ventilation as well as the technology used in the control and management of the heating system highly influences the energy consumption and, consequently, the building energy efficiency. Recent development in the field of Smart Buildings allows substantial energy saving. Thanks to the digital technology including advanced monitoring, control system and optimization software, significant energy saving could be obtained in existing buildings. This technology allows an optimal control of the heating/cooling system to the real use of buildings. It allows the integration of renewable energy, the energy cooperation between buildings. It also allows the buildings thermal inertia for shifting the building heating to low price energy time intervals.

Table 1.5: Quality of building factors that affect of energy use in social housing

Quality of buildings
Date of construction
Environment
Architecture
Orientation
Windows
Doors
Materials
Insulation
Space / Volume [m˛/m^3]
Number of rooms
Number of floors
Location
Quality of construction
Size of the entire building
State of the materials (related to the age)

1.6 Policy for energy saving

With the increase in the energy price and the reinforcement of the interest in energy reduction for the both the preservation of natural resources and the reduction of the greenhouse emission, the public and private sectors as well as users have to act rapidly to reduce the energy consumption. Since the majority of new constructions is old with low energy performance, we need huge effort for achieving this goal. In the next sections we focus on the specific measurement for the social housing. These measurements should be associated with general measurements concerning the improvement of the buildings energy efficiency through the improvement of the thermal insulation, the buildings appliances, and energy optimal control.

1.6.1 Regulation of the internal temperature in social housing

Figure 1.13 shows the repartition of the social housing buildings according to their internal temperature in France, Germany, and Northern Irelands (SAVE@Work4Homes, 2009). It shows a high variation in the internal temperature in each country and among countries. In France, the internal temperature exceeds 20°C in about 25% of the social housing buildings and in 90% of buildings the internal temperature exceeds 18°C. In Germany, the internal temperature exceeds 20°C in about 52% of the social housing buildings and in 96% of buildings the internal temperature exceeds 18°C. In the Netherlands, the internal temperature exceeds 20°C in about 80% of social housing buildings and in 97% of buildings the internal temperature exceeds 18°C.

The precedent analysis shows that significant energy saving could be achieved by the control of the internal temperature in social housing to "reasonable" level. Indeed, a recent study on energy saving in social housing (Figure 1.14) proved that the reduction of the internal temperature in the social housing in France to 18°C leads to 15.7% energy saving. It also showed that the reduction of the temperature to 19°C leads to 10.2% energy saving.

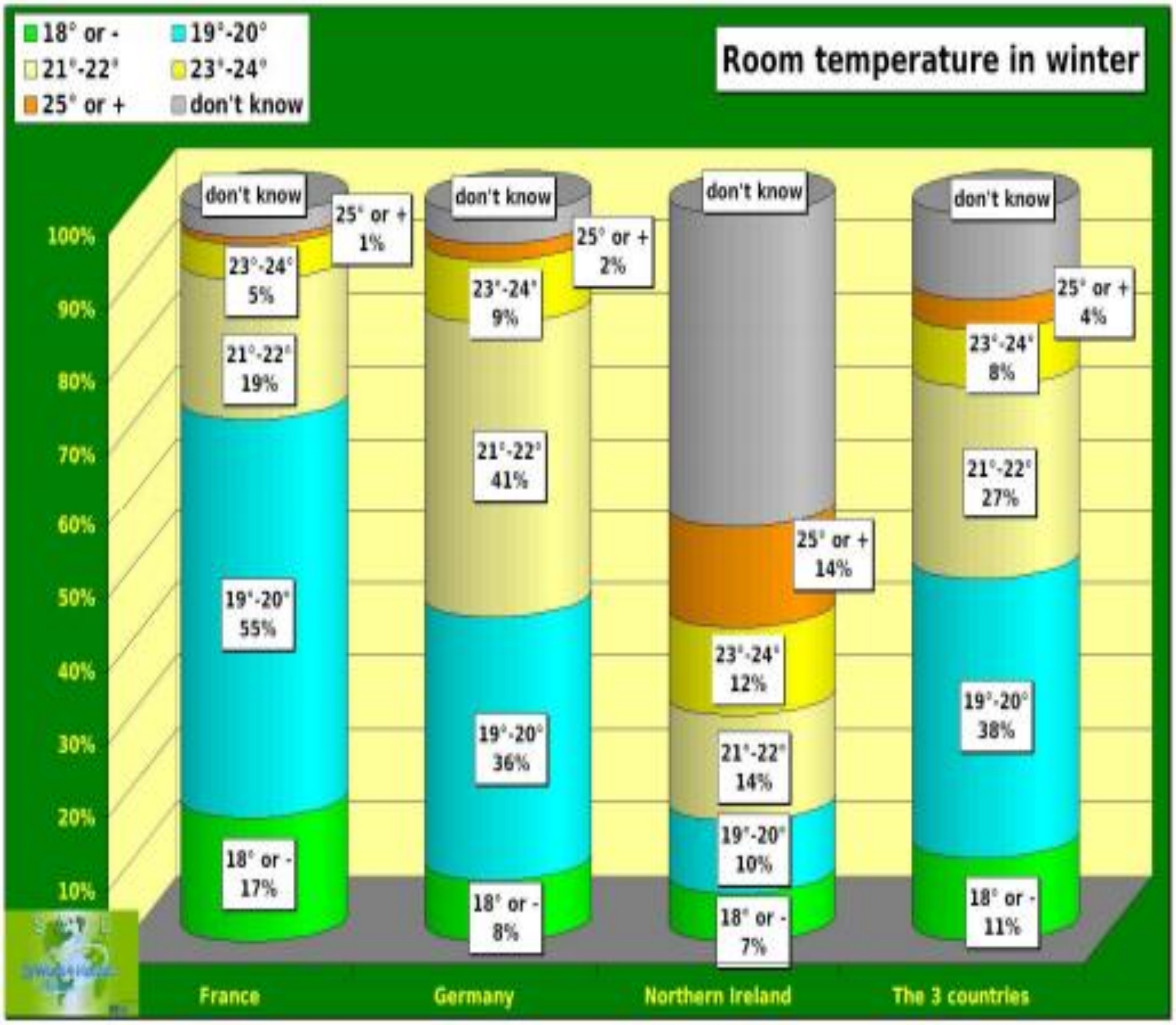

Figure 1.13: Internal temperature in winter in social housing in France, Germany and Northern Ireland.

(*SAVE@Work4Homes, 2009; http://www.federcasa.it*)

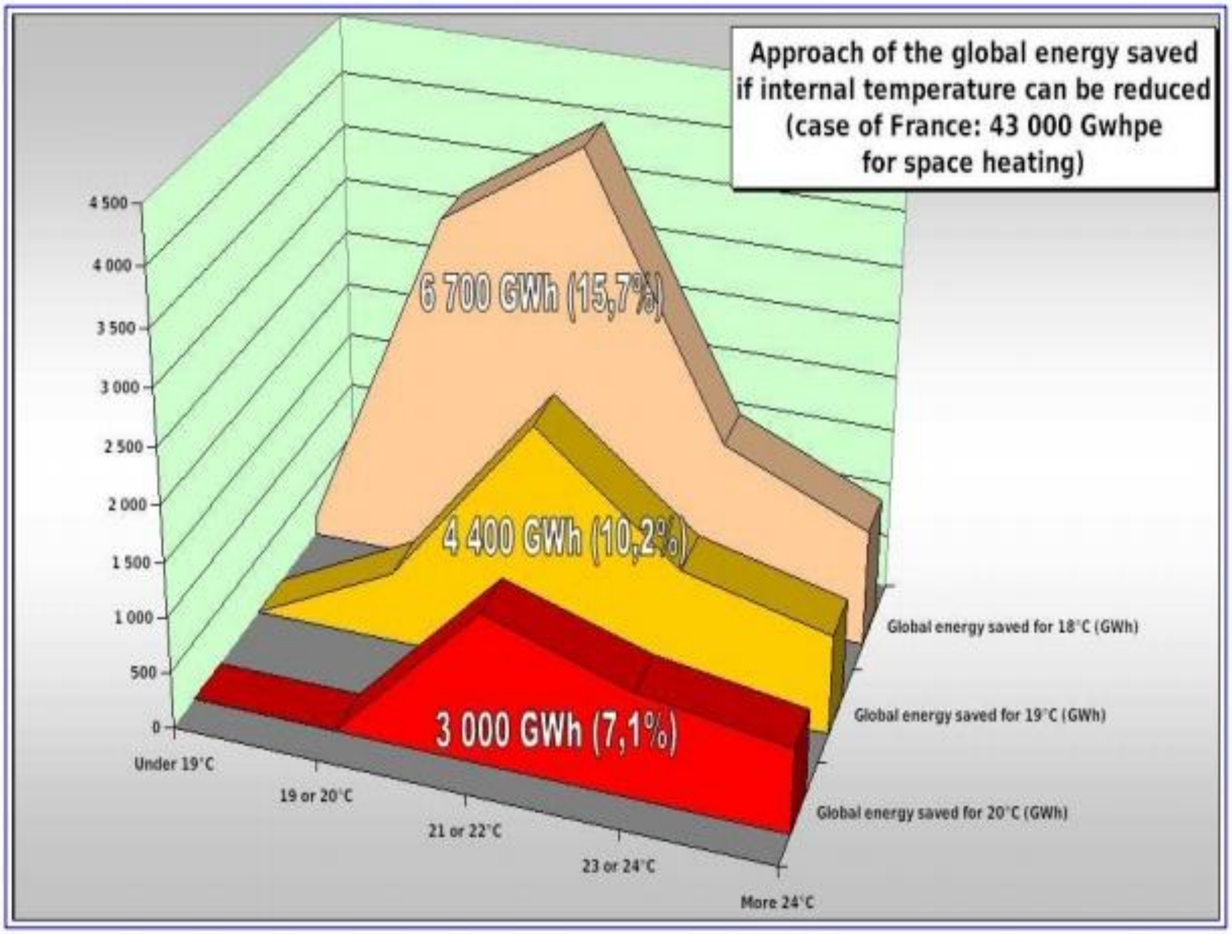

Figure 1.14: Impact of the internal temperature control on energy saving

(SAVE@Work4Homes, 2009).

1.6.2 Allowances system

In France, the housing allowance (A) is determined as following:

$$A = K(R + C - R_0)$$

R: the rent, up to a reference rent function of family size and geographical location.

C: a fixed amount (depending on the family size).

R_0: the minimum housing expenses that should be paid by the household.

K: a coefficient between 0 and 0.9, which decreases with the income and increases with the family size.

We observe that the French allowance system does not include the running costs in the social housing sector. Tenants have to ensure the expenses related to the energy consumption. In the social housing sector, low-income tenants could face major difficulties to live in decent conditions. In some cases, this situation could lead to “energy poverty” (Fr. *précarité énergétique*).

The consideration of the energy consumption in the allowance system should combine both the tenants’ responsibility and awareness, but also the right of low-income tenants to live in descent condition. The response to this statement requires an important effort for the improvement of the building energy efficiency through renovation programs including both building insulation and the optimal control of the energy using smart technology.

The equation of public assistant in Germany is different. It considers running cost specially in energy consumption, in particular an increase in allowance with the decrease in energy consumption. Grosche (2009, 2010) showed that about 3 million households in Germany receive a social assistance from the housing allowance program. This assistance covers the cost of housing and heating for part of tenants.

1.7 Conclusion

The social housing has been deeply embedded in the European history. It played a key role in reinforcing the social cohesion as well as in economic development. The issue of social housing bacame crucial in non-European developing countries such as China, Maghreb, Latin America, and South Africa, who have experienced powerful economic development and mass migration to cities, which led to explosive urban growth. The European experience could be beneficial for these countries.

This sector faces large challenges, which result from the economic crisis, the increase in the social and economic difficulties of low-income population, the high increase in the energy price, the aging of the social housing buildings, the non-adaptation of these buildings to sustainability requirement and the planet protection, and the lack of public funding for the renovation of existing buildings, as well as for the construction of new ones. In this context, we do need to conduct innovative research, which combine both (i) a deep understanding and diagnostic of the existing social housing sector, and (ii) the development of new materials, appliance and smart systems, which allow to optimize the investments and maintenance expenses devoted to energy saving as well as improvement of the life quality in the social housing.

This doctoral research concerns the understanding and diagnostic of the existing social housing sector and the energy consumption in this sector. It aims at understanding the energy expenses and its relationship with both the physical characteristics of buildings and the socio-economic indicators of the tenants. The study is based on the analysis of the data provided by one of the largest social housing managers in the North of France (Lille Metropole Habitat – LMH), in charge of about 30 000 social housing dwellings.

In the following chapters, we present the data including the physical and socio-economic indicators (Chapter 2), the analysis of the energy consumption and its relationship with physical and socio-economic indicators (Chapter 3), and a numerical modeling of the energy consumption using Linear Regression and Artificial Neural Network methods (Chapter 4).

CHAPTER 2: Analysis of the LMH social housing stock – Data collection

2.1 Introduction

This chapter presents the collection of data related to the energy consumption in the LMH (Lille Métropole Habitat) social housing stock in Lille Metropolis.

Lille Metropolis comprises 85 municipalities and spreads over an area of 61,145 hectares. With 1,106,885 inhabitants, it is ranked as the 4th metropolis in France, after Paris, Lyon and Marseille, but the second in population density (1,785 inhabitant per km^2). Four towns of the Metropolis have more than 65,000 inhabitants: Lille, Roubaix, Tourcoing and Villeneuve d'Ascq.

In Nord-Pas-de-Calais department around 1,030 per 10,000 inhabitants live in social housing (10%) (INSEE, 2012), which ranks the department in the 6th position after Seine-Saint-Denis, Vale-de-Marne, Hauts-de-Seine, Marne and Seine-Maritime. Table 2.1 shows the repartition of housing in this department.

Table 2.1: Repartition of the housing in the Pas de Calais department

All Residences	**1,594,741**	
- Locative	**676,342**	**42%**
- Private	367,889	23%
- Social	308,453	19%
- Land Owners	**890,751**	**56%**
others	**27,648**	**2%**

(INSEE 2012)

This study was conducted in cooperation with the major social housing landlord (Bailleur Social) “Lille Métropole Habitat” (LMH). LMH has a stock of about 29,778 dwellings in 499 residences. This stock is representative of the social housing in Lille Metropolis (http://www.lmh.fr).

This chapter presents a global view of the housing stock of LMH, and then it describes both the technical and socio-economic characteristics. Statistical analyses will be used for a right understanding of this social housing stock.

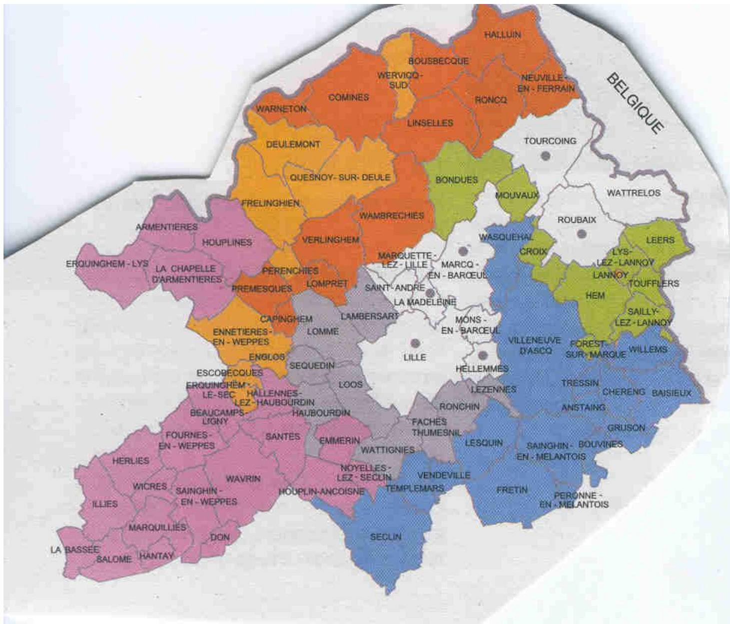

Figure 2.1: Lille Metropolis territory

2.2 Global overview of the LMH social housing stock

The LMH stock is composed of 499 residences including 29,778 dwellings. About 52% of these dwellings use collective heating, while 40% use individual heating, and only 8% use a mixed heating system. Concerning the energy used in heating, 43% of the dwellings use natural gas, 50% use a mixed system (i.e. natural gas and fuel system) and only 8% use electric power.

Figure 2.2 and 2.3 summarize the history of construction of the LMH housing stock. It shows that most of the dwellings were built before 1978, with peaks in 1950, 1968, 1970, 1973, 1975, 1976, 1977 and 1978. After this period, few dwellings were constructed. The year of construction constitutes a major indicator for the quality of buildings: in addition to the building age, it reveals the quality of material used in the construction, the building insulation, the construction process as well as the construction standard and rules.

In the following section we focus on collective residences that use collective heating. First, we present analysis of the physical characteristics of the housing stock, and then the analysis of the socio-economic parameters.

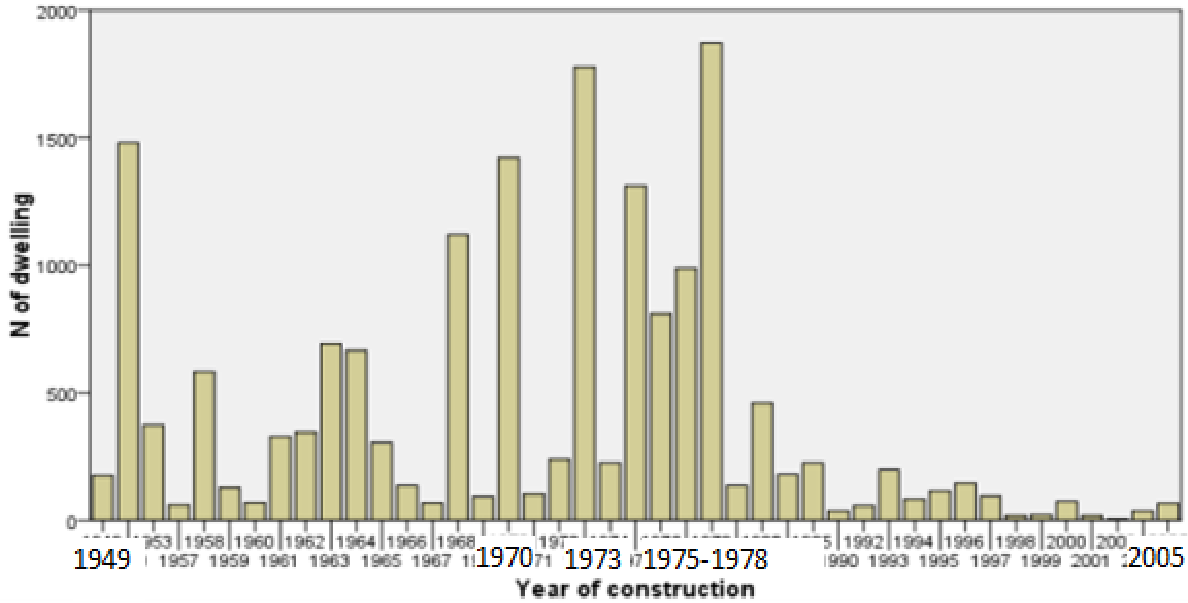

Figure 2.2: History of construction of the LMH social housing stock

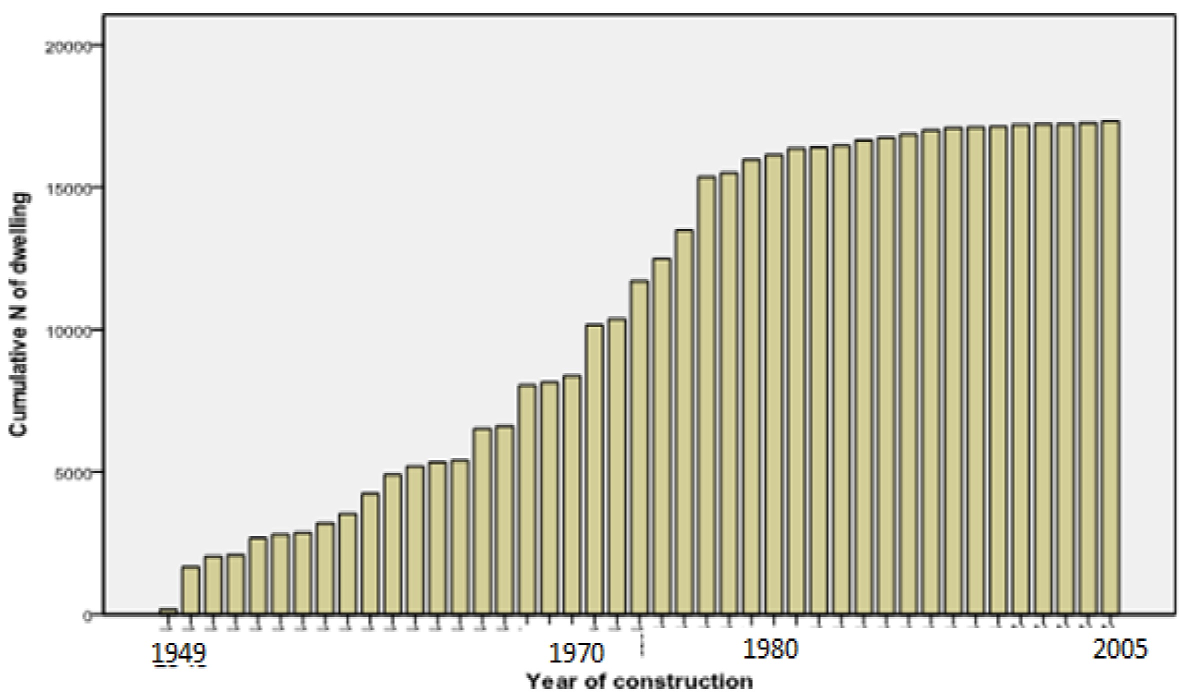

Figure 2.3: History of construction of the LMH social housing stock (cumulative)

2.3 Analysis of the physical characteristics of the LMH stock

In the following sections we present the physical characteristics of the LMH housing stock through the following available indicators:

- Diagnostic de Performance Energétique (DPE)
- Dwelling are
- Type of heating energy used in heating
- Number of floors of buildings.

2.3.1 DPE - Diagnostic de performance énergétique

The Diagnostic de performance énergétique (DPE) (Eng. *Energy Performance Certificate*) indicates the energy performance of buildings according to the European Union Directive 2002/91/EC. In France, the DPE is required for all property sales since November 1, 2006, and for property rentals since July 1, 2007.

The DPE can be determined by applying two approaches. The first one is based on the energy characterization of the buildings, such as insulation, ventilations, domestic boiler, hot water tank, radiators, windows, etc. This approach is commonly used in France. The second approach is based on the analysis of the historical data of energy consumption.

Figure 2.4 illustrates seven categories of buildings according to their energy consumption. The A category indicates the most performing buildings with consumption inferior to 50 kW/m^2/year. The B category indicates buildings with a good energy performance (consumption between 51 and 90 kW/m^2/year). The F and G categories designate poor energy performance (consumption higher than 330 kw/m^2/year).

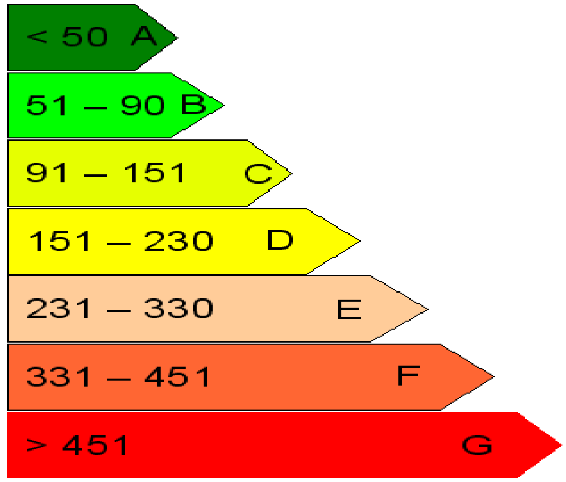

Figure 2.4: Buildings categories according to the DPE (Diagnostic de performance énergétique)

Figure 2.5 summarizes the repartition of the LMH housing stock according to the DPE. It shows the following repartition:

- 368 dwellings in the category B (2.30%)
- 4,080 dwellings in the category C (25.55%)
- 5,543 dwellings in the category D (34.72%)
- 5,976 dwellings under rate E (37.43%).

Figure 2.6 illustrates the relation between the DPE and the year of construction. It shows that most of old buildings are in the category E, while recent dwelling are in the category C. It shows also buildings under the category E (exclude one residence) were built before 1980, while buildings under the category D were built between 1970 and 1981; and those under the category C were built between 1986 and 1997.

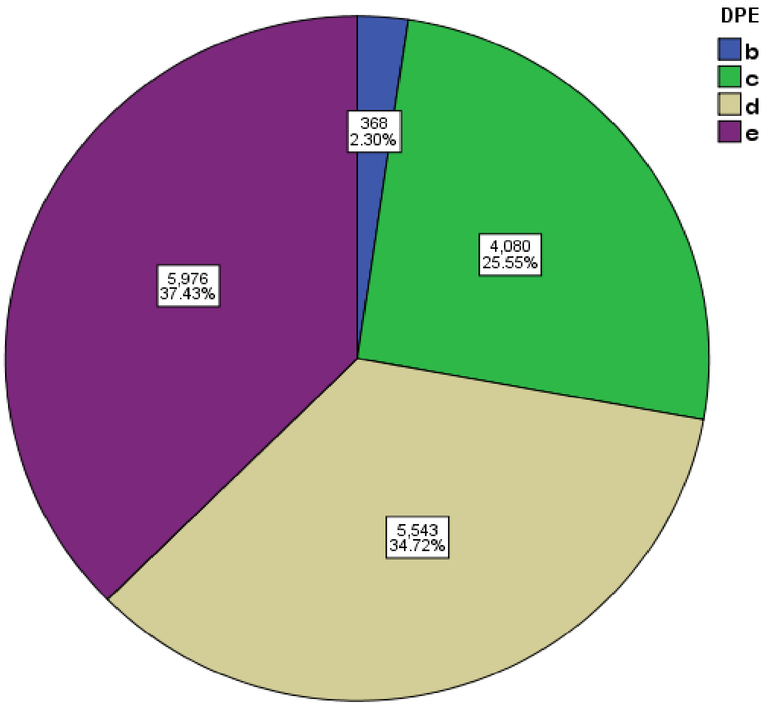

Figure 2.5: Repartition of the LMH housing stock according to their DPE

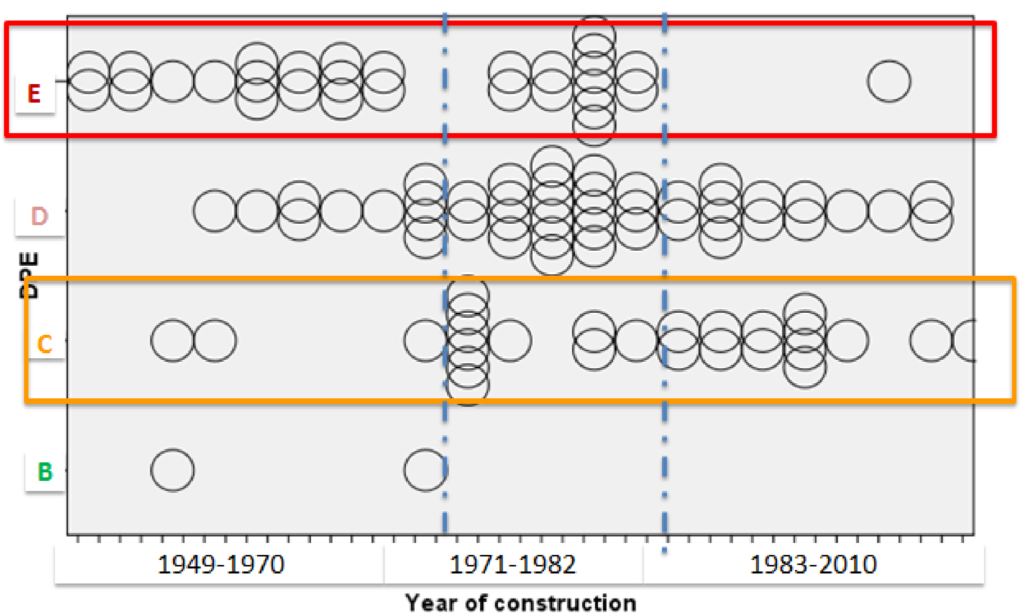

Figure 2.6: Relation between the year of construction and the DPE

2.3.2 Dwelling area

Figure 2.7 shows the distribution of dwellings according to their area. We observe that the maximum dwelling area is equal to 90 m^2, the minimum is equal to 40 m^2 and the average is equal to 67 m^2 with a standard deviation of 10 m^2.

Figure 2.8 shows the relationship between the dwellings' area and the year of construction. For the buildings constructed before 1990, we observe a positive correlation between these parameters with the Person Correlation = 0.30 (P-value < 0.05). After 1990, we do not observe significant correlations. The increase in the dwellings area indicates an improvement in the life quality.

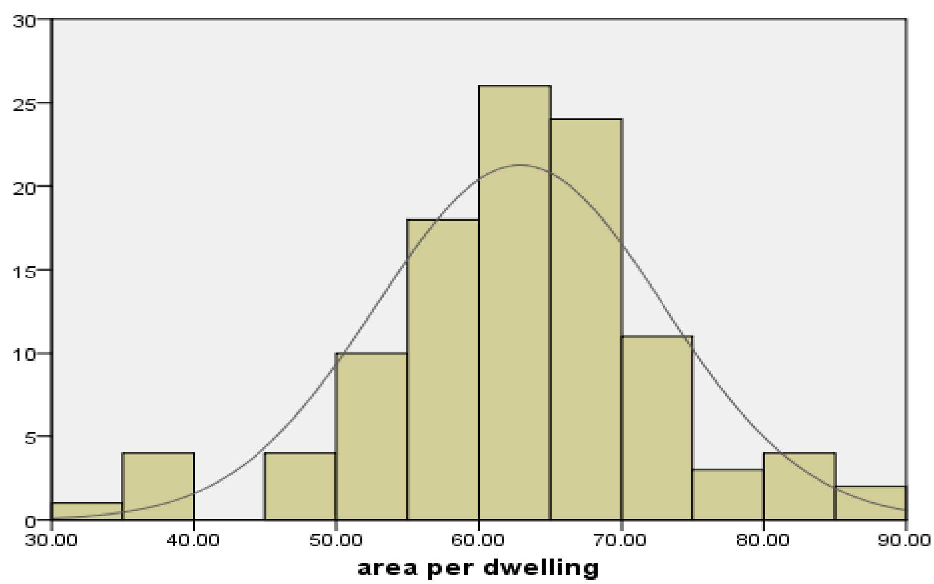

Figure 2.7: Distribution of the LMH housing stock according to their area

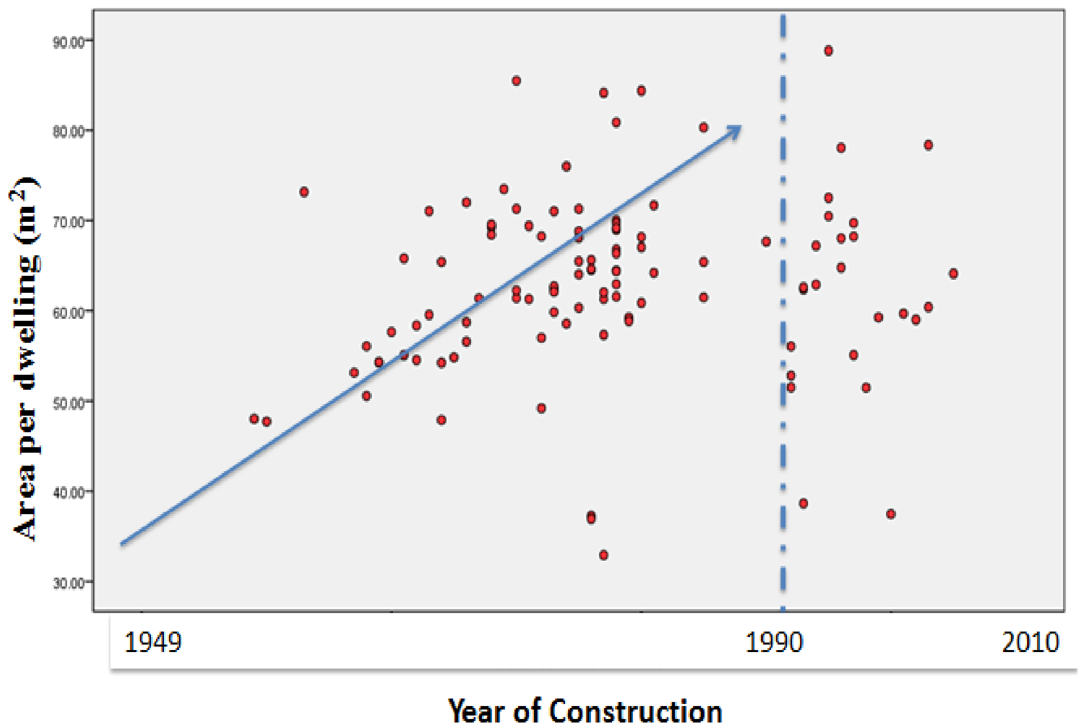

Figure 2.8: Relation between the year of construction and the dwellings area

2.3.3 Type of heating energy

Figure 2.9 shows the evolution of the energy used in heating in the LMH stock. It can be observed that the gas is used in the majority of buildings. It is used since 1956 increased rapidly until 1975. The use of the electrical energy is low (about 8%). It was used in the three periods: 1956–1960, 1971–1975 and the majority in1976–1980 because of the gas and oil world crisis. The “mix” energy (mainly gas) has been used since 1950.

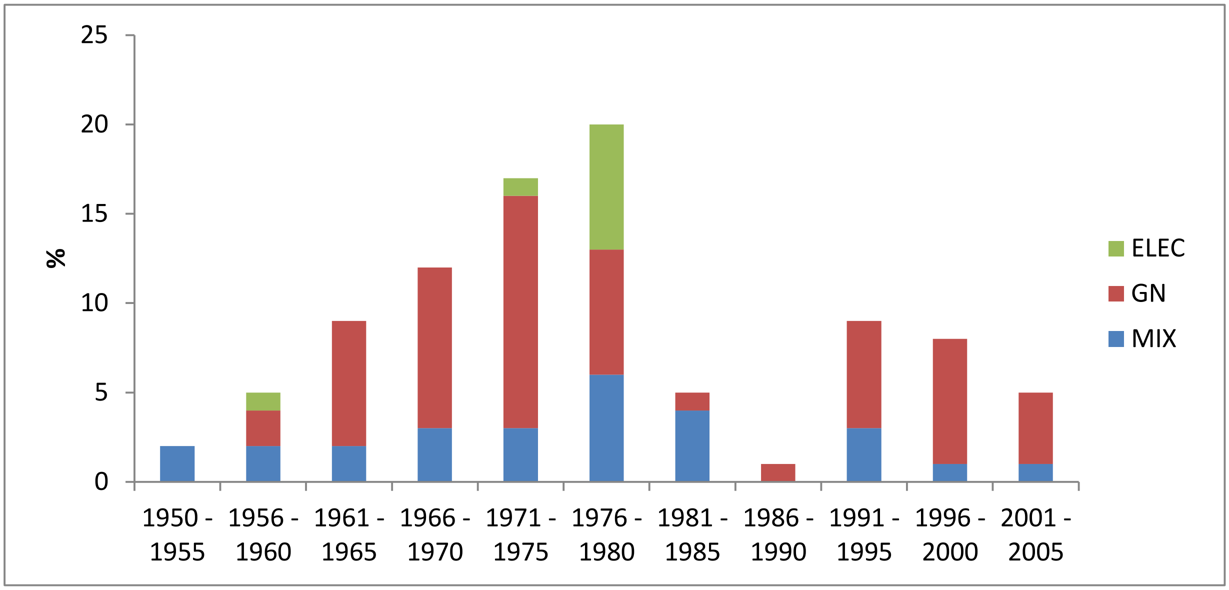

Figure 2.9: Relation between the year of construction and the type of heating energy

2.3.4 Number of floors

Figure 2.10 shows the distribution of the LMH stock according to the number of floors. We observe that the number of floors varies between 1 and 19 with peaks at 9, 5, 8 and 16 floors. The stock does not include buildings with 2 floors.

Figure 2.11 shows the relationship between the number of floors and the year of construction. It shows that after 1981, residences were built with a number of floors between 3 and 6, while high residences were built in the period 1960–1980.

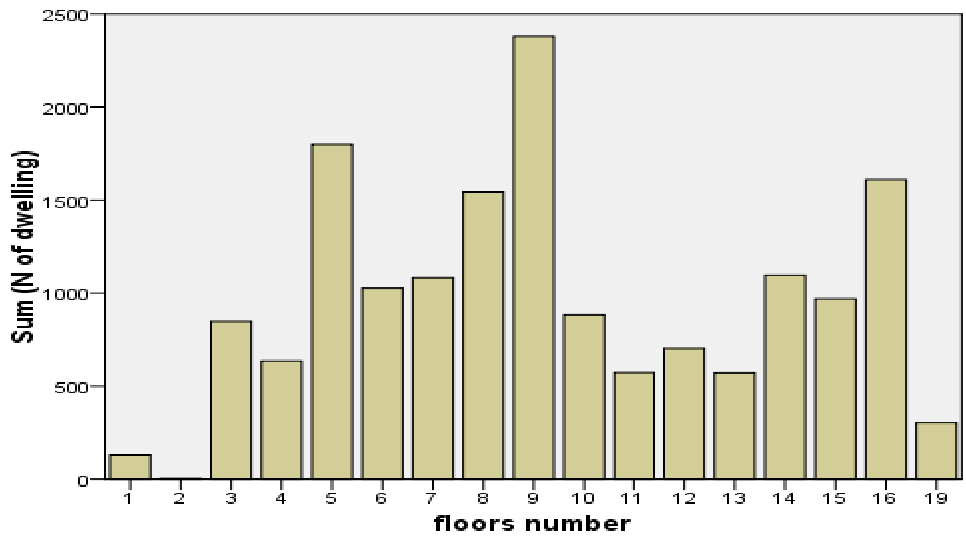

Figure 2.10: Distribution of dwellings according the buildings number of floors

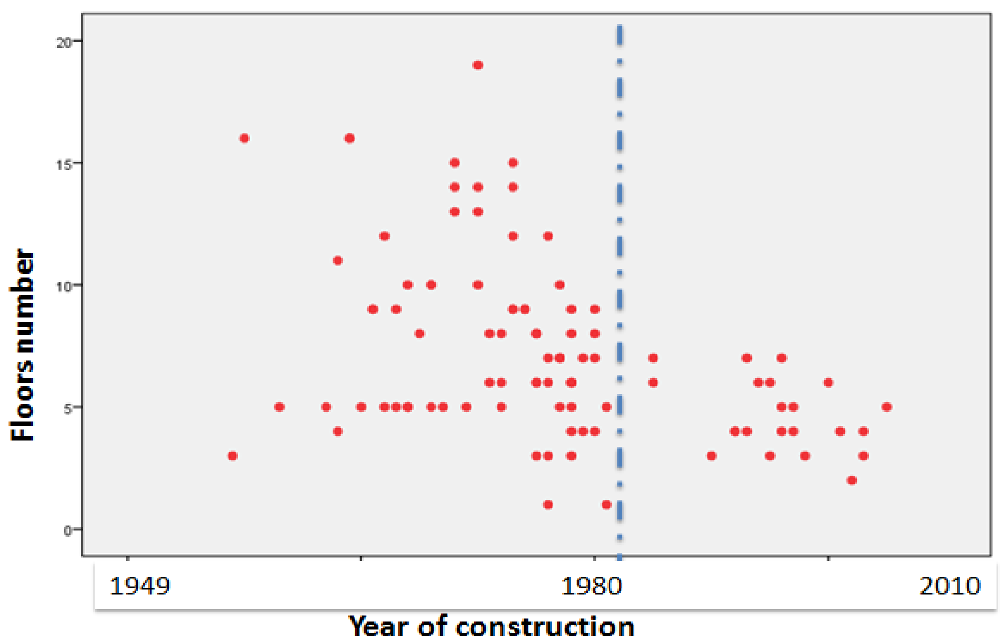

Figure 2.11: Relation between the year of construction and the buildings number of floors

2.3.5 Correlation analysis

The Pearson correlation Matrix has been used for the analysis of the relationship between the physical parameters of the LMH residences. Table 2.2 presents the matrix of correlations between the following parameters: year of construction, dwellings area, number of floors, and DPE. We observe a significant negative correlation between the year of construction and the number of floors in buildings, which indicates an improvement with time of the construction quality through the reduction of the number of floors. We also observe a negative correlation between the year of construction and the DPE, which also indicates an improvement in the buildings energy efficiency with time. We also observe low correlation between the number of floors and the DPE. Concerning the correlations between DPE classification (C, D, E) and other indicators, we observe (Table 2.2) a negative correlation for the number of floors and all the buildings category, and a negative significant correlation between classes D and E and the year of construction, but insignificant correlation for the category C. Finally, we observe insignificant correlations between the buildings category (C, D, E) and the dwellings' area.

Table 2.2: Pearson correlations between the indicators

	Year of construction	Area per dwelling	Number of floors	DPE quantity
Year of construction	1			
Area per dwelling	.137 (.158)	1		
Number of Floors	-.442** (.000)	.102 (.320)	1	
DPE quantity	-.494** (.000)	-.174 (.078)	-.110 (.291)	
C	-.186 (.363)	.144 (.483)	-.032 (.887)	1
D	-.314* (.038)	.004 (.978)	-.043 (.787)	
E	-.372* (.047)	.097 (.617)	-.063 (.762)	

The numbers in parentheses are confidence error for significant test.

***. Correlation is significant at the 0.01 level (2-tailed).*

**. Correlation is significant at the 0.05 level (2-tailed).*

2.4 Socioeconomic indicators

In this section we focus on three socioeconomic indicators: tenants' age, tenants' marital status, and tenants income. Table 2.3 shows the sub-classes of the socioeconomic indicators used in this study.

Table 2.3: Socioeconomic indicators and the slices that were used in each indicator in this study

Parameter	Designation	Classes
X1	Tenants age by residence	less than 26 years old
		between 26 to 40 years old
		between 41 to 60 years old
		between 61 to 75 years old
		More than 75 years old
X2	Marital status by residence	single tenants
		single tenants with 1 or 2 children
		single tenants with more than 3 children
		couples tenants
		couples tenants with 1 or 2 children
		couples tenants with more than 3 children
X3	Income by residence	up to 40% of the maximum resources
		= 40%-60% of the maximum resources
		= 60%-100% of the maximum resources
		= 100%-130% of the maximum resources
		= more than 130% of the maximum resources

2.4.1 Tenants' age

The age of tenants is a significant indicator in the behavioral use of the energy. Figure 2.12 shows the distribution of the dwellings tenants according to their age. We observe the following repartition of the tenants:

- 40% are between 41- 60 years
- 29% are between 26 – 40 years
- 17% are between 61 – 75 years
- 9% are older than 75 years
- 5% are younger than 26 years.

This reparation shows three categories: 34% of young tenants (younger than 40 years), 26 % of old tenants (older than 61 year), and 40% of intermediate age tenants (between 41 and 60 years).

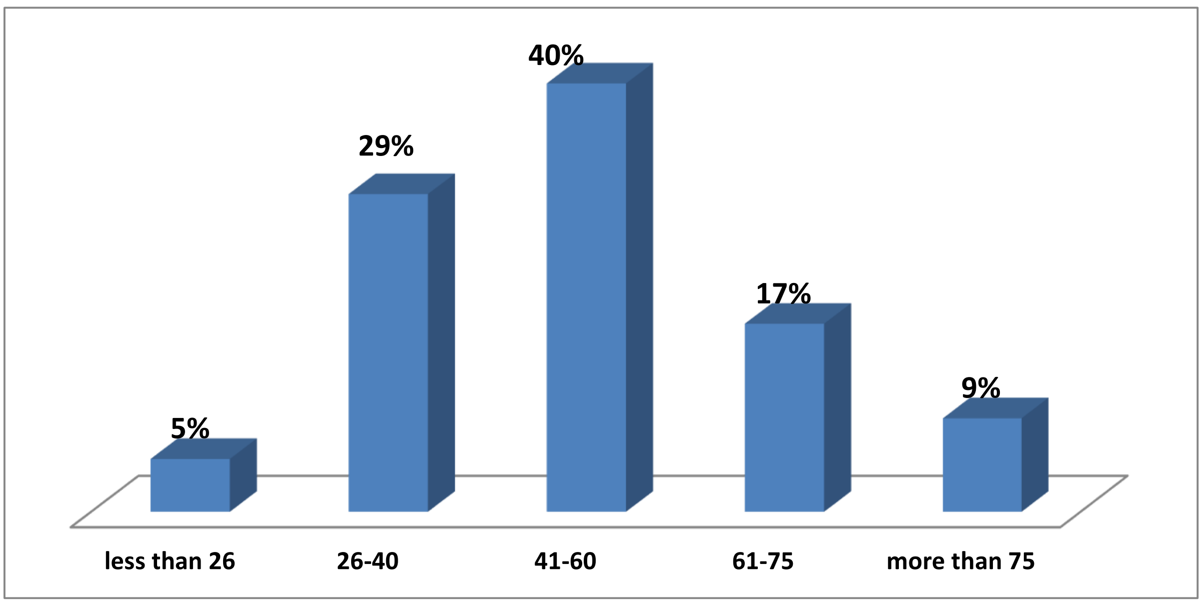

Figure 2.12: Socioeconomic indicators and the slices that were used in each indicator in this study

2.4.2 Tenants Marital Status

The repartition of the LMH tenants according to the family status is summarized in Figure 2.13. It shows the following repartition of tenants:

- About 42% of the tenants are single without children
- About 16% of the tenants are single with 1 or 2 children
- 16% of the tenants are couple with 1 or 2 children
- 12% of the tenants are couple without children
- 9% of the tenants are couple with at least 3 children
- 4% of the tenants are single with at least 3 children.

This repartition shows that about 64% of the tenants are single, 54% do not have children and 13% have at least 3 children.

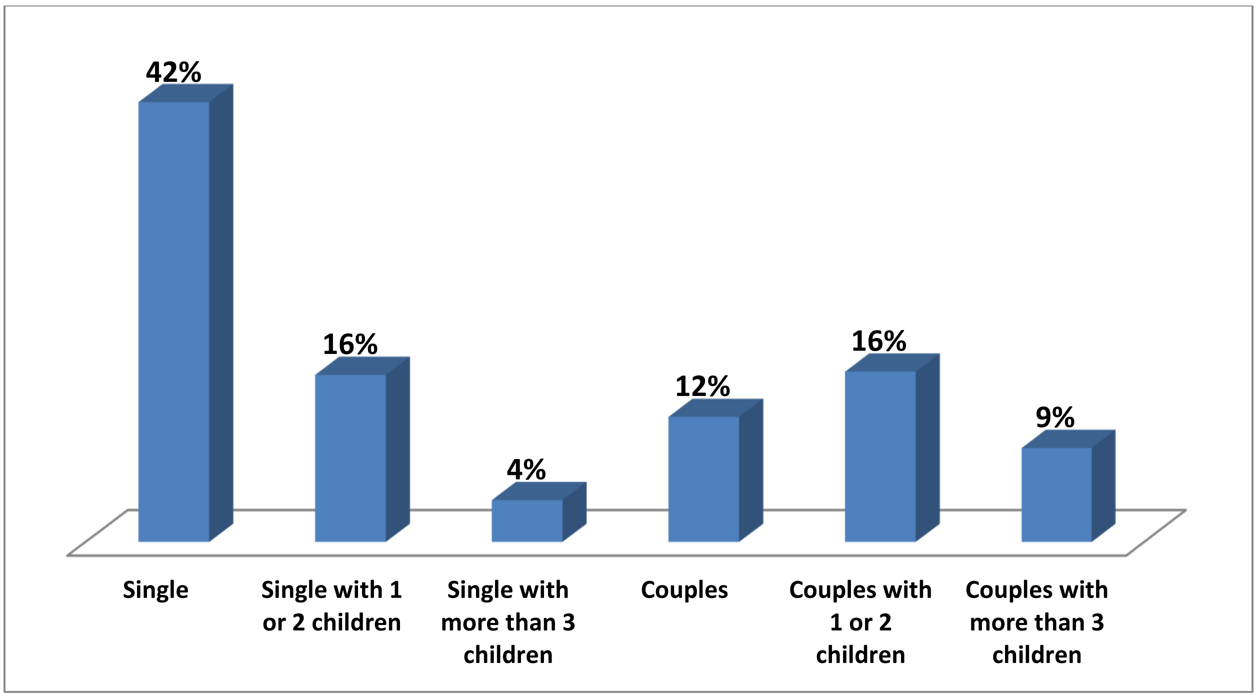

Figure 2.13: Repartition of tenants according to their family status

2.4.3 Tenants Income

The social housing aid in France is based on the classification of tenants in several categories. Tables 2.4 and 2.5 summarize these categories. The social housing aid is based on the family composition (Table 2.4), which includes six categories. It also depends on the category of the social aid, which includes four categories. For each family composition and aid category, an income ceiling is defined (Table 2.5).

Figure 2.14 summarizes the repartition of the tenants according to their income. It shows that:

- 53% of the tenants' income is lower than 40% of the social housing ceiling
- 21 % of the tenants' income is between 60 and 100% of the social housing ceiling
- 18 % of the tenants' income is between 40 and 60% of the social housing ceiling
- 8 % of the tenants' income is higher than 100% of the social housing ceiling

This repartition shows that about 71% of the tenants income is lower than 60% of the social housing ceiling, which indicates that the majority of tenants have low income.

Table 2.4: Tenants categories according the family composition

Category	Define
1	1 person
2	2 person except young couple (couples whose combined age is 55 years maximum)
3	3 person or 1 person + 1 dependent or couple young couple (couples whose combined age is 55 years maximum)
4	4 person or 1 person + 2 dependents
5	5 person or 1 person + 3 dependents
6	6 person or 1 person + 4 dependents

(http://vosdroits.service-public.fr/particuliers/F869.xhtml#N100CF, 3/5/2014)

Table 2.5: Income ceiling for social housing (HLM) (Ile-de-France, 2013)

Household	Housing funded by PLAI	Housing funded by un PLUS	Housing funded by PLS	Housing funded by PLI
Category 1	12 662 €	23 019 €	29 925 €	32 021 €
Category 2	20 643 €	34 403 €	44 724 €	42 760 €
Category 3	24 812 €	41 356 €	53 763 €	51 424 €
Category 4	27 245 €	49 536 €	64 397 €	62 080 €
Category 5	32 255 €	58 641 €	76 233 €	73 029 €
Category 6	36 295 €	65 990 €	85 787	82 304 €
Each additional person	+ 4 043 €	+ 7 353 €	+ 9 559 €	+ 9 181 €

(http://vosdroits.service-public.fr/particuliers/F869.xhtml#N100CF, 3/5/2014)

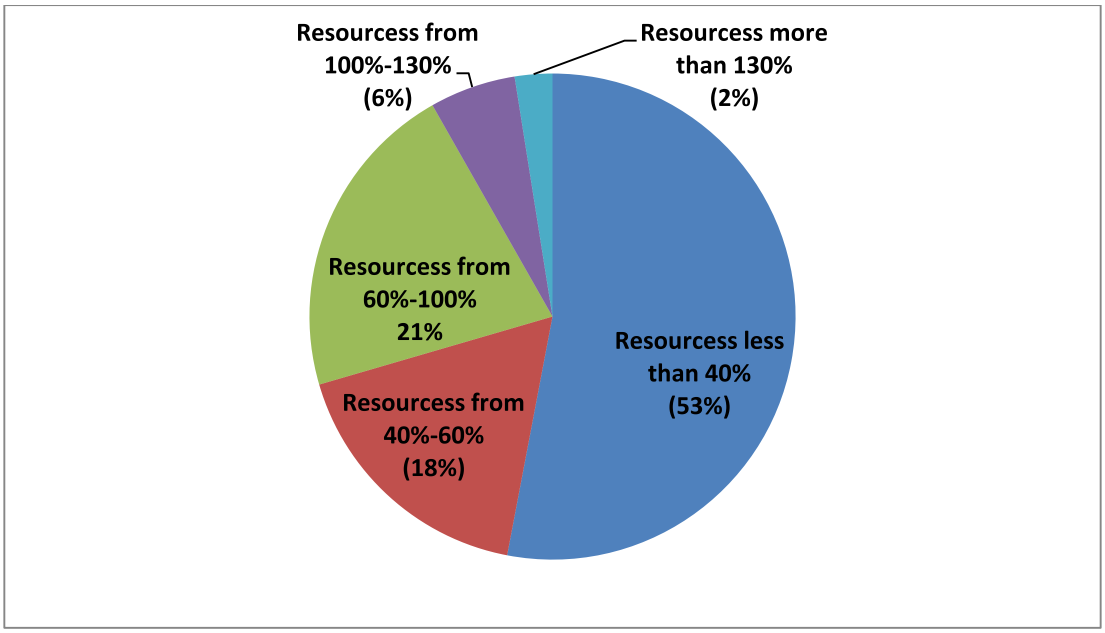

Figure 2.14: Repartition of the LMH tenants according to their income

2.5 Summary and Conclusion

This chapter included an analysis of the LMH stock, which is used in this research. Analysis shows a housing stock with a large variety in the year of construction (between 1949 and 2005), the DPE (between B and E), the number of floors (between 1 and 16), the dwellings area (between 30 and 90 m2), the family composition (single or couple, without children or with 1 or 2 children or more than 3 children), the tenants' age (younger than 26 years, 26–40, 41–60, 61–75 and more than 75 years old) and the income (five categories).

After 1981, the number of floors was limited to six. While before this date, the number of floors of some buildings exceeded 12. The high number of floors indicates higher difficulties for the buildings maintenance and renovation.

Concerning the quality of construction, the majority of the stock has low energy efficiency: the DPE of approximately 72% of the stock is lower than D. Consequently, important measurements are required for the improvement of the stock quality as well as the management of the energy.

Analysis of the socio-economic parameters shows that about 71 % of the tenants' income is lower than 60% of the social housing ceiling, which indicates that the majority of tenants have low income. Concerning the tenants family composition, about 64% of the tenants are single, 54% do not have children and 13% have at least 3 children. The tenants' age repartition shows 34% of young tenants (less than 40 year) and 40% of intermediate age (between 41 and 60 years old).

In the next chapter, we will present the energy consumption and analyze the relationship between this consumption and the buildings physical and socio-economic parameters.

CHAPTER 3: Analyses of heating consumption

3.1 Introduction

Figure 3.1 and Table 3.1 show the distribution of the heating consumption (€ /m^2) in the period 2008 to 2011. It shows that the heating expenses of per square meter varied between 4.4 and 12.3 € with an average around 7.57 €. It indicates a large variation in the consumption, which could be related to several factors, such as the building energy efficiency, the equipment of the building, the management of the energy, and social factors, such as the income, the family composition, and culture.

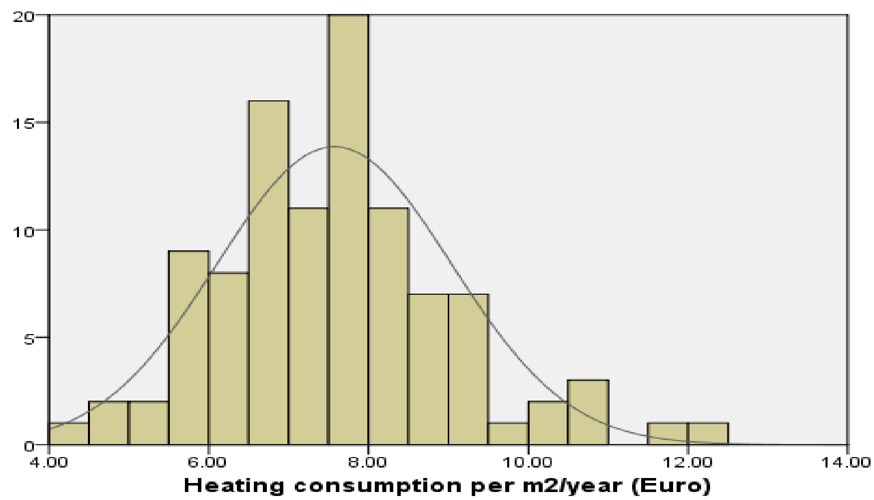

Figure 3.1: The distribution of the heating expenses (€ /m2/year) in the LMH stock

Figure 3.2 and Table 3.1 present the energy expenses distribution for years 2008, 2009, 2010 and 2011. The average of consumption varies between 7.32 € /m^2 (2011) and 8.17 € /m^2 (2010). This variation could be related to the weather condition. Indeed, the DJU (Degrés Jour Unifies, Eng. *Unified Degree Day*) in 2010 was about 3155 DJU, to be compared with 2011 (2418 DJU) and 2009 (2712 DJU).

In the next sections we present analysis of the influence of technical factors (year of construction, type of energy used in heating, DPE, dwellings surface area, number of floors) as well as socio-economic factors (family size, age of tenants and their income) on the energy consumption.

Table 3.1: Heating consumption (€/m2)

	Minimum	Maximum	Mean	Std. Deviation
2008	3.97	12.69	7.42	1.65
2009	4.00	14.36	7.37	1.77
2010	4.20	17.53	8.17	1.86
2011	4.41	12.73	7.32	1.50

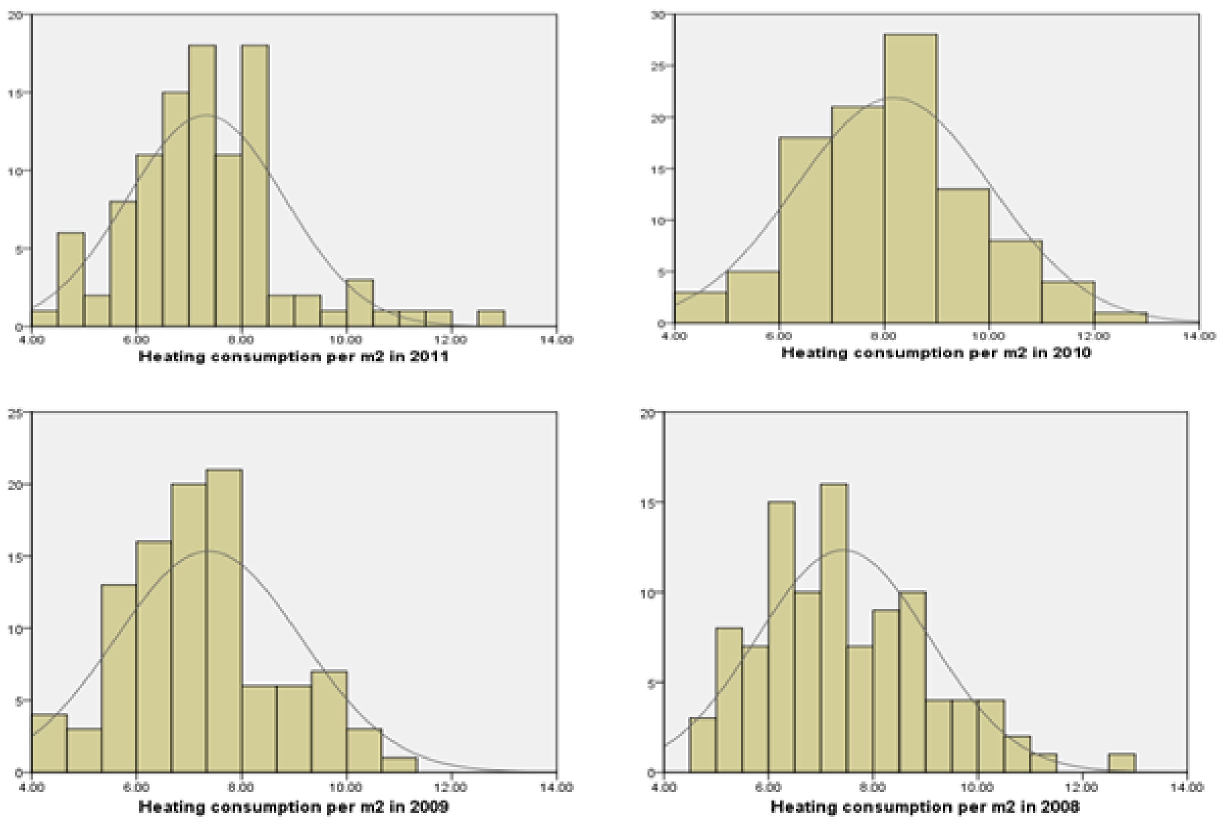

Figure 3.2: The distribution of the expenses of the heating consumption during the period 2008-2011 (€ /m2) a) 2011 b) 2010, c) 2009, d) 2008.

3.2 Influence of physical parameters

3.2.1 Year of construction

As explained earlier, the year of construction is an important parameter that affects the building energy efficiency. Figure 3.3 shows the variation of the heating expenses during the period 2008– 2011(*€ /m²/year*) with the year of construction. We observe a high variation in the heating expenses with the year of construction with peaks (exceeding 11 € /m²) for the years of construction 1960, 1966 and 2002. Minima of expenses (around 4.5 €/m²) appear for the years 1953 and 1995. The maxima and minima of consumption could not be explained by only the year of construction. They should be related to other physical and socio-economic factors, which will be explored in the following sections.

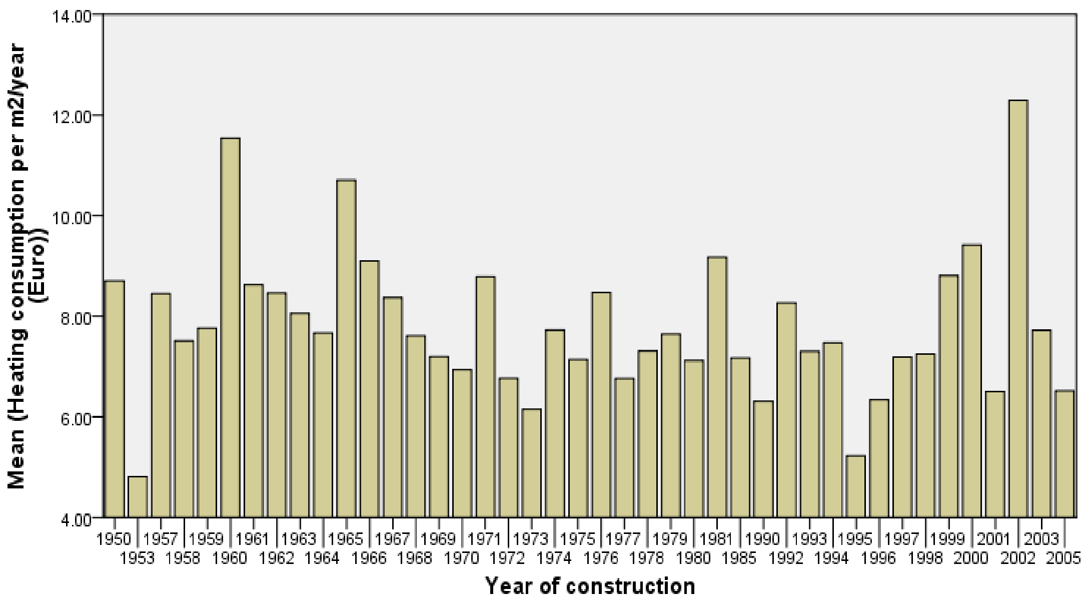

Figure 3.3: Influence of the year of construction on the heating expenses (€ /m2/year) (period 2008-2011)

Figure 3.4 illustrates the relationship between the heating expenses (*€ /m²/year*) and the year of construction. We can distinguish two categories of buildings:

- Buildings constructed before 1990. For these buildings, a significant negative correlation (P-value = 0.05) is observed between the year of construction and the heating expenses

(Pearson correlation = -0.22). This means that for these buildings, the energy efficiency increased with the year of construction.

- Buildings constructed after 1990. For these buildings, week correlation is observed between the heating expenses and the period of construction.

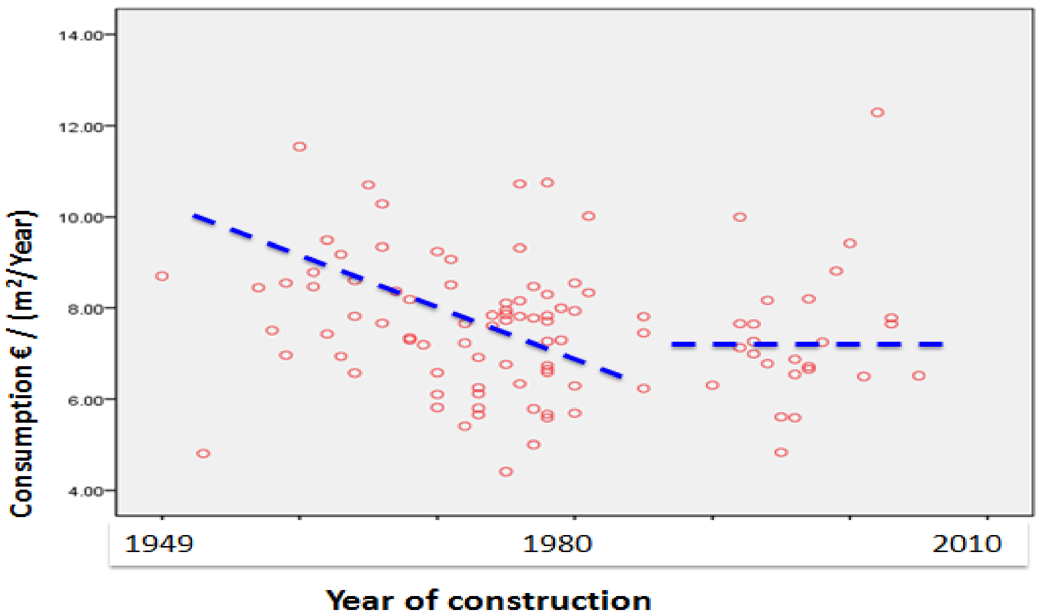

Figure 3.4: Relation between heating expenses (in €/m2/year) and the year of construction (period 2008-2011)

3.2.2 Area per dwelling

Figure 3.5 illustrates the relationship between the heating expenses and the dwellings' area. It shows that the increase in the dwellings' area globally leads to a decrease in the heating expenses (Pearson correlation = -0.35). Data clearly show that that the heating expenses per square meter of small dwellings is higher than that of large area dwellings.

Figure 3.6 shows the variation of the heating expenses with the parameter "Number of dwelling ratio", which is defined as follows:

$$Nofdwellingratio = \frac{Nofdwelling}{Area} * 100$$

This parameter provides a measurement of the composition of buildings regarding their number of dwellings area. Low values indicate high concentration of large area dwellings, while high values indicate high concentration in small area dwellings. The figure shows high scattering, with however a tendency for a reduction of the heating expenses with the increase in the “Number of dwelling ratio”.

Buildings with small dwellings area globally contain more services space (kitchen, bathrooms, appliance), what could explain the increase in the heating expenses per square meter (Oral, 2000; Liu and Harris, 2008).

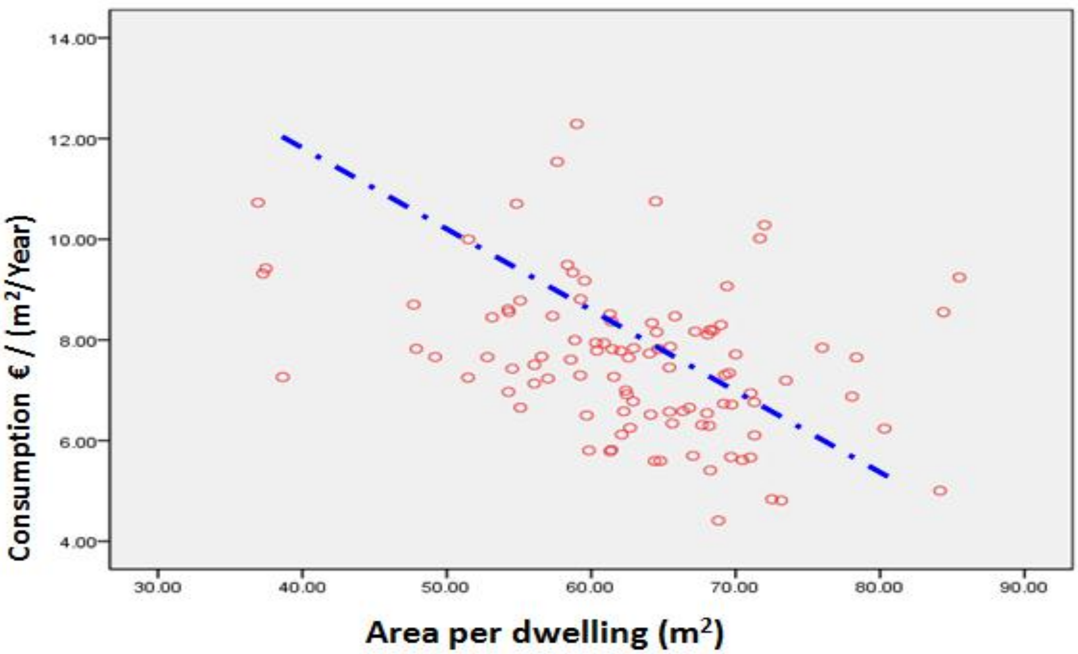

Figure 3.5: Relation between heating expenses (in €/m2/year) and the dwellings’ area (period 2008-2011)

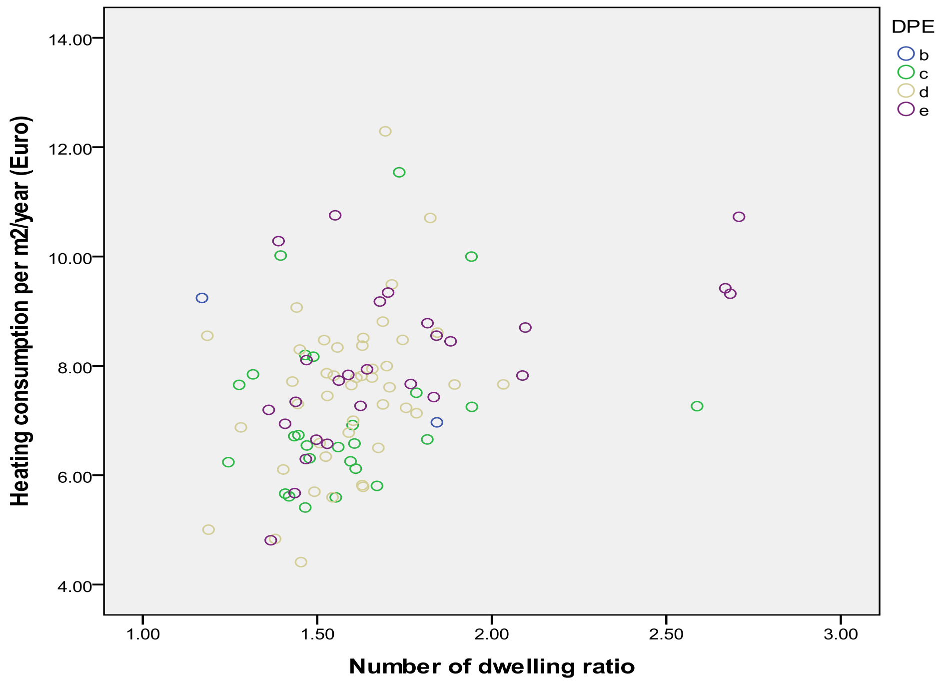

Figure 3.6: Relation between the number of dwelling ratio and the heating expenses (in €/m2/year) (period 2008-2011)

3.2.3 Type of heating energy

Figure 3.7 and Table 3.1 present the variation of the heating expenses (in €/m^2/year) with the type of energy (electricity, gas, mix). We observe that the use of natural gas leads to the lowest heating expenses: the average of the heating expenses with natural gas is equal to 7.4 €/m^2/year, to be compared to the expenses using electricity or mix energy, which are equal to 8.12 and 8.14 €/m^2/year, respectively. This result clearly shows the interest of the use of natural gas in the LMH stock. However, this result could not be used as a planning policy, because it requires more investigation in the prediction of the energy market in the future, as well as the evolution of the energy consumption with the improvement of the buildings energy efficiency. Indeed, in these buildings, the use of electrical energy should be analyzed, because of both the low investment at the construction phase and the reduce in the energy consumption during the exploitation phase.

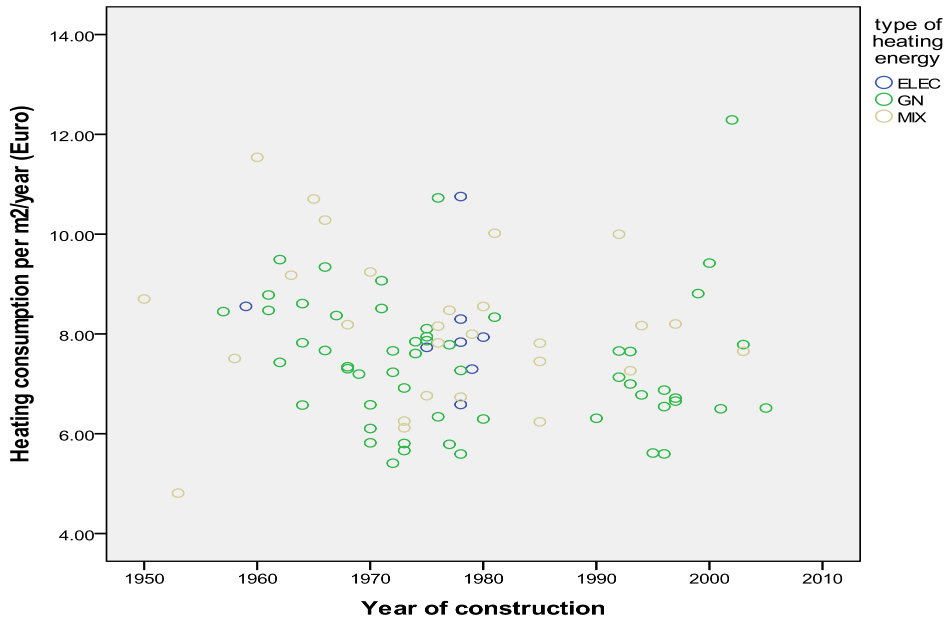

Figure 3.7: Relation between the heating expenses (in €/m2/year) and the type of energy used in heating (period 2008-2011)

3.2.4 Number of floors

Figure 3.8 and Table 3.2 show the variation of the heating expenses with the number of floors of buildings. We observe the following trends:

- For buildings with than less than 4 floors: the heating expenses decrease with the increase in the floors number (Pearson correlation = -0.29; P-value = 0.09)
- For Buildings with 4 to 8 floors: increase in the heating expenses with the increase in the number of floors (Pearson correlation = 0.73; P-value = 0.01)
- For Buildings with more than 8 floors: a larger dispersion in the heating expenses regarding the buildings number of floors, (P-value = 0.90)

Globally, these results show that the 4-floor buildings correspond to the optimal energy efficiency.

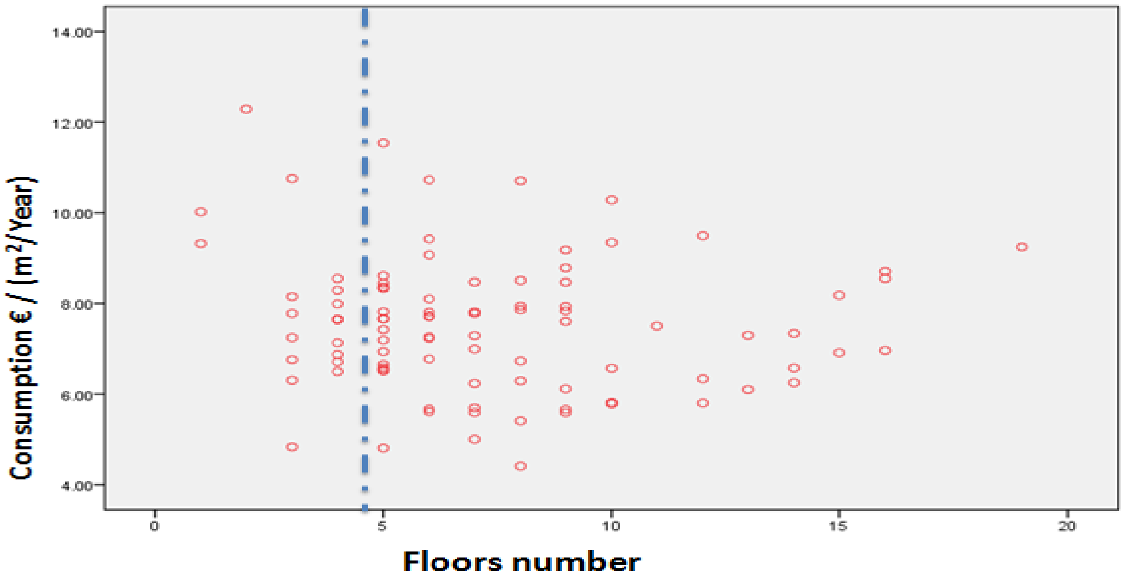

Figure 3.8: Relation between the heating expenses (in €/m2/year) and the and the number of floors (period 2008-2011)

Table 3.2: Relation between the heating expenses (in €/m2/year) and the number of floors (period 2008-2011)

	Number of floors (0-4)	Number of floors (4-8)	Number of floors (more than 8)
Heating consumption per m^2 in 2011	-0.29^{*} (0.09)	0.733^{**} (0.01)	0.02 (0.90)

The numbers between parentheses are confidence error for significant test.

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.10 level (2-tailed).

Figure 3.9 shows the variation of the heating expenses with the buildings Vertical Ratio (VR):

$$VR = \frac{Number of floors}{Used space area} * 100$$

We can observe a high dispersion in the heating expenses with the buildings Vertical Ratio (VR), which indicates the absence of correlation between these parameters.

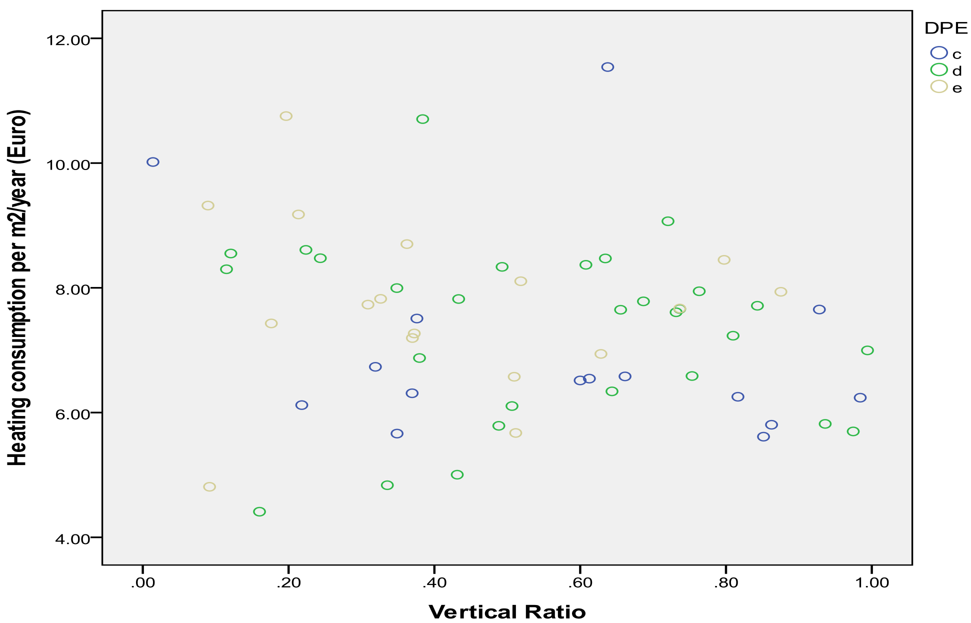

Figure 3.9: Relation between the heating expenses €/m2/year) and the building vertical ratio

3.3 Relation between DPE and the heating consumption

The DPE (Energy Performance Diagnostic) classification depends on the physical characteristics of buildings. This parameter is widely used as an indicator of the building energy efficiency. The DPE used in this study were determined using technical standards.

Figure 3.10 and Table 3.3 show a comparison between the consumption of buildings related to the DPE to that recorded consumption. We observe a large gap between the DPE and the recorded consumption. The DPE overestimates the building consumption in about 65% of the LMH stock and under-estimates this consumption in about 15% of this stock.

Figure 3.11 shows the relation between the DPE values determined using the technical method (X – Axis) and the real consumption (Y – Axis). It can be observed that:

- A good agreement in the "category C", except 2 buildings, which are in category D.
- A good agreement in the "category D", except 1 building in the category E and 8 in the category C.
- Poor agreement in the "category E"; the majority of buildings are in category D or C.

This analysis shows that the determination of the DPE for existing buildings should be based on recorded data, which give a more reliable estimation of the buildings energy efficiency.

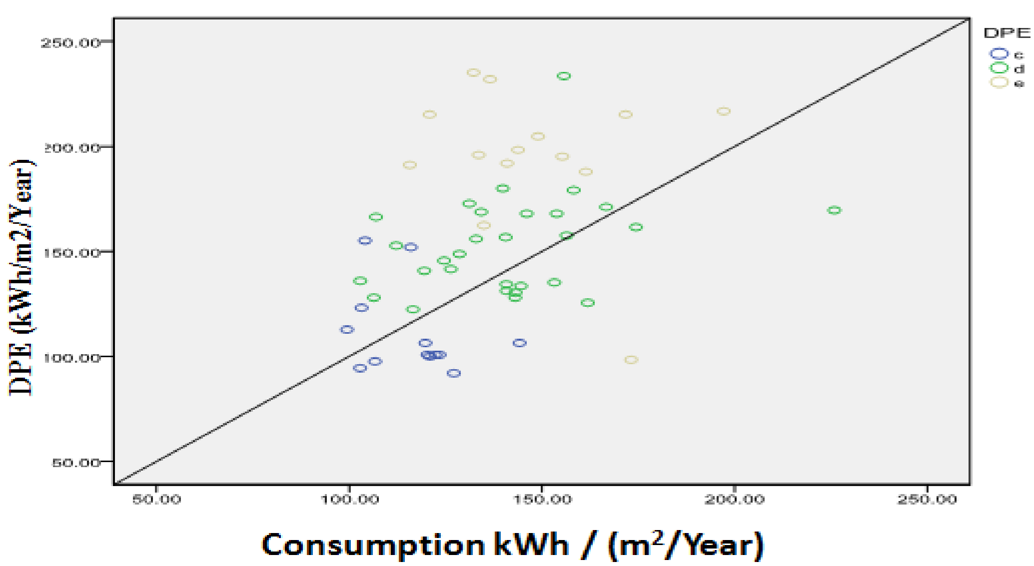

Figure 3.10: Relation between the DPE estimation and the recorded consumption

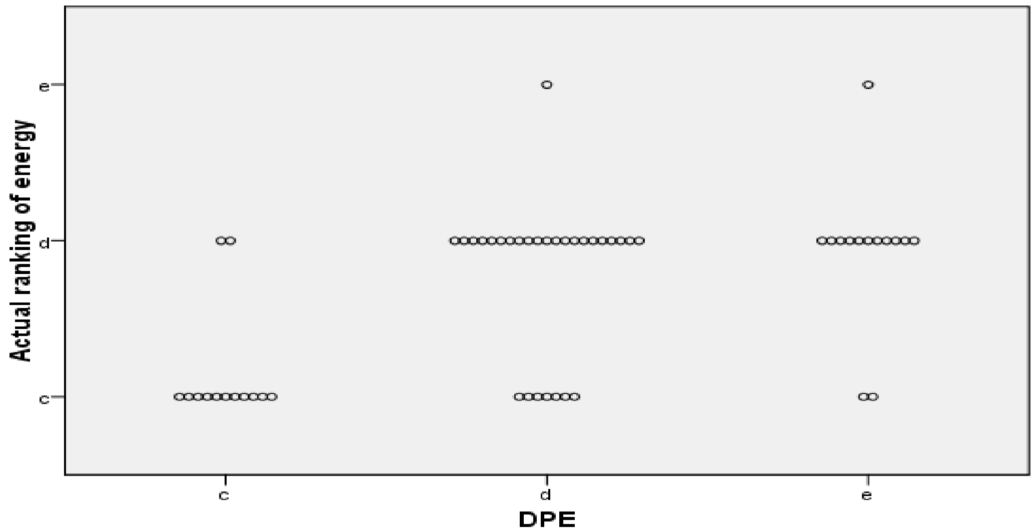

Figure 3.11: The matching between recorded and estimated (DPE) heating consumption

Table 3.3: The cumulative energy consumption gap between recorded and estimated (DPE) heating consumption

The gap %	No. of residences	%
10→more than 70	34	65.38
10→70	32	55.17
10→50	28	49.12
10→30	18	31.58
10→-10 (Identical)	12	21.05
-10→ -30	11	19.30
-30→50	12	17.54

3.4 Socioeconomic Indicators

3.4.1 Age of tenants

The age of tenants was classified into five groups:

- Group 1, which includes tenants younger than 26 years
- Group 2, which includes tenants between 26 and 40 years
- Group 3, which includes tenants between 41 and 60 years
- Group 4, which includes tenants between 61 and 75 years
- Group 5, which includes tenants older than 70 years.

Figure 3.12 shows the heating expenses (€/m^2/year) with the percentage of tenants for three groups (1 and 2), 3 and (4 and 5). We can observe a global increase in the heating expenses for tenants older than 60 years.

Table 3.4 summarizes the Pearson correlation matrix between the percentage of the tenants' age and the heating expenses. It shows positive correlations for the first, four and fifth groups, but negative correlations for the groups 2 and 3. This result indicates:

- An increase in the heating expenses with the tenants' age for the categories 1 (less than 26 years), 4 (between 61 and 75 years) and 5 (older than 75 years).
- A decrease in the heating expenses with tenants' age for the categories 2 (between 26 and 40 years) and 3 (between 41 and 60 years)

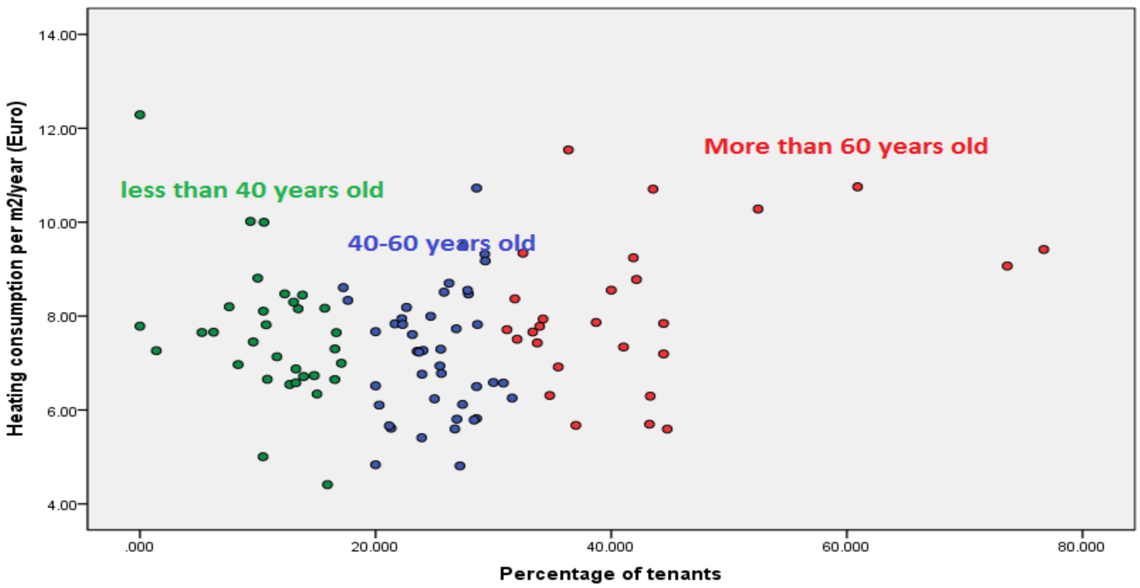

Figure 3.12: Variation of the heating expenses with tenants' age

Table 3.4: Pearson Correlation matrix between percentage of age of tenants and heating expenses

Heating Consumption per m^2	Less than 26 years old	Between 26 and 40 years old	Between 41 and 60 years old	Between 61 and 75 years old	More than 75 years old
2011	.088 (.382)	-.201* (.043)	-.189* (.057)	.158 (.114)	.281*** (.004)
2010	.247** (.012)	-.005 (.962)	-.278*** (.005)	-.011 (.913)	.059 (.553)
2009	.144 (.148)	-.049 (.627)	-.296*** (.003)	.079 (.428)	.197** (.048)
2008	.064 (.520)	-.118 (.237)	-.166* (.096)	.120 (.231)	.190* (.056)
Average (2008-2011)	**.162*** **(.103)**	**-.101** **(.313)**	**-.272**** **(.006)**	**.094** **(.345)**	**.203**** **(0.04)**

The numbers between parentheses are confidence error for significant test.
***. Correlation is significant at the 0.01 level (2-tailed).
**. Correlation is significant at the 0.05 level (2-tailed).
*. Correlation is significant at the 0.10 level (2-tailed).

3.4.2 Family composition

The tenants' family composition was classified into six groups: (1) alone, (2) separated (alone) with one or two children, (3) separated with more than three children, (4) couples, (5) couples with one or two children, and (6) couples with more than three children.

Figure 3.13 summarizes the relationship between the heating expenses and the family size. It shows that the heating expenses of dwellings with more children are lower than others (couples or those living alone). This result is surprising; we do not have enough data to understand it. In a future work, we should explore this result using additional information on the use of heating by the different social categories.

Table 3.5 shows the Pearson correlation matrix between the family size and the heating expenses. Each row shows the year from 2008 to 2011, the final row shows the average for these years. It shows:

- A positive correlation for single tenants (Pearson correlation = 0.18; P-value = 0.70) and couples without children (Pearson correlation = 0.21; P-value = 0.04)
- A negative correlation for single tenants with 1 or 2 children (Pearson correlation = -0.22; P-value = 0.02) and couples with 1 or 2 children (Pearson correlation = -0.22; P-value = 0.03) and couples with more than 3 children (Pearson correlation -0.20; P-value = 0.04)
- An insignificant correlation for the single tenants with more than 3 children (P-value = 0.18).

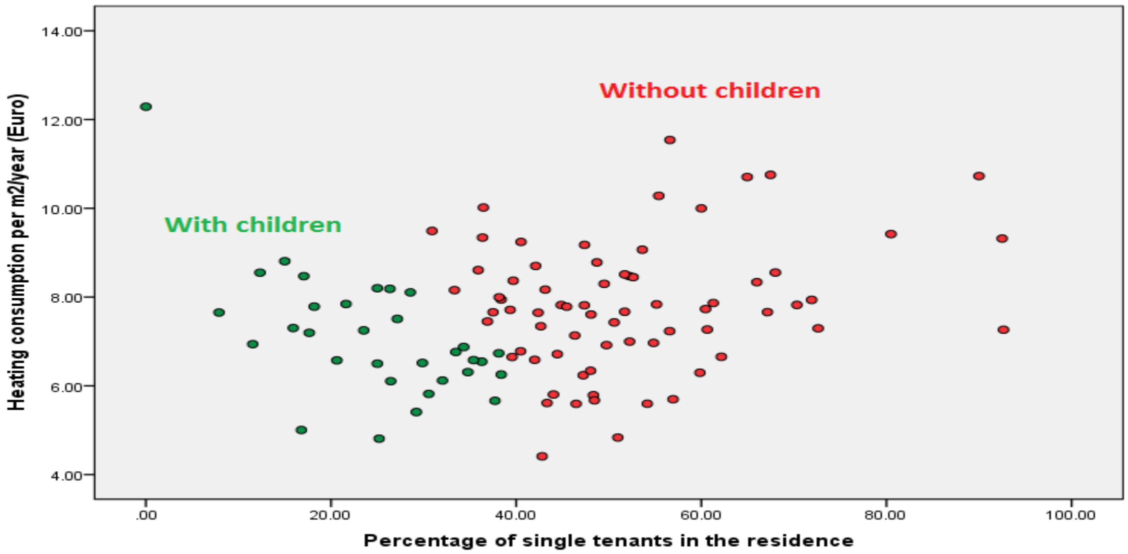

Figure 3.13: Relation between the family composition and the heating expenses (period 2008-2011)

Table 3.5: Pearson correlation matrix between family composition and the heating expenses (period 2008-2011)

Heating Consumption per m^2	Single tenants	Single tenants with 1 or 2 children	Single tenants more than 3 children	Couples tenants	Couples tenants with 1 or 2 children	Couples tenants with more than 3 children
2011	.233** (.019)	-.289*** (.003)	-.146 (.142)	.105 (.292)	-.220** (.027)	-.153 (.125)
2010	-.024 (.812)	-.142 (.154)	-.067 (.500)	.399*** (.000)	-.060 (.546)	-.161 (.107)
2009	.203** (.041)	-.220** (.026)	-.182* (.067)	.255*** (.010)	-.221** (.026)	-.291*** (.003)
2008	.239** (.015)	-.139 (.165)	-.070 (.482)	-.079 (.429)	-.268*** (.007)	-.093 (.354)
Average (2008-2011)	**.180* (.070)**	**.-224** (.023)**	**-.134 (.181)**	**.208** (.036)**	**-.217** (.028)**	**-.204** (.040)**

The numbers between parentheses are confidence error for significant test.
***. Correlation is significant at the 0.01 level (2-tailed).
**. Correlation is significant at the 0.05 level (2-tailed).
*. Correlation is significant at the 0.10 level (2-tailed).

3.4.3 Tents Income

The tenants income in social housing is generally low with small variation. Figure 3.14 shows the variation of the heating expenses (€/m^2/year) during the period 2008–2011 and the ratio if tenants with an income exceeding 40% the maximum resource in social housing. This figure shows a high dispersion, which means that the heating consumption is weakly related to the tenants' income.

Table 3.6 shows the Pearson correlation matrix between the tenants' income and the heating expenses. We observe insufficient correlations for all the tenants' income categories, because for all of these categories the P-value largely exceeds 0.05. This result shows that the heating expenses are weakly related to the tenants' income.

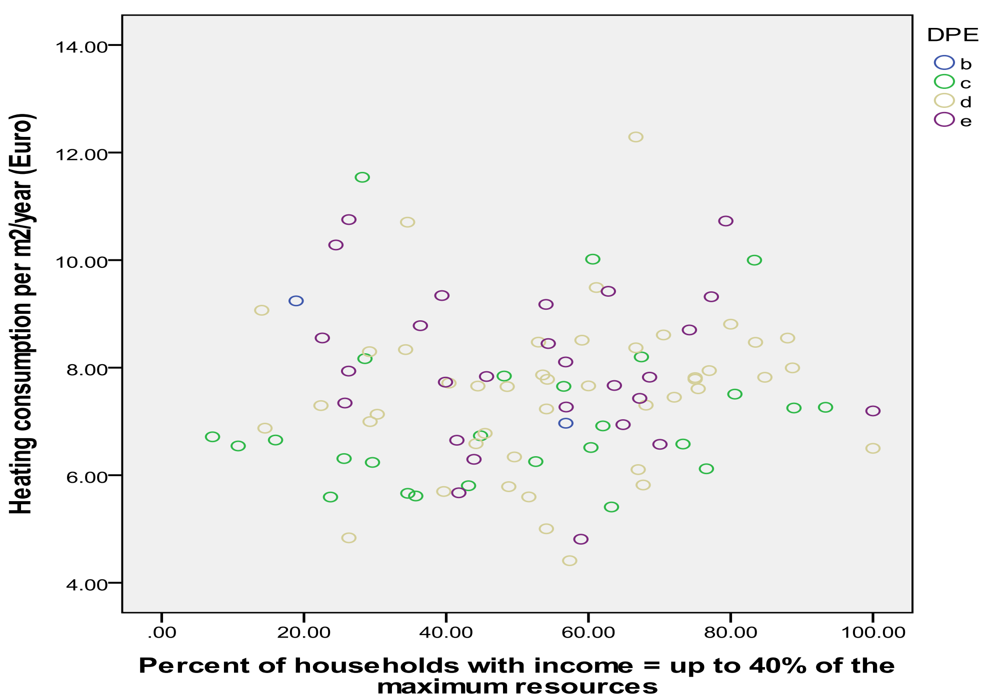

Figure 3.14: Relation between the tenants' income and the heating expenses (period 2008-2011)

Table 3.6: Pearson correlation matrix between income and the heating expenses (2008-2011)

Heating Consumption per m^2	Income = up to 40% of the maximum resource	Income = 40% to 60% of the maximum resource	Income = 60% to100% of the maximum resource	Income = 100% to130% of the maximum resource	Income = more than 130% of the maximum resource
2011	.009 (.929)	-.078 (.435)	-.048 (.633)	.071 (.479)	.168* (.091)
2010	.121 (.225)	-.145 (.146)	-.093 (.353)	-.065 (.518)	.053 (.595)
2009	.009 (.931)	-.013 (.893)	.024 (.813)	-.061 (.545)	-.007 (.942)
2008	.145 (.147)	.013 (.897)	-.222** (.025)	-.054 (.588)	.038 (.701)
Average (2008-2011)	**.084 (.401)**	**-.066 (.507)**	**-.097 (.333)**	**-.036 (.720)**	**.069 (.493)**

The numbers between parentheses are confidence error for significant test.

***. Correlation is significant at the 0.01 level (2-tailed).

**. Correlation is significant at the 0.05 level (2-tailed).

*. Correlation is significant at the 0.10 level (2-tailed).

3.5 Conclusion

This chapter presented the analysis of the heating expenses in the LMH housing stock and the study of the influence of available parameters on these expenses. Analysis covered the influence of the following parameters: DPE, year of construction, dwellings' area, number of floors, tenants' age, family composition, and tenants' income.

Globally, we obtained large scattering, which could result from the cross influence of multiple indicators . However, some interesting trends were observed, mainly:

- A poor correlation between the DPE and the recorded consumption
- The heating expenses per m^2 decrease with the increase in the dwellings age
- The heating expenses per m^2 decrease with the increase in the dwelling' area
- The optimal heating consumption is observed in 4-floor buildings
- Tenants older than 60 years consume more heating than younger tenants
- Tenants with children consume less heating than the tenants without children
- The tenants' income has insignificant influence on the heating consumption.

In next chapter, we present the development of mathematical models for the prediction of the heating expenses using the classical Ordinary Least Squares method (OLS) and the Artificial Neural Networks (ANN).

Chapter 4: Numerical Modeling of the Heating Expenses in the LMH Housing Stock

4.1 Introduction

This chapter presents the elaboration of prediction models for the heating expenses in the LMH housing stock and the use of these models to analyze the investment policy in the renovation of this stock.

Models are developed using the data presented in the third chapter, these data concern of collective residences equipped by collective heating system. The heating expenses data covered the period from 2008 to 2011. The input parameters are split into two categories:

- Physical parameters, which concern the age of buildings, the DPE, the number of floors and the dwellings area.
- Socio-economic parameters, which concern the age of tenants, their marital status and income.

Analyses were conducted using the IBM SPSS program version 19 (SPSS/ IBM version 19, 2010;SPSS/IBM Statistics 20 Brief Guide, 2011). SPSS is Statistical Package for the Social Sciences. This program is largely used in statistical analysis in social science (http://www-03.ibm.com/software/products/en/spss-advanced-stats;http://www-01.ibm.com). It is used in this study for descriptive statistics, Ordinary Least Squares modeling (OLS) and Artificial Neural Networks modeling (ANN).

Two methods are used in this chapter. The first one is based on the classical Ordinary Least Squares method (OLS), while the second uses the Artificial Neural Networks (ANN) (https://www.csun.edu/sites/default/files/neural-network20-32bit.pdf;
http://www.chsbs.cmich.edu/fattah/courses/empirical/29.html) For each method, we present modeling concerning successively the physical parameters (model A), the socio-economic parameters (model B), and both the physical and socio-economic parameters (model C)

4.2 Ordinary Least Squares method (OLS)

4.2.1 Presentation of the method

The linear regression model assumes a linear relationship between the output variable y and the input parameters x:

$$y_i = \beta_1 x_{i1} + \cdots + \beta_p x_{ip} \quad i = 1, \ldots, n,$$

In this work, we used normalized variables according to the following normalization expression:

$$x_{ni} = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

We used R-Square R^2 as criteria for the performances of the numerical modeling. The calculation of R^2 is conducted according to the following expressions:

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

$SS_{tot} = \sum_i (y_i - \bar{y})^2$: the total sum of squares (proportional to the sample variance);

$SS_{reg} = \sum_i (\hat{y}_i - \bar{y})^2$: the regression sum of squares, also called the explained sum of squares ($\hat{y}_i$: predicted value)

$SS_{res} = \sum_i (y_i - \hat{y}_i)^2$: The sum of squares of residuals, also called the residual sum of squares.

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$$

R^2 ranges from 0 to 1. The quality of modeling increases with the increase in the value of this coefficient.

The adjusted R^2 statistic is the same as the R^2 except that it takes into account the number of independent variables (k). The adjusted R^2 will increase, decrease or stay the same when a variable is added to an equation depending on whether the improvement in fit, outweighs the loss of the degree of freedom (n-k-1):

$$Adusted\ R^2 = 1 - (1 - R^2) * (\frac{n-1}{n-k-1})$$

The adjusted R^2 is useful when comparing regression models with different numbers of independent variables.

We use a global test that encompasses all coefficients (β's) and test the following hypothesis:

$$H_0 : \beta_1 = \beta_2 \ldots = \beta_k = 0$$

$$H_\alpha : at\ least\ one\ \beta_j \neq 0$$

The F statistic is the ratio of the explained variability to the unexplained variability, adjusted for the number of independent variables (k) and the degrees of freedom (n-k-1):

$$F = \frac{R^2/K}{(1 - R^2)/[n - (K + 1)]}$$

The F statistic allows users to determine whether the whole model is statistically significant. And then we use P-value to find the significance level for this model (the p-value is the probability of obtaining a test statistic result at least as extreme or as close to the one that was actually observed, assuming that the null hypothesis is true. The user will "reject the null hypothesis" when the p-value turns out to be less than a predetermined significance level, often 0.05 or 0.01) (Stigler, 2008; Dallal, 2012).

4.2.2 Model A (Physical parameters)

Input parameters

This model uses the following input parameters: age of buildings, DPE, number of floors and the dwellings area. Table 4.1 summarizes these parameters as well as their statistical characteristics (Max, Min, Average and Standard deviation). We can observe that the average age is equal to 35 years, the maximum is equal to 62 years and the minimum to 7 years. The average of the DPE is equal to 200 kW/m^2/year, the maximum is equal to 344 kW/m^2/year and the minimum to 98 kW/m^2/year. The average of the number of floors is equal to 3.4, the maximum to 15 and the minimum to 0. Finally, the average of the dwelling area is equal to 62.6 m^2, the maximum to 84.4 m^2 and the minimum to 36.9 m^2.

Table 4.1: Parameters used in the model A (Physical Parameters)

Parameter	Designation	Unit	Max	Min	Average	Standard deviation
X1	Age of building	Year	62	7	34.64	12.49
X2	DPE	kW/m^2/year	344	98	200.31	56.85
X3	Number of floors	-	15	0	6.33	3.4
X4	Dwellings area	Square meter	84.39	36.93	62.56	8.95

Test of orthogonality of input parameters (correlation matrix)

Table 4.2 shows the results of the test of orthogonality of these parameters (DPE, Number of floors and Dwelling area). We observe:

- A significant positive correlation between the DPE and the buildings' age, the Pearson correlation is equal to 0.48 (P-value = 0.000).
- A significant positive correlation between the building age and the number of floors; the Pearson correlation is equal to 0.56 (P-value = 0.000)
- A significant negative correlation between the age of building and the dwellings area; the Pearson correlation is equal to -0.19 (P-value = 0.000).
- A low correlation between the DPE and the number of floors (P-value = 0.685).

- A negative correlation between the DPE and the dwellings' area; the Pearson correlation is equal to -0.21 (P-value = 0.056).
- An insignificant correlation between the number of floors and dwelling area (P-Value = 0.807)

Table 4.2: Correlation matrix of the input parameters used in the model A (Physical Parameters)

	Age of building	DPE	Number of floors	Dwelling area
Age of building		0.484*** (0.000)	0.556*** (0.000)	-0.190*** (0.000)
DPE			-0.045 (0.685)	-0.210* (0.056)
Number of floors				-0.027 (0.807)

The numbers between parentheses are confidence error for significant test (P-value).

***. Correlation is significant at the 0.01 (2-tailed).

**. Correlation is significant at the 0.05 (2-tailed).

*. Correlation is significant at the 0.10 (2-tailed).

Results

Figure 4.1 and Table 4.3 show the results of the linear regression approximation. It can be observed that the value of R^2 is equal to 0.37, which means that the model does not reproduce well the heating expenses using only physical parameters as input data. The F test and P-value analyses show that the model is significant at 0.95 confidence level. The F–value is equal to 11.69 and the P-value is close to zero.

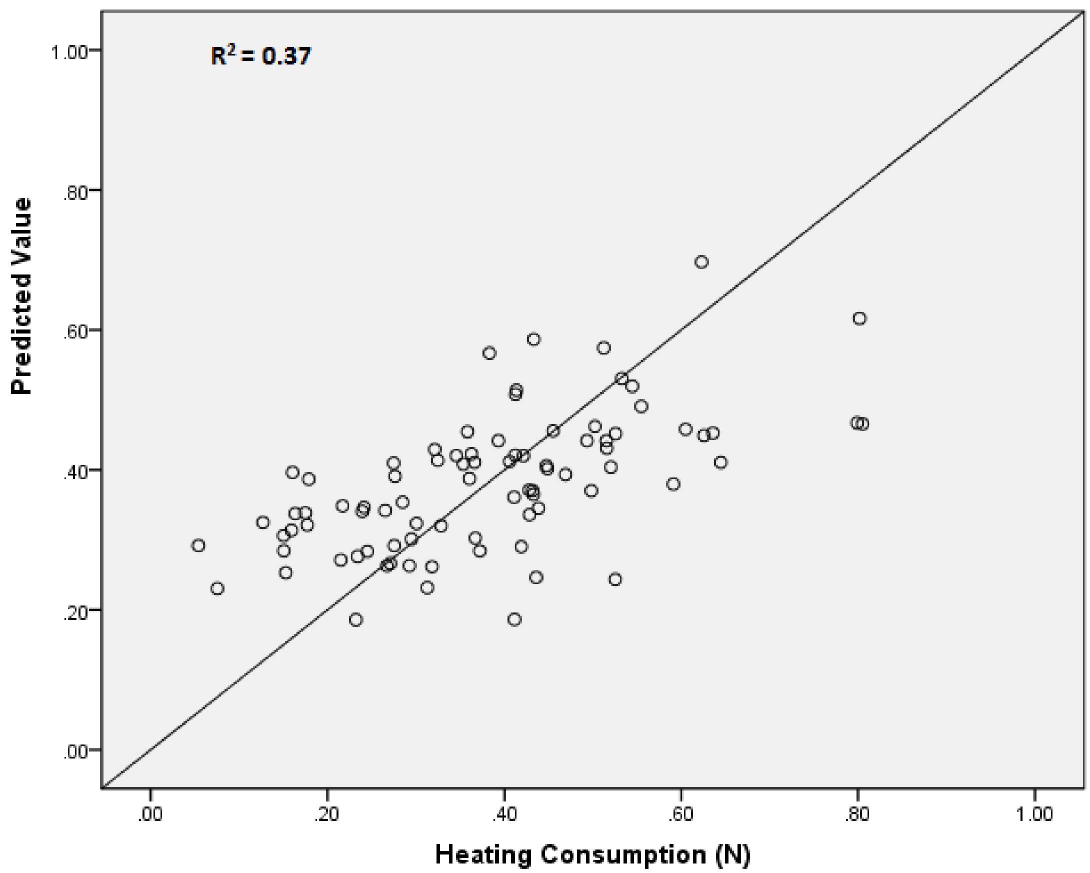

Figure 4.1: Result of the OLS Regression – Model A

Table 4.3: Results of the OLS regression (model A)

R^2	0.372
Adjusted R^2	0.340
Std. Error of the Estimate	0.130
F calculated	11.691
P-value	0.000

Table 4.4 provides the values of the linear regression coefficient as well as the t-value and P-value.

The value of the coefficient A1 (related to the building age) is equal to 0.21, the t-value and P-value are equal to 2.19 and 0.031, which indicate that when the buildings' age increases the heating expenses increases, this relation is significant in the confidence level 0.95. The value of coefficient A2 (related to the DPE) is equal to 0.108, the t-value and P-value are equal to 1.499 and 0.138, which indicate that there is insignificant correlation between DPE and heating expenses in the confidence level 0.95 (P- value > 0.05). The value of A3 (related to the number of floors) is equal to -0.227, the t-value and P-value are equal to -2.265 and 0.026, which indicate that when number of floors increases the heating consumption decreases. It means that high buildings consume less than low buildings. A significant correlation exists between the number of floors and the heating expenses in the confidence level 0.95 (P- value < 0.05).

The value of A4 (related to the area per dwelling) is equal to -0.395, the t-value and P-value are equal to -4.281 and 0.000, which indicate that when the dwellings' area increases, the heating consumption decreases. This result could be attributed to the presence of higher ratio per square meter of dwelling services (bathroom, kitchen).

Table 4.4: Results of OLS regression (model A)

Coefficient	Coefficient	t-value	P-value
Y_0 (Constant)	0.513	7.297	0.000
A1 (Building age)	0.213	2.196	0.031
A2 (DPE)	0.108	1.499	0.138
A3 (Number of floors)	-0.227	-2.265	0.026
A4 (Area)	-0.395	-4.281	0.000

4.2.3 Model B (Socio-economic parameters)

Input parameters

This model uses the following input parameters: tenants' age, marital status and income. Table 4.5 summarizes these parameters as well as their statistical characteristics (Max, Min, Average and Standard deviation).

Table 4.5: Input parameters used in model B (socio-economic parameters)

Parameter	Designation	Unit	Max	Min	Average	Standard deviation
X1	Ratio of tenants older than 60 years old	%	76.71	0	26.62	13.27
X2	Ratio of single tenants	%	92.50	7.89	44.34	17.22
X3	Ratio of tenants with income lower than 40% of the maximum resources	%	100	7.14	52.7	21.41

Table 4.6 shows the analysis of the orthogonality of the socio-economic parameters based on the correlation matrix. It shows

- A significant positive correlation between the ratio of tenants older than 60 years and the ratio of single tenants; the Pearson correlation reached is equal to 0.308 and the P-value = 0.004. This result indicates that with the increase in the age, the tenants become more likely to live alone.
- An insignificant correlation between the ratio of tenants older than 60 years and the ratio of tenants with income lower than 40% of the maximum resources (P-value = 0.467).

- A significant negative correlation between the ratio of single tenants and the ratio of tenants with income lower than 40% of the maximum resources. The Pearson correlation reached is equal to -0.323 (P-value = 0.003).

Table 4.6: Input parameters used in model B (Socioeconomic Parameters)

	Ratio of tenants older than 60 years old		Ratio of tenants with income lower than 40% of the maximum resources
Ratio of tenants older than 60 years		0.308*** (0.004)	-0.08 (0.467)
			-0.323*** (0.003)

The numbers between parentheses are confidence error for significant test (P-value).

***. Correlation is significant at the 0.01 level (2-tailed).

**. Correlation is significant at the 0.05 level (2-tailed).

*. Correlation is significant at the 0.10 level (2-tailed).

Results

Figure 4.2 and Table 4.7 show the results of the linear regression approximation. It can be observed that R^2 is equal to 0.21, which means that the model does not reproduce well the heating expenses using the socioeconomic parameters as input data. The ANOVA analysis shows that the model is significant at 0.95 confidence level. The F–value is equal to 7.68 and the P-value is close to zero.

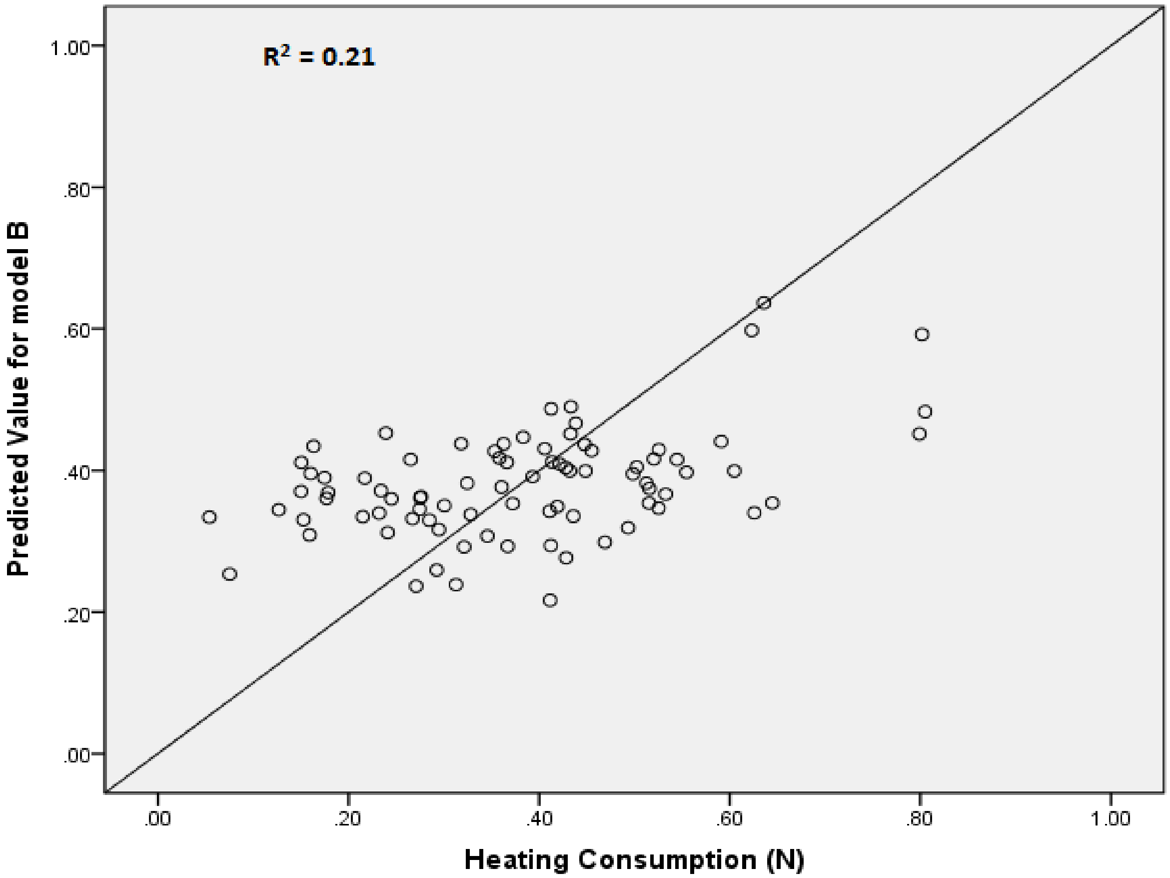

Figure 4.2: Result of the OLS Regression – Model B

Table 4.7: Results of the OLS regression (model B)

R^2	0.21
Adjusted R^2	0.18
Std. Error of the Estimate	0.145
F calculated	7.068
P-value	0.000

Table 4.8 provides the values of the linear regression coefficients as well as the t-value and P-value.

The value of the coefficient A1 (related to the Tenants age) is equal to 0.205; the t-value and P-value are equal to 1.810 and 0.074, respectively. This result indicates that when the tenants' age increases the heating expenses increases (this relation is significant in the confidence level 0.90).

The value of coefficient A2 is equal to 0.108, the t-value and P-value are equal to 3.275 and 0.0.002, respectively. This result indicates that when the ratio of single tenants increases, the heating expenses increases (this relation is significant in the confidence level 0.95).

The value of A3 (related to the low income tenants) is equal to 0.188; the t-value and P-value are equal to 2.569 and 0.012, respectively. This result indicates that when the ratio of low-income tenants increases the heating expenses increase.

Table 4.8: Results of OLS regression (model B)

Coefficient	Coefficient	t-value	P-value
Y_0 (Constant)	0.120	1.961	0.053
A1 (Ratio of tenants older than 60 years old)	0.205	1.810	0.074
A2 (Ratio of single tenants)	0.273	3.275	0.002
A3 (Ratio of tenants with income lower than 40% of the maximum resources)	0.188	2.569	0.012

4.2.4 Model C (physical and socio-economic parameters)

Input parameters

This model uses both physical and socio-economic parameters presented in the previous sections (4.2.2 and 4.2.3) and summarized in Table 4.9.

Table 4.9: Parameters used in model C (physical and socio-economic parameters)

Parameter	Designation	Unit	Max	Min	Average	Standard deviation
X1	Age of building	Year	62	7	34.64	12.49
X2	DPE	-	344	98	200.31	56.85
X3	Number of floors	-	15	0	6.33	3.4
X4	Dwellings area	Square meter	84.39	36.93	62.56	8.95
X5	Ratio of tenants older than 60 years old	%	76.71	0	26.62	13.27
X6	Ratio of single tenants	%	92.5	7.89	44.34	17.22
X7	Ratio of tenants with income lower than 40% of the maximum resources	%	100	7.14	52.70	21.41

Table 4.10 shows the analysis of the orthogonality test. It shows:

- A significant positive correlation between the DPE and the buildings' age; the Pearson correlation is equal to 0.484 and the P-value = 0.000.
- A significant positive correlation between the number of floors and the buildings' age; the Pearson correlation is equal to 0.556 and the P-value = 0.000.
- A significant negative correlation between the dwellings' area and the buildings' age; the Pearson correlation is equal to -0.190 and the P-value = 0.000.

- A positive correlation between the ratio of tenants older than 60 years old and the buildings' age; the Pearson correlation is equal to 0.221 and the P-value = 0.043.
- Insignificant correlation between the ratio of single tenants and the buildings' age (P-value = 0.718).
- A significant positive correlation between the ratio of low-income tenants and the buildings' age; the Pearson correlation is equal to 0.237 and the P-value = 0.030.
- Insignificant correlation between the DPE and the number of floors (P-value = 0.685).
- A negative correlation between the DPE and the dwellings' area; the Pearson correlation is equal to -0.210 and the P-value = 0.056.
- Insignificant correlation between the DPE and the ratio of tenants older than 60 years old (P-value = 0.252).
- A positive correlation between the DPE and the ratio of single tenants; the Pearson correlation is equal to 0.233 and the P-value = 0.033.
- Insignificant correlation between the DPE and the ratio of low-income tenants (P-value = 0.410).
- Insignificant correlations between the number of floors and the (i) dwellings area (P-value = 0.807); (ii) the ratio of tenants older than 60 years old (P-value = 0.338) and (iii) the ratio of low-income tenants ((P-value = 0.745).
- Insignificant correlation between the dwellings' area and the ratio of tenants older than 60 years old (P-value = 0.269).
- A significant negative correlation between the dwellings' area and the ratio of single tenants; the Pearson correlation is equal to -0.593 and the P-value = 0.000.
- A significant negative correlation between the dwellings' area and the ratio of low-income tenants; the Pearson correlation is equal to -0.248 and the P-value = 0.023).
- A significant positive correlation between the ratio of tenants older than 60 years old and the ratio of single tenants; the Pearson correlation is equal to 0.308 and the P-value = 0.004.
- Insignificant correlation between the ratio of tenants older than 60 years and the ratio of low-income tenants (P-value = 0.467).

- A significant negative correlation between the ratio of single tenants and the ratio of low-income tenants; the Pearson correlation is equal to -0.323 and the P-value = 0.003.

Table 4.10: Input parameters used in model C (the physical and socio-economic parameters)

	Age of building	DPE	Number of floors	Dwelling area	Ratio of tenants older than 60 years old	Ratio of single tenants)	Ratio of tenants with income lower than 40% of the maximum resources
Age of building		0.484*** (0.000)	0.556*** (0.000)	-0.190*** (0.000)	0.221** (0.043)	0.040 (0.718)	0.237** (0.030)
DPE			-0.045 (0.685)	-0.210* (0.056)	0.126 (0.252)	0.233** (0.033)	0.091 (0.410)
Number of floors				-0.027 (0.807)	0.106 (0.338)	-0.069 (0.530)	0.036 (0.745)
Dwelling area					-0.122 (0.269)	-0.593*** (0.000)	-0.248** (0.023)
Ratio of tenants older than 60 years old						0.308*** (0.004)	-0.080 (0.467)
Ratio of single tenants							-0.323*** (0.003)

The numbers between parentheses are confidence error for significant test (P-value).

***. Correlation is significant at the 0.01 level (2-tailed).

**. Correlation is significant at the 0.05 level (2-tailed).

*. Correlation is significant at the 0.10 level (2-tailed).

Results

Figure 4.3 and table 4.11 show the results of the linear regression analysis. It can be observed that the R^2 is equal to 0.405, which means that the model improves the modeling quality with regards to that conducted with the previous two models. The F test and P-value analysis show that the model is significant at 0.95 confidence level. F–value is equal to 7.389, the P-value is close to zero.

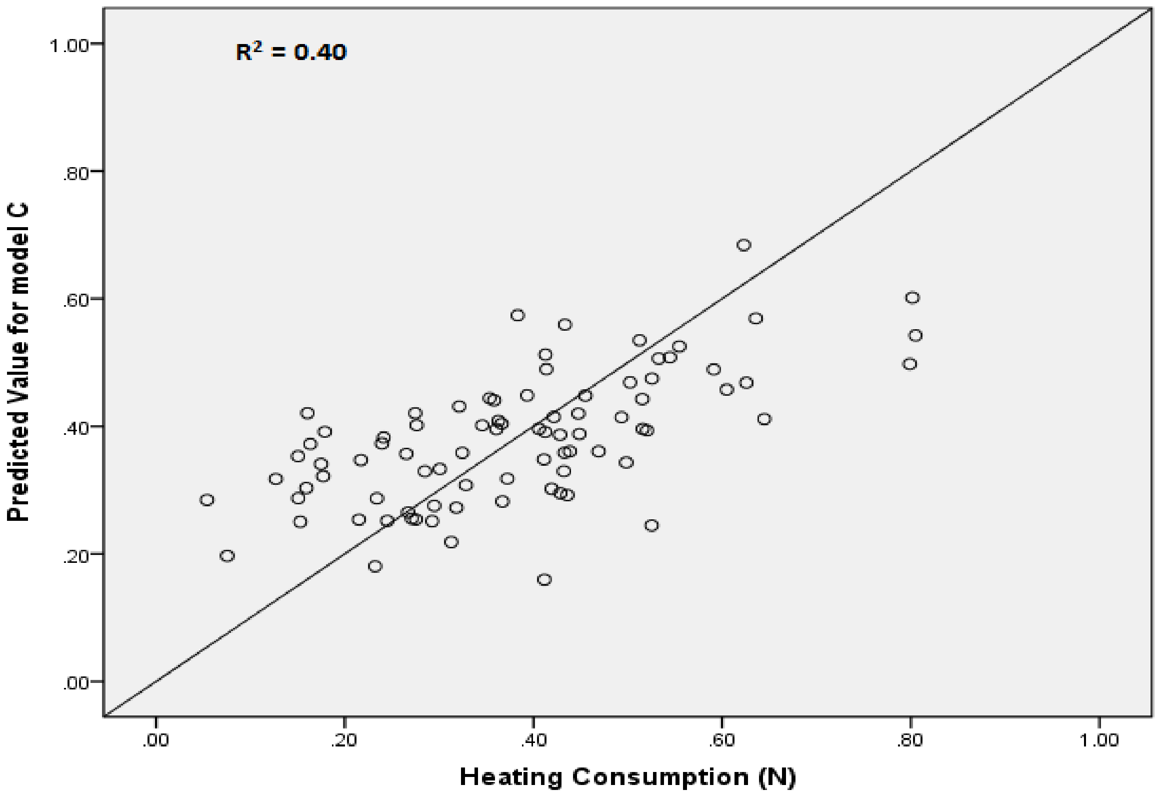

Figure 4.3: Result of the OLS Regression – Model C

Table 4.11: Results of OLS regression (Model C)

Indicator	**Value**
R^2	0.405
Adjusted R^2	0.350
Std. Error of the Estimate	0.129
F-value	7.389
P-value	0.000

Table 4.12 provides the values of the linear regression as well as the t-value and P-value.

- The value of the coefficient A1 (related to the building age) is equal to 0.185; the t-value and P-value are equal to 1.835 and 0.070, respectively. This result confirms that obtained in the previous section: increase in the heating expenses with the increase in the dwellings' age.
- The value of A2 (related to the DPE) is equal to 0.113, the t-value and P-value are equal to 1.542 and 0.127, respectively. This result confirms that obtained in the previous section: insignificant correlation between the DPE value and the heating expenses.
- The value of A3 (related to the number of floors) is equal to -0.229, the t-value and P-value are equal to -2.272 and 0.026, respectively. This result confirms that obtained in the previous section: decrease in the heating expenses with the increase in the number of floors.
- The value of A4 (related to the dwellings' area) is equal to -0.421, the t-value and P-value are equal to -3.079 and 0.003, respectively. This result confirms that obtained in the previous section: decrease in the heating expenses with the increase in the dwellings' area.
- The value of A5 (related to the ratio of old tenants) is equal to 0.209; the t-value and P-value are equal to 2.002 and 0.049, respectively. This result indicates is slightly different from that obtained in the previous section (P- value < 0.074).
- The value of A6 (related to the ratio single tenants) is equal to -0.044, the t-value and P-value are equal to -0.395 and 0.694, respectively. This result confirms that obtained in the previous section (insignificant correlation between the heating expenses and the ratio of single tenants).

- The value of coefficient A7 (related to the low income tenants) is equal to -0.026, the t-value and P-value are equal to -0.316 and 0.753, respectively. This result indicates insignificant correlation between the heating expenses and the ratio of low-income tenants. It is different from that obtained in the previous section (significant positive correlation between heating expenses and the ratio of low-income tenants)

Table 4.12: Results of the OLS regression (Model C)

Parameter	Coefficients	t -value	P-value
Y_0 (Constant)	0.510	3.608	0.001
A1 (Building age)	0.185	1.835	0.070
A2 DPE	0.113	1.542	0.127
A3 (Number of floors)	-0.229	-2.272	0.026
A4 (Area)	-0.421	-3.079	0.003
A5 (Tenants age more than 60)	0.209	2.002	0.049
A6 (single tenants)	-0.044	-0.395	0.694
A7 (low income tenants)	-0.026	-0.316	0.753

4.3 Artificial Neural Networks

4.3.1 Presentation of the Artificial Neural Networks

The Artificial Neural Networks approach (ANNs) constitutes a powerful tool for the analysis and modeling of complex physical or social phenomena by using observational data. It allows the construction of relationship between the input variables (parameters affecting the phenomena) and the output variables (parameters characterizing the phenomena). This approach mimics the ability of the human brain in predicting patterns based on learning and recalling processes (Najjar et al., 1997; Al-Barqawi & Zayed 2006). It includes artificial neurons known as "processing elements", "nodes" or "neurons". Processing elements in ANNs are usually arranged in layers: an input layer, an output layer and one or more intermediate layers called hidden layers. Each layer includes individual neurons such as that depicted in Fig. 4.4. ANN application refers to the interconnections between input and output variables by connecting the neurons in the different layers (hidden layers).

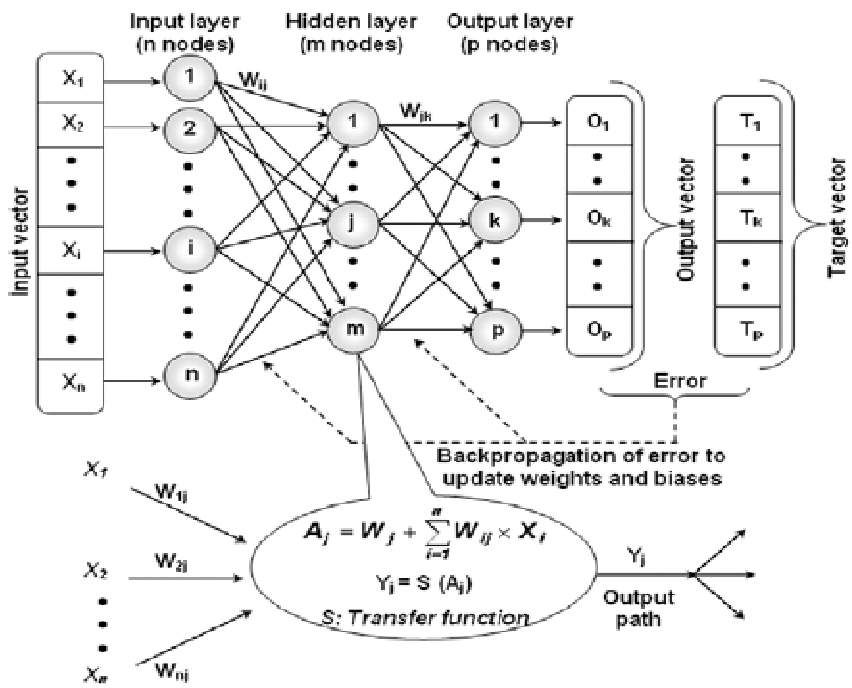

Figure 4.4: Typical multilayer back-propagation Artificial Neural Network.

This study uses the multilayer back-propagation neural network (BPNN). Figure 4.4 presents a typical three-layer back-propagation neural network. Mathematically, a three-layer ANN with n, m, and p as the number of input, hidden and output nodes, respectively, is based on the following equation:

$$Y_k = S\left(\sum_{j=1}^{m} W_{jk} \times S\left(\sum_{i=1}^{n} W_{ij} X_i\right)\right)$$

Where Y_k stands for the output values and $X_i$denotes the input values; W_{ij} gives the weights of connection between the input layer and the hidden layer.

The determination of the network architecture constitutes one of the major and difficult tasks in the use of the ANN. The overall performance of an ANN model depends on the numbers of hidden layers and hidden nodes. The optimal ANN structure is generally determined by fixing the number of layers and the number of nodes in each layer. It has been shown that one hidden layer is sufficient for approximating any continuous function (Hornik, Stinchcombe & White, 1989; Hecht-Nielsen, 1989) provided arguments that a single hidden layer of neurons, operating a sigmoidal activation function, is adequate for modeling any solution surface of practical interest. In some applications, one hidden layer is commonly used (Najjar, Basheer & Hajmeer, 1997).

4.3.2 Data reparation (training, testing and validation)

The use of the ANNs approach is based in splitting the data into three sets:

- The training set, which is used to train the neural network and adjust the connection weights.
- The testing set, which measures the ability of the model to be generalized; the performance of the model is checked during this phase, which is also used to determine the optimum network architecture.
- The holdout set, which is used to determine the performance of a neural network on patterns, which were not used in the previous phases.

Table 4.13 shows the scenarios tested in the model. Since scenario 5 gives the best results (R^2 = 0.48 in model A and 0.74 in model C), it will be used in the analyses presented below. Table 4.14 shows the repartition that used in the ANN model : 74% for training, 18% for testing and 8% for validation.

Table 4.13: Determination of the optimal data repartition in the ANN modeling

Repartition Scenarios	% of training	% of testing	% of Holdout	Total R^2 for physical parameters	Total R^2 for physical +socioeconomic parameters
1	50	25	25	0.46	0.71
2	70	30	0	0.43	0.58
3	100	0	0	0.46	0.72
4	66	26	8	0.48	0.67
5	**74**	**18**	**8**	**0.48**	**0.74**

Table 4.14: Repartition of data in the ANN modeling

	Number of residences	**Number of dwellings**	**%**
Training	62	8986	74%
Testing	15	3296	18%
Holdout	7	897	8%
Total	84	13179	100%

4.3.3 Model A (Physical parameters)

The description and analysis of the input parameters were given in Section 4.2.2.

Table 4.15 and Figure 4.5 present the results obtained with different configurations of hidden layers. Results show slight influence of the configuration architecture on the modeling performance. The value of R^2 is around 0.47, which means that this model is not accurate. However, this value is better than that obtained by the OLS method (R^2 = 0.37).

The configuration 1 (1 hidden layer with 2 neurons) provides the best results (R^2 = 0.48). Table 4.16 provides the coefficients of connections in the neural network. For example, H (1:1) designates the weight of the connection between the input cell 1 and the 1st cell in the hidden layer.

Table 4.15: Determination of the optimal ANN architecture (model A)

Model	No. of Hidden layers	No. of nodes	Training Sum of squares error	Testing Sum of squares error	Training R^2	Testing R^2	Total R^2
A1	1	2	18.14	3.04	0.595	0.356	0.48
A2	1	3	18.12	3.02	0.594	0.354	0.47
A3	2	3-2	17.62	2.95	0.579	0.346	0.47

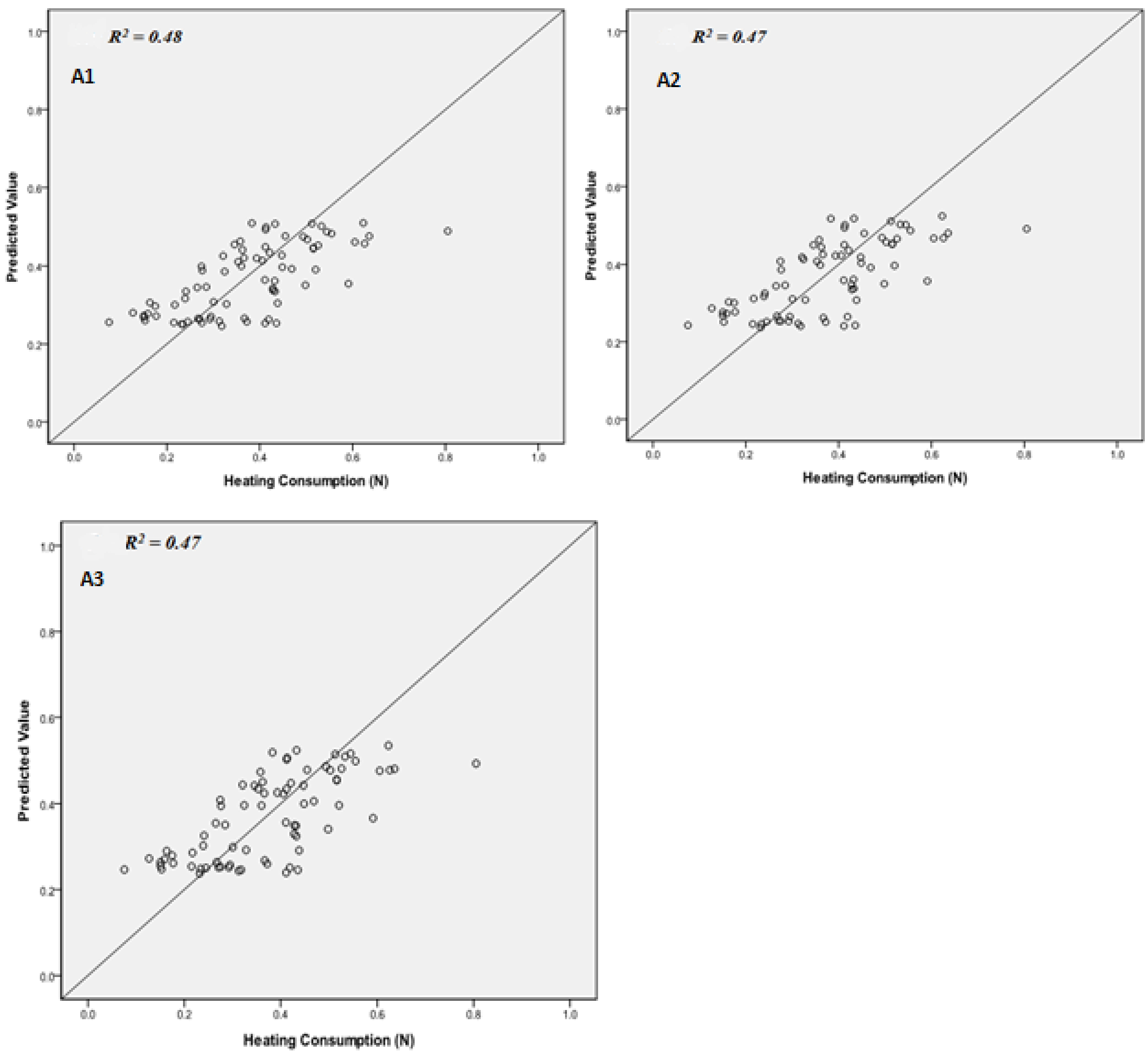

Figure 4.5: Result of the ANN modeling (Model A, physical parameters)

Table 4.16: Weights of connections in the neural network (model A1)

Predictor		Predicted		
		Hidden Layer 1		Output Layer
		H(1:1)	H(1:2)	HCC
Input Layer	(Bias)	.238	-.157	
	Building Age	.113	.381	
	DPE	.129	.403	
	Number of floors	-.352	-.526	
	Area	.362	-.806	
Hidden Layer 1	(Bias)			.095
	H(1:1)			.068
	H(1:2)			.965

Figure 4.6 indicates the weight of each input parameters on the ANN model prediction. This result is compared to that obtained by the OLS method in Figure 4.7. It can be observed that the results obtained with these methods are close. The dwellings' area has the highest weight, followed by the number of floors, the DPE and the buildings' age.

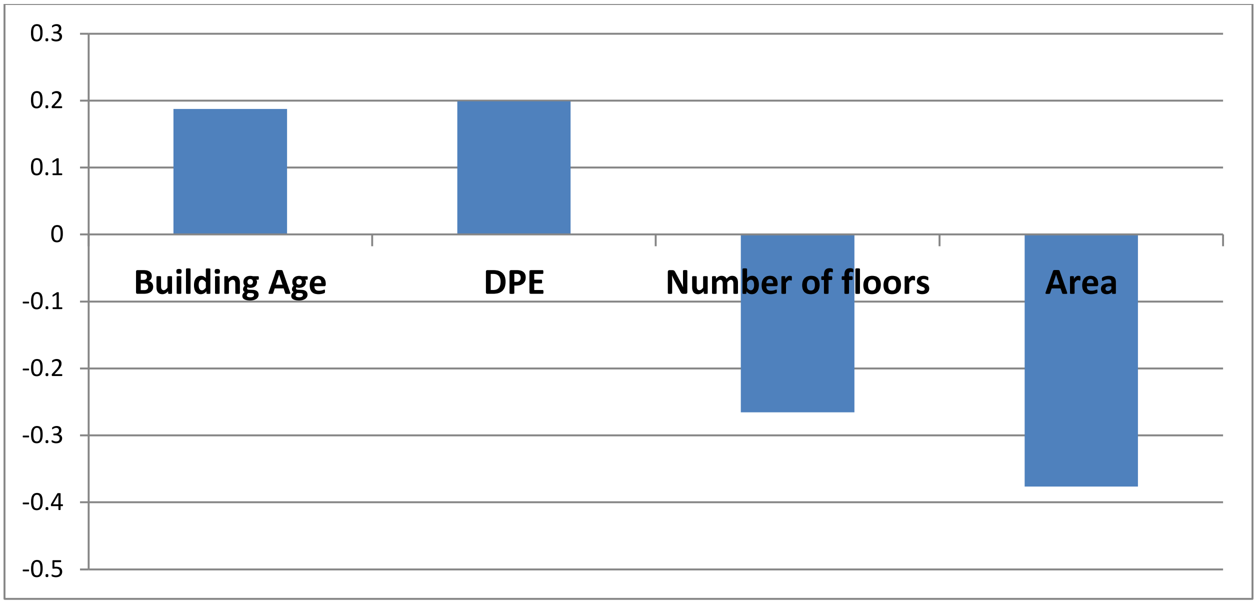

Figure 4.6: Importance value of the indicators for ANN methods (Building Characters model)

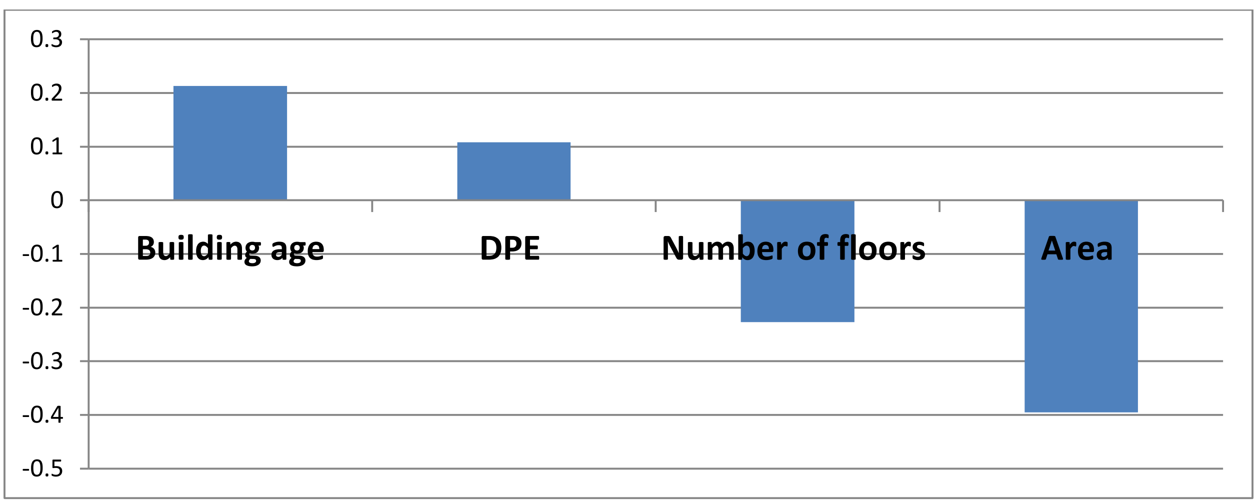

Figure 4.7: Importance value of the indicators for OLS regression methods (Building Characters model)

4.3.4 Model C (Physical and socio-economic parameters)

Table 4.17 and Figure 4.8 present the results obtained with different configurations of hidden layers. Results show important influence of the configuration architecture on the modeling performance. The configuration C3 (1 hidden layer and 5 nodes) gives the best result ($R^2 = 0.74$). This value is better than that obtained by the OLS method (R2 = 0.405). Table 4.18 provides the coefficients of connections in the neural network.

Table 4.17: Determination of the optimal ANN architecture (model C)

Model	No. of Hidden layers	No. of nodes	Training Sum of squares error	Testing Sum of squares error	Total R^2
C1	1	3	14.23	1.14	0.62
C2	1	4	11.85	1.74	0.66
C3	**1**	**5**	**9.16**	**1.58**	**0.74**
C4	1	6	9.94	1.76	0.71
C5	2	4-2	16.39	2.42	0.54

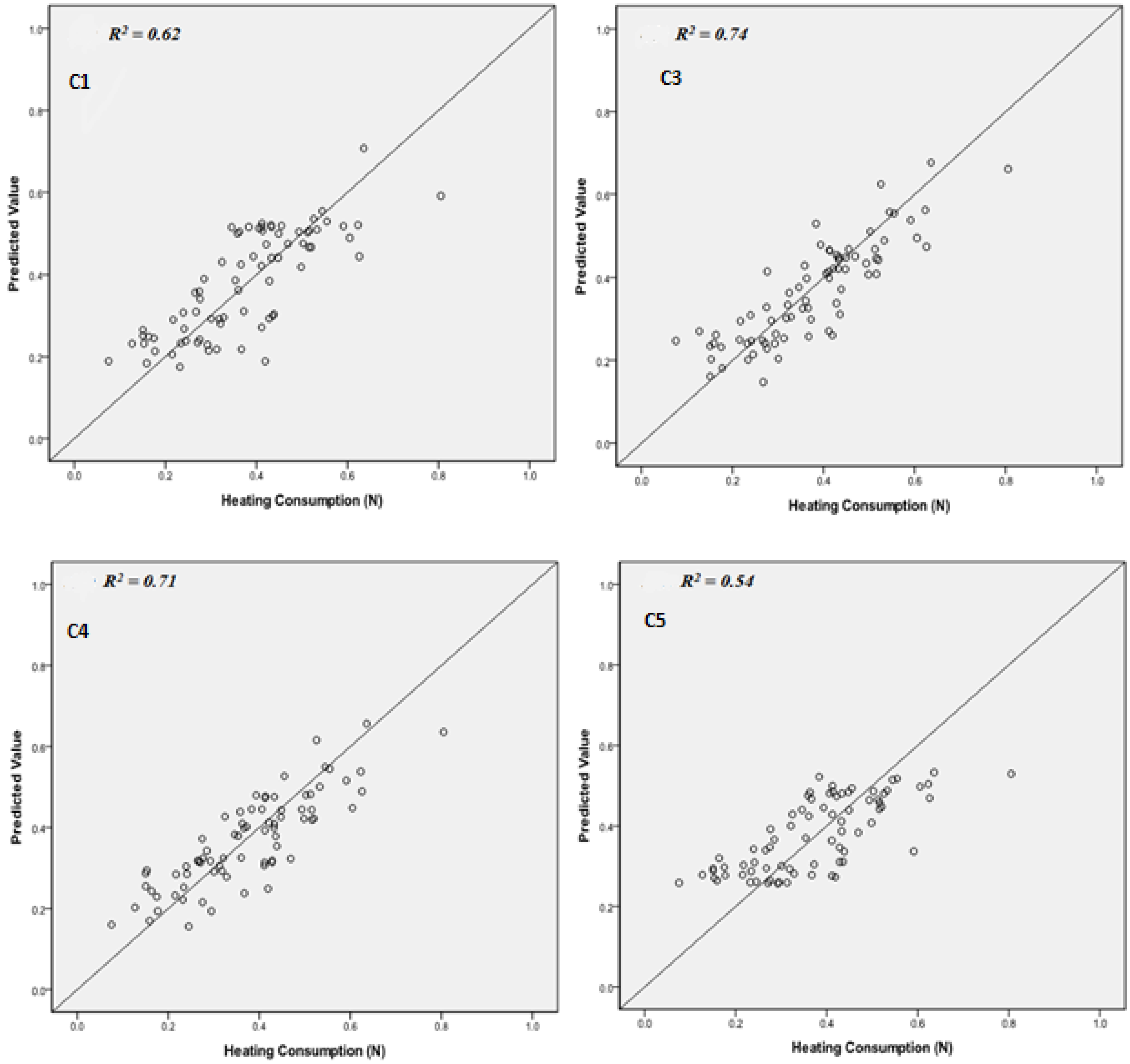

Figure 4.8: ANN Model for Building characters and socioeconomic indicators (A)

Table 4.18: Parameter estimated for best model (A3)

Predictor		Predicted					
		Hidden Layer 1					Output Layer
		H(1:1)	H(1:2)	H(1:3)	H(1:4)	H(1:5)	HCC
Input Layer	(Bias)	-.882	2.052	-.723	.887	.071	
	Building Age	.822	.160	-1.048	.994	.234	
	DPE	.040	-.057	-.035	1.070	.265	
	Number of floors	.087	-.577	.718	-1.628	.221	
	Area	-.291	.361	-.806	-2.370	.219	
	Age	1.200	-1.112	.424	-1.773	.161	
	Marital status	-.321	-.920	.709	1.878	.232	
	Income	.210	-.308	.066	.512	-.117	
Hidden Layer 1	(Bias)						.686
	H(1:1)						.313
	H(1:2)						-1.159
	H(1:3)						-.690
	H(1:4)						.754
	H(1:5)						-.212

Figures 4.9 indicates the weight of each input parameters on the ANN model prediction. This result is compared to that obtained by the OLS method in Figure 4.10. We observe a large gap between these methods, in particular for the socio-economic indicators.

In the ANN model, the martial status has the highest weight, followed by dwellings' area, the buildings' age, the number of floors, the DPE, the tenants' income and finally the tenants' age. In the OLS model, the dwellings' area has the highest weight, followed by the number of floors, the tenants' age, the buildings' age, the DPE, the martial status and finally the tenants' income.

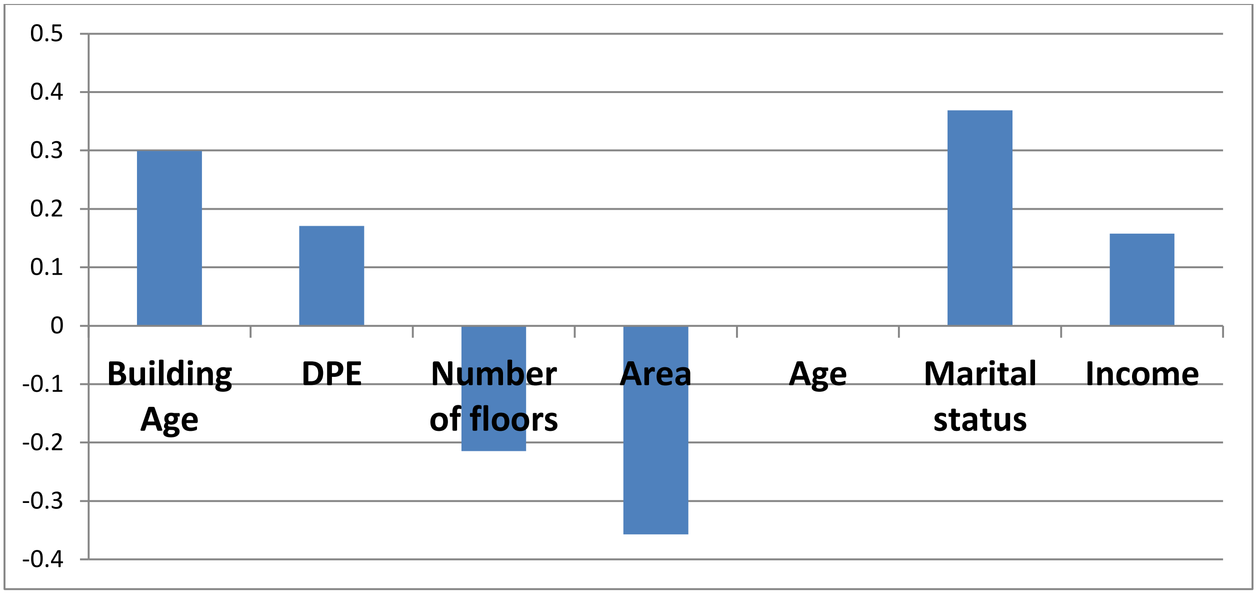

Figure 4.9: Weight of each indicator of the ANN prediction (model C)

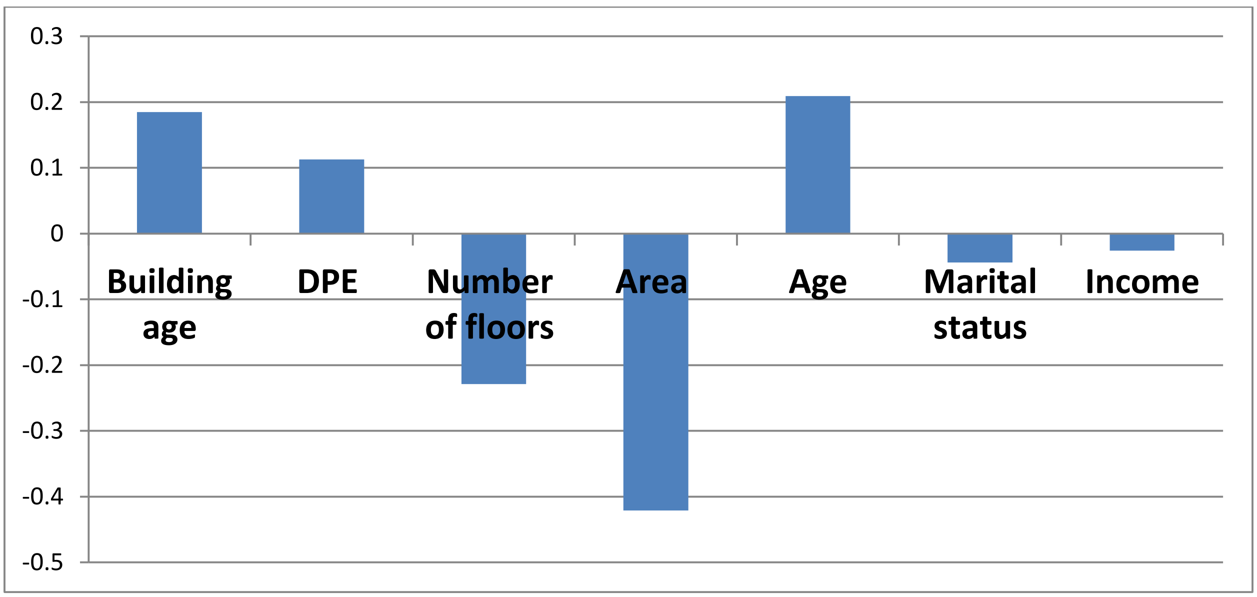

Figure 4.10: Weight of each indicator of the OLS prediction (model C)

4.3.5 Application of the ANN model to optimize the renovation program

In this section we use the ANN model (C3) to analyze the impact of the transformation of some buildings from the low DPE categories (C, D and E) to category B. This kind of transformation could conducted by the improvement of the buildings equipment and management. Figures 4.11 to 4.14 present the influence of the number of "improved" residences on the expenses reduction. We observe that we could obtain a reduction of about 45% of the heating expenses.

Table 4.19 summarizes the impact of the improvement of category "e" residences on the reduction of the heating expenses. It can be observed that the latter varies between 10% and 45%. This table provides information, which allows the residence manager to optimize the renovation program.

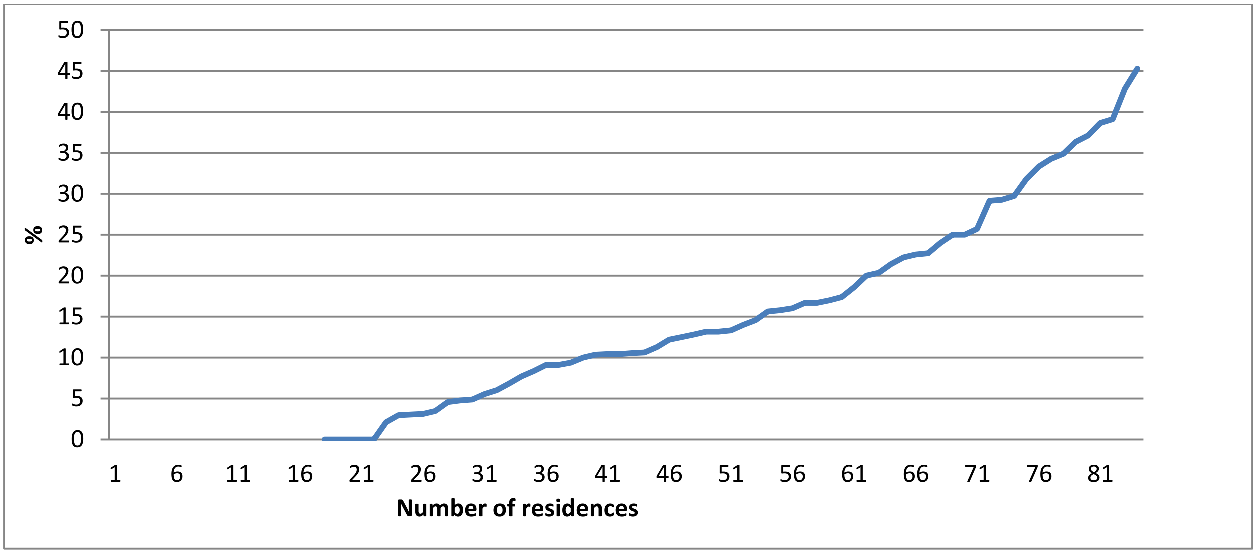

Figure 4.11: Impact of the number of "improved" residences on the reduction of the heating expenses

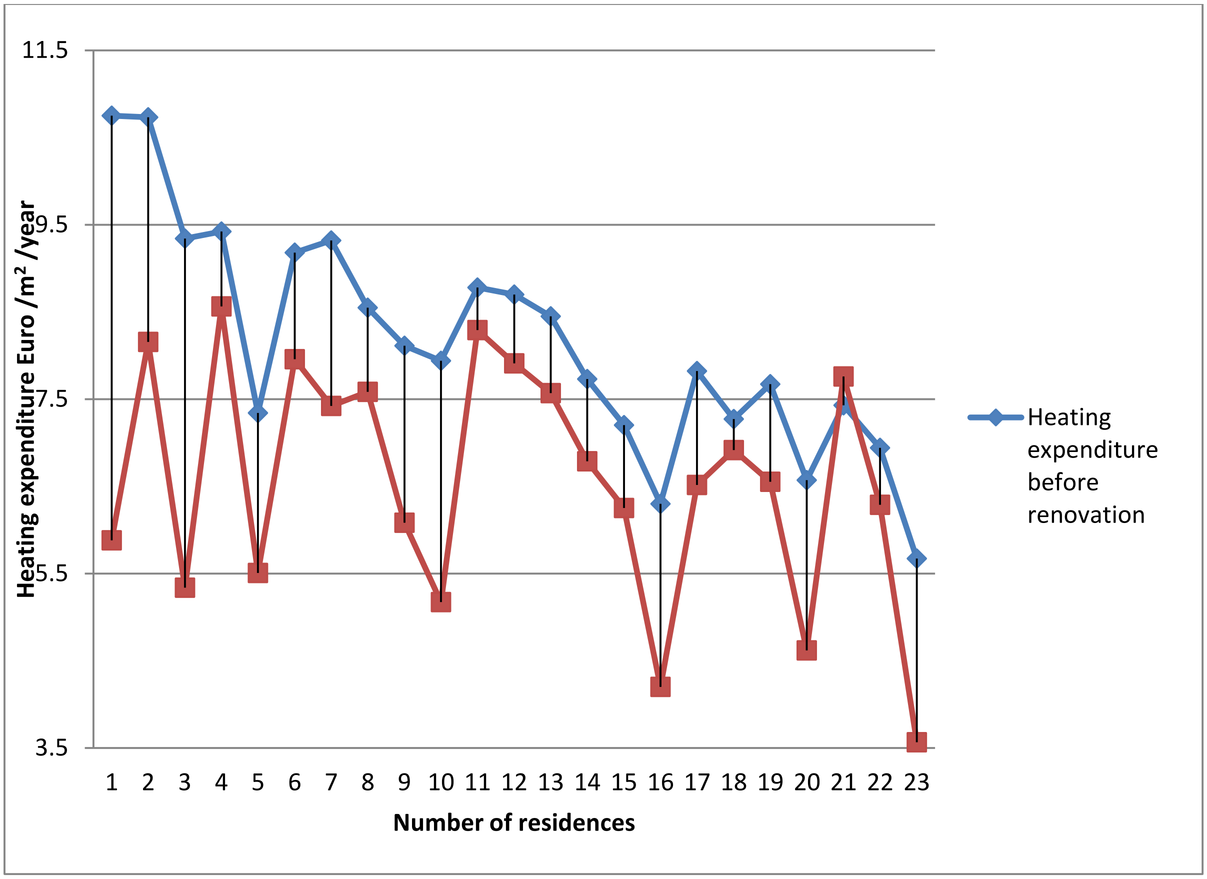

Figure 4.12: Impact of residences renovation on the reduction of the heating expenses (Category E residences)

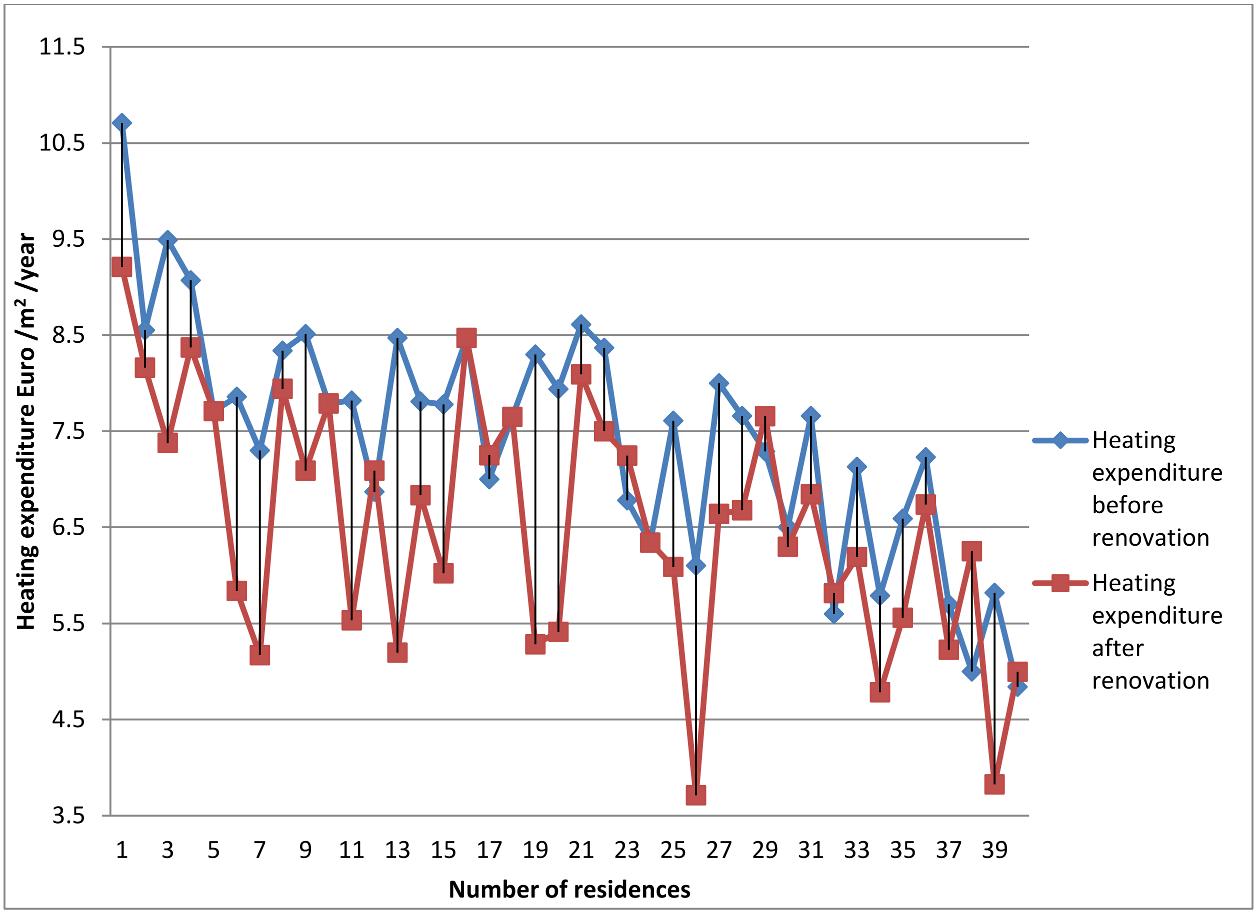

Figure 4.13: Impact of residences renovation on the reduction of the heating expenses (Category D residences)

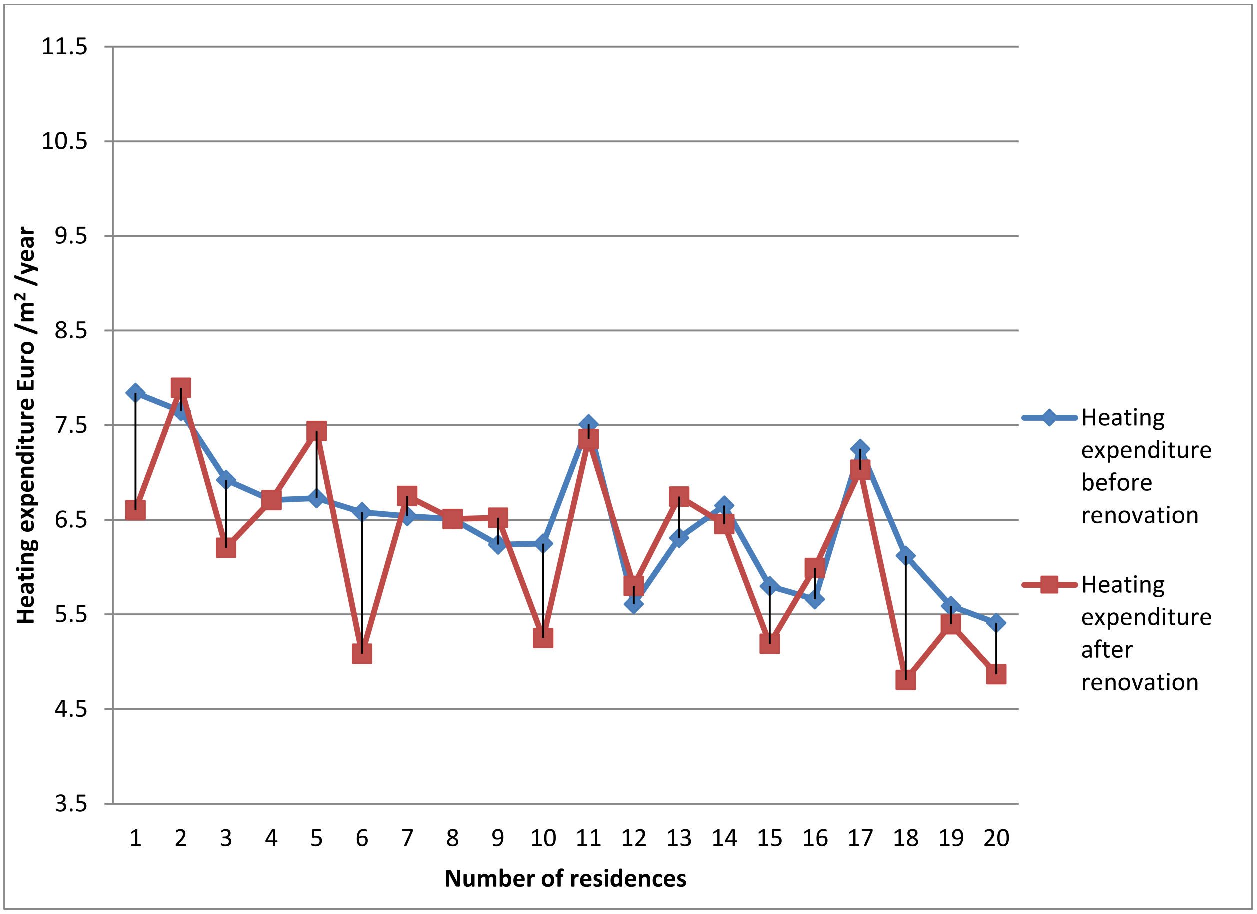

Figure 4.14: Impact of residences renovation on the reduction of the heating expenses (Category C residences)

Table 4.19: The result of improvement simulation in residences under class E in DPE

Residence Code	DPE	N. of dwelling	Building age	Area per dwelling	Heating expenditure before improvement	Heating expenditure after improvement	Percentage changes %
630	e	71	34	64.46	10.75	5.88	-45.31
340	e	40	46	58.73	9.34	5.34	-42.86
T036	e	101	34	69.67	5.67	3.56	-37.14
244	e	152	32	60.88	7.94	5.17	-34.88
101	e	76	32	68.16	6.30	4.20	-33.33
310	e	300	48	65.42	6.57	4.62	-29.73
R012	e	102	37	68.07	8.11	6.08	-25.00
380	e	238	44	69.53	7.34	5.51	-25.00
540	e	40	36	36.93	10.73	8.15	-24.00
530	e	30	36	37.27	9.32	7.42	-20.37
T010	e	160	48	47.89	7.82	6.52	-16.67
T013	e	60	46	56.57	7.67	6.55	-14.58
R008	e	637	49	59.54	9.18	7.96	-13.33
390	e	92	43	73.48	7.20	6.25	-13.16
470	e	182	37	64.03	7.73	6.79	-12.20
R101	e	64	53	54.3	8.55	7.58	-11.29
R115	e	59	55	53.14	8.45	7.57	-10.42

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4.4 Conclusions

This chapter included modeling of the heating expenses in the LMH housing stock using the OLS and ANN method. Modeling was conducted with available input data: buildings parameters (age, DPE, number of floors, and dwellings area) and socio-economic parameters (tenants' age, marital status and income). Globally, the ANN model provided better results than the OLS model. Best results were obtained using both buildings parameters and the socio-economic indicators.

In the ANN modeling, the martial status has the highest weight, followed by the dwellings' area, the buildings' age, the number of floors the DPE, the tenants' income and finally the tenants' age. In the OLS modeling, the dwellings' area has the highest weight, followed by the number of floors, the tenants' age, the buildings' age, the DPE, the martial status and finally the tenants' income and finally.

The ANN model was used to analyze the impact of the residences renovation on the reduction of the heating expenses. The results of this study could help in establishing an optimized renovation program.

General conclusion

This research concerned a major socio-economic and environmental issue that of the energy expenses in the social housing sector. This sector faces large challenges resulted by the economic crisis, the increase in the social and economic difficulties of low-income population, the high increase in the energy price, the aging of the social housing buildings, the non-adaptation of these buildings to sustainability requirement and the planet protection and the lack of public funding for the renovation of existing buildings as well as for the construction of new ones. In this context, we need to conduct innovative research, which combine both (i) a deep understanding and diagnostic of the existing social housing sector, and (ii) the development of new materials, appliance and smart systems, which allow to optimize the investments and maintenance expenses devoted to energy saving as well as improvement of the life quality in the social housing.

This work aimed at analyzing the influence of both the physical characteristics of buildings and the socio-economic indicators of the tenants on the heating expenses, which present the major part of the energy expenses in social housing. The research was based on the analysis of the data provided by one of the largest social housing managers in the North of France (Lille Metropole Habitat – LMH), who is in charge of about 30 000 social housing dwellings. The data covered a large social housing stock including both building characteristics (age, DPE, dwellings' area, number of floors) and tenants' socio-economic parameters (age, marital status, and income).

Analysis of the LMH social housing stock showed a large variety in the year of construction (between 1949 and 2005), the DPE (between B and E), the number of floors (between 1 and 16°), the dwellings area (between 30 and 90 m2), the family composition (single or couple, without children or with 1 or 2 children or more than 3 children), the tenants' age and income. Concerning the quality of construction, the majority of the stock has low energy efficiency: The DPE of about 72% of the stock is lower than D. Consequently, important measurements are required for the improvement of the stock quality as well as the management of the energy. Analysis of the socio-economic parameters showed that about 71 % of the tenants' income are lower than 60% of the social housing ceiling. Concerning the tenants family composition, about

64% of the tenants are single, 54% do not have children and 13% have at least 3 children. The tenants' age repartition shows 34% of young tenants (less than 40 year) and 40% of intermediate age (between 41 and 60 years old).

Analysis of the influence of the building characteristics (age, DPE, dwellings' area, number of floors) and tenants' socio-economic parameters (age, marital status and income) on the heating expenses showed interested trends, in particular poor correlation between the DPE and the recorded heating consumption, the heating expenses per m^2 decrease with the increase in the dwellings age, and increase with the decrease in the dwelling' area, the optimal heating consumption is observed in 4-floor buildings, the tenants older than 60 years consume more heating than younger tenants, the tenants with children consume less than the tenants without children, the tenants' income has insignificant influence on the heating consumption.

The prediction of the heating expenses was modeled using the classical Ordinary Least Squares method (OLS) and the Artificial Neural Networks (ANN). Modeling was conducted with available input data: buildings parameters (age, DPE, number of floors, and dwellings area) and socio-economic parameters (tenants age, martial status, and income). Globally, the ANN method provided better results than the OLS method. Best results were obtained using both buildings parameters and the socio-economic indicators. In the ANN modeling, the martial status has the highest weight, followed by the dwellings' area, the building age, the number of floors, the DPE, the tenants income and finally the tenants age. In the OLS modeling, the dwellings' area has the highest weight, followed by the number of floors, the tenants' age, the building age, the DPE, the martial status and finally the tenants income and finally. The ANN model was used to analyze the impact of the residences renovation on the reduction of the heating expenses. The results of this study could help in establishing an optimized renovation program.

This study was based on global data per residence, because of the lack of data per dwelling. Analysis suffered from this restriction. In the future, it would be interesting to collect data per dwelling, in particular that related to the tenants behavior and the energy expenses including that of the electricity. These data will allow a deep analysis of the behavioral indicators on the energy expenses and to develop incentive measurements for the energy saving.

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