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Spatial approach of the energy demand modeling at urban scale

Quentin Darakdjian

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ensanantes
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MASTER SCIENCES ET TECHNIQUES DES ENVIRONNEMENTS URBAINS

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Présentée et soutenue par :

QUENTIN DARAKDJIAN

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à l'Ecole des Mines de Nantes

TITRE: APPROCHE SPATIALISEE DE LA MODELISATION DE LA DEMANDE D'ENERGIE A L'ECHELLE URBAINE
TITLE: SPATIAL APPROACH OF THE ENERGY DEMAND MODELING AT URBAN SCALE

JURY

Président :	Bernard Bourges	Professeur – EMN
Examineurs :	Bruno Lacarrière Gwendall Petit Marjorie Musy	Enseignant Chercheur - EMN Ingénieur - IRSTV Ingénieur de Recherches - ENSAN

Directeur de mémoire : Bruno Lacarrière
Laboratoire/Institution : GEPEA, Ecole des Mines de Nantes
Co-encadrant : Bernard Bourges

Abstract in english

In the European Union, the residential building sector is responsible for about 22 % of the total energy consumption. Over the last decades policy-makers recognized the high potential of this sector to contribute towards reductions of CO_2 emissions through the energy consumption reduction.

Thermal buildings models is the subject of several researches and several model tools resulted in. Diversity of local contexts, data availability and stakeholders goals lead to search flexible models, with ability to create information for different application. However, renewal of buildings are decided at urban scale, hence the interest to expend the knowledge of the energy demand at a local scale instead of single building.

The main goal of this stage is to link three well-known and complementary approaches: The physics of buildings, the typological approach and the Geographical Information Systems. By exploring the potential of bottom-up approaches, the models existing for single buildings are extrapolated for a complete set of households in a neighbourhood.

Two models of the heating demand at a district scale have been developed and tested on the neighbourhood of St Felix in Nantes. The first one is static and mainly inspired of EPCs (Energy Performance Certificates) while the second one is dynamic and funded on an electrical analogy (5R2C). Both of them couple GIS, the typological approach and building physics. Results are analysed to check relevancy of the prototypical approach and to study energy retrofitting potential from different actions.

Résumé en français

Dans l'Union Européenne, le secteur des bâtiments résidentiel est responsable d'environ 22 % des consommations énergétique. Depuis plusieurs décennies, les politiques reconnaissent le potentiel de ce secteur à pouvoir contribuer significativement à la réduction des émissions de gaz à effet de serre grâce à la réduction des consommations énergétique.

La modélisation thermique des bâtiments fait l'objet de nombreux travaux de recherche et de nombreux outils de modélisation en ont aboutis. Néanmoins, les larges actions de rénovation se décident à l'échelle locale, d'où l'intérêt de connaître les demandes en énergie à l'échelle du quartier et non plus à celle du bâtiment individuel.

L'objectif de ce stage est de lier trois approches maîtrisées: La physique des bâtiments, l'approche typologique et les Systèmes d'Informations Géographique. En explorant le potentiel des approches ascendantes, les modèles existants pour les bâtiments seuls sont extrapolés pour un ensemble de logements d'un quartier.

Deux modèles de demande en chauffage sont développés et testés à St Felix à Nantes. Le premier est statique et principalement inspiré des DPE (Diagnostiques de Performance Energétique) alors que le deuxième est dynamique et fondé sur une analogie électrique (5R2C). Les deux approches couplent les SIG, l'approche typologique et la physique des bâtiments. Les résultats sont analysés pour vérifier l'intérêt de l'approche typologique et pour étudier le potentiel d'amélioration du rendement énergétique de différentes actions.

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I dedicate to them my past and future successes.

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Nomenclature

3CL	Energy rating method for consumption housing calculation
AP	Attachment Proportion
APUR	Parisian Urbanism Agency
CAD	Computer-Aided Design
CAUE	Architecture Urban Environment Council
CERMA	Laboratory Architectural and Urban Ambient Environment
CNRS	National Center for Scientific Research
DHW	Domestic Hot Water
DSEE	Energy Systems and Environment Department
EPC	Energy Performance Certificate
EPFL	Swiss Federal Institute of Technology in Lausanne
ESP-r	Energy Systems Research Unit, building performance software
GIS	Geographical Information System
GHG	Greenhouses Gases
GEPEA	Process Engineering for Environment and Food Laboratory
GR	Glazing Ratio
HN	Heating Needs
IGN	National Geographic Institute
INSEE	National Institute for Statistics and Economic Studies
IPCC	Intergovernmental Panel on Climate Change
IRIS	Detailed geographical statistics
IRSTV	Research Institute of Urban Sciences and Technologies
MATLAB	MATrix LABoratory
MEDUS	Modelling Energy Demand at Urban Scale
MET	Metabolic Equivalent of Task
PREBAT	National Program for Research and Experimentation on Building energy
SQL	Structured Query Language
xRyC	Equivalent electric circuit with x Resistors and y Capacitors

General context and challenges

Climate change and global warming are phenomena that all scientists agree with. IPCC [1] showed that there are several likely scenarios for the further coming years of the Earth, but that all of them follow an average rise of the temperatures, an elevation of the sea level and more natural disasters. Natural reasons, but above all anthropogenic ones explain these changes. Indeed, GHG are mainly released in the atmosphere due to the massive use of fossil energy since the industrial revolution. With this abundant use of energy per inhabitant and the radical rise of the Earth population, the impact on the ecosystem and the human being would lead to an irreversible situation if no measures are taken.

Under these challenges, France, signing the Rio declaration in 1992 and the Kyoto protocol in 2000, promised to develop a program based on sustainable development for the XXI century, according to the French government [2]. Even if the Kyoto protocol shows effort in reducing emission, it is still far from the 50 % reduction recommended by the scientist community. In Europe, countries secure a 20 % reduction of their GHG for 2020. France, put its greenhouse gases reduction target at a division of 4 times for 2050 based on 2010.

Once, those targets fixed it is necessary to write action plans to estimate the potential in different sectors. Indeed, every activity sector emit GHG, but what is important, is to know where the reductions would be significant. The environmental aspect is predominant, but an energetic transition has also to be driven by the economy and the social point of view. As *Nantes Métropole* [3], communities establish concrete projects to reach international targets acting on waste and water management, urban policy, energy and so on. Always according *Nantes Métropole* [3], among all economic sectors, the residential is the largest energy consumer in the region with 30 % of total final energy, and has the largest reduction potential. Considering all buildings, that is to say by adding tertiary infrastructure the total rise to 51 % of the total final energy.

The emission of waste heat from energy consuming activities plays a significant role in the development of urban heat island. Until recently, there are relatively few studies on the urban climate that have explicitly included waste heat (anthropogenic heating) in their analyses. One reason for this is the relative difficulty in obtaining the necessary data for estimating spatial and temporal profiles of anthropogenic heating.

Intern ship context

The training took place in the *Ecole des Mines de Nantes* in the DSEE (Energy Systems and Environment) department. The main aim of this laboratory is to develop research activities in the field of process engineering applied to energy management and environmental systems. DSEE actively participates in the Master *Sciences et Techniques des Environnements Urbains* and prepares students of this Master to deal with various aspects of what the department treats. DSEE also belongs to the CNRS (*Centre National de la Recherche Scientifique*) laboratory through its strong implication onto the energy engineering where researchers of the school work on energy production and sustainable energy system at local scale. Moreover, the department and the IRSTV (*Institut de Recherche Sciences et Techniques de la Ville*) are co-workers and I had the chance to strengthen the links during these 6 months of intern-ship by the use of OrbisGIS which is a software developed by the IRSTV.

This Master Thesis is the following work of Alexis Monteil [4] and David Garcia-Sanchez [5], about the energy consumption at local scale and on coupling physical and statistical approach. The interest of thermal behaviour modelling of buildings do not need to be demonstrated and is well mastered, as show the numerous computer software and different tools dedicated to the subject. Since, it is long and expensive to study in details each household to get the Energy Performance Certificates, Monteil [4] and Garcia Sanchez [5] showed that a prototypical approach by period and type is relevant to gather buildings and to study them.

The initial title of this stage was "Evaluation model of the energy demand at a district scale based on GIS" but finally turns into "Spatial approach of the energy demand modelling at urban scale" to avoid the word evaluation which is not the main work of this intern-ship. This report presents the physical models, the spatial approach and the corresponding evaluation of the energy consumptions. This work broadly treats about the exploring of bottom-up approaches and the integration of a GIS in engineering models developed originally for isolated buildings.

Chapter 1

Literature survey

This first chapter is a bibliography review of the buildings energy consumption modelling. It presents the objectives of simulations of the energy demand at urban scale, some basics of building engineering, data bases, Geographical Information Systems and varieties of modelling approaches. Based on related works, this literature survey will permit to build a model coupling a prototypical approach, spatial treatments and buildings physic.

1.1 Energy demand at local scale

1.1.1 Objectives of the simulation

The major aim of any model is to represent from a limited number of input data, the reality of a situation to reach objectives. The adapted degree of details is the one which allows the user to make a decision based on sure informations. The importance to integrate the objectives of the modelling is easily understandable to avoid useless parameters. Contrariwise, having a modelling tool built with the target to answer to several objectives is actually never fully adapted to fill one. This does not mean to build one model by objective but to limit the specificities of each simulation.

In the application of the energy demand at urban scales the basics rules are unchanged. According to the users and the cases, output data, given by the model, are different. The target can be the power profiles, yearly consumptions, temporal variables or greenhouse gases emissions for instance. Consequently, input data to gather for the simulation are not the same.

In intern ship objective is to create a tool able to generate energy performance certificates for a district where households characteristics are partially unknown and bills not available. In addition to the attribution of etiquettes, the tool should output consumption depending on the time and should localize results on maps. The approach selected is the bottom-up and is based on whole buildings. To reach this aim, there is a necessity to combine available data as: the topographic or cadastral databases, aerial imagery, meteorological data, various measurements, surveys and so on. From these relevant input data an engineering model based on physics buildings, statistics and Geographical Information Systems should lead to different forms of output. The objectives

and possibilities of the simulation are multiples and are listed in the non-exhaustive following list:

- Visualize energy consumptions or maximum power needed for each building on maps.
- Get power profiles of individual buildings or buildings by type if the simulation is dynamical.
- Easiness and high flexibility to adapt and update maps for any changes (construction, destruction or retrofitting) in the neighbourhood. The output changes are directly visible, localized and can be quantify.
- The localized informations allow decisions making as the setting of a district heating or the estimating solar potential on roofs for instance.
- Evaluate the internal thermal comfort with dynamical simulations.

1.1.2 Related works

The aim of this subsection is to present some works that this project is based on, in term of physics, geographical approaches, prototypical studies and possible combinations of models or approaches.

As the subsection 1.5.1 is dedicated to, models follow either bottom-up strategy or top-down one. In the first case the result giving the energy consumption at the urban scale is an aggregation of individual simulation for each building, while the top-down strategy gives results by breaking up known results at bigger scales.

Heiple and Sailor [6] combined their work on geo-spatial modelling and on a prototypical building approach. This approach is applied to large U.S cities to obtain day-specific estimation and his model is also based on engineering sciences. Based on Swan and Ugursal [7] classification 1.2, Heiple and Sailor [6] couple the statistical and the engineering aspects, which attest that techniques can be coupled.

Swan and Ugursal [7] and Kavgic et al. [8] agree on the way of classification of residential energy consumption models, but in addition, Kavgic reviews the different bottom-up approaches to estimate the baseline energy demand of existing buildings stock. He shows that bottom-up building physics stock models are used to explicitly determine and quantify the impact of different combinations of technological measures on delivered energy use.

Popescu et al. [9] develops a simulation and prediction MATLAB model for the space heating consumption of buildings connected to a partially-controlled system. Statistical and neural network modelling are used to develop the model and fix parameters as the wind velocity, the solar radiation or the human behaviour. Following the Swan's classification 1.2, Popescu's model is listed in Bottom-up > Statistical > Neural network.

1.2 Building engineering physics

1.2.1 Energy consumption parameters

The aim of this part is to present parameters that impact the building energy consumptions. Main factors that affect energy consumption in buildings are clearly identify by scientists. Depending on the level of precision needed, some parameters are essential while other can be considered or not. According to Ratti et al. [10], climate is unmanageable but guides choices of construction which are made by urban planners, designers, architects and system engineers. Urban context, thermo-physical of the building envelop, systems efficiency and behaviour of occupants are considered for several scientists like Ratti et al. [10] and Popescu et al. [9] as minimal and sufficient for simple calculation of the energy performances.

The impacts of the following parameters are not quantified but give an overview of the diversity of parameters:

- **Climate:**
 - Temperature
 - Latitude and longitude
 - Wind velocity
 - Relative Humidity
 - Solar radiation
- **Occupants:**
 - Number of occupants
 - Activity
 - Behaviour
 - Opening and closing of windows
- **Urban context:**
 - Close and distant obstructions
 - Attachment to heated rooms
 - Urban organization
- **Buildings:**
 - Size and shape
 - Heat transfer coefficients U
 - Wall and glazing surface
 - Albedo
 - Air renewal
 - Orientation of glazing
- **Systems:**
 - Heating system type

- Temperature setpoint
- Devices power and efficiency

For each building these parameters can be quantified and are for most of them manageable. For historical, cultural and geographical reasons, urban contexts, buildings and systems parameter change. For instance, urbanism laws evolve with the time, prospect rules fix maximal heights of building depending on the width of streets and so close obstructions impacts are different depending on the laws.

Buildings can be classified by typology, for instance by climate (Chen et al. [11]), by shape (Zeferos et al. [12]) or by age as it is often the case (Caldera et al. [13] and Dorfner [14]). Classifications are not limited to one parameter, in the present project a classification by year of construction associated to a differentiation by size (collective or individual building) is made.

1.2.2 Energy performance

The energy performances directly depend on the quality of the building envelop which is the main parameter urban planners and architects can act on. Thermal regulations fix standards and features that changed with the time. Indeed, buildings built under the first thermal regulation of 1974 are less efficient than those built under the last regulations because targets in terms of bioclimatic needs¹ and in term of energy consumptions change from one regulation to another.

Softwares, as Perrenoud, accurately calculate the energy consumptions and all needs for individual buildings. But thermal studies are long and expensive because it is necessary to inform the software of the composing of walls, windows and all thermal bridges. These studies are based on numerical methods that simulate the maximum detailed components of buildings. That is why it is impossible to lead a campaign of EPCs at urban scales and why the statistical approach is selected.

To get an interesting building energy evaluation of a district the maximum parameters listed in the subsection 1.2.1 should be taken into account in the model. When the amount of input data is limited and in order to take into account urban context parameters and geometries, geolocalized approaches are adapted and powerful. Geographical Information Systems (GIS) work on the Structure Query Language (subsection 1.4.2) and permit to complete the model with informations that data bases do not give.

1.3 Data Bases

1.3.1 National institutes

Data are not centralized in one single institute, but in several data file depending on what they treat. It is important to notice that comparison between similar data can lead to significant differences due to the updates or due to the count method and references. Databases are often

¹Indicator used in the Thermal Regulation 2012 that evaluates the sustainable performances of the project, that is to say the envelop performances

private and they are either charged or given in case of partnership. Here is a non-exhaustive list of specialized institutes:

- **IGN**: French National Geographic Institute specialized on geodesy, geography and aerial photography. The institution products mainly topographic and road maps of France but also of some other countries.
- **INSEE**: French National Institute for Statistics and Economic Studies. It collects and publishes informations on the French economy and society, which is useful for Top-down modelling. This data-base is given from the national scale to the IRIS, which are French districts.
- **Meteo France**: French national meteorological service. It collects and stores meteorological data. Weather informations are unavoidable to model thermal situations to represent external excitation as the temperature, wind, rain, pressure or solar radiation.
- **FILOCOM**: French communal accommodation files. Households data built by the local taxation centre (DGI) on buildings features and occupation. The data are geo-referenced and so compatible with any GIS but are confidential.
- Extra data can be available from other institutes, as **Perval** which are managed by public notaries. We can also find energetic file as the **CEREN** which is a French statistical observatory energy demand or **ENERDATA** which makes researches on the global energy industry.

Databases are used by most organizations for their business operations and the interest of geo-referenced them makes them more powerful, this is the aim of Geographical Information Systems.

1.3.2 Maps databases

If data of national institutes are insufficient to feed a project, web mapping services applications can help to complete a database. Nowadays, web mapping services are varied and have different aims, the following list presents some of them and their uses:

- **Google Maps** provides high-resolution aerial or satellite images for most urban areas all over the world. Not all areas on satellite images are covered in the same resolution. The powerfulness of Google Maps is to give an overview of buildings with high accuracy of their shape, disposal and morphology (Figure 1.1 (left)).
- **Google Street View** is a technology featured included in Google Maps that provides panoramic views from positions along streets. It permits to the user to virtually walk in cities and visualize with high accuracy façades of buildings, morphologies, types, number of windows and so on.
- **OpenStreetMap** is a collaborative project also called Wikipedia of maps, where all Internet users browsing the web can contribute to the creation and digitization of maps. It

does not show images, but maps close to cadastral plans. They are useful to differentiate activities and feed databases (Figure 1.1 (right)).

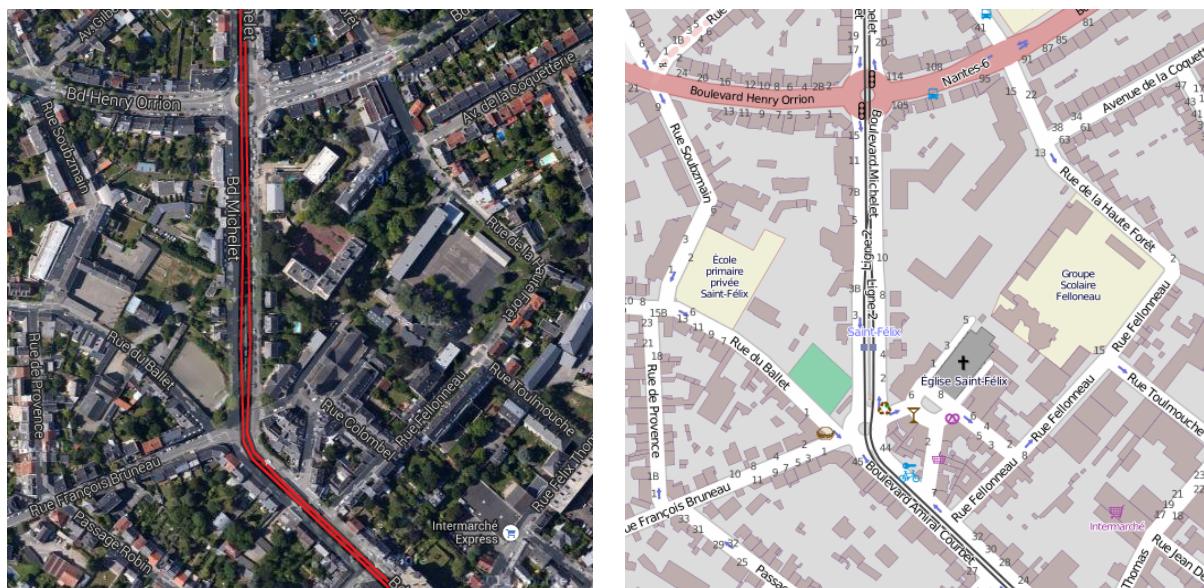


Figure 1.1: Comparison of satellite map of Google Maps (left) and collaborative map of OpenStreetMap (right) of the same part of Nantes shows different informations

To use data from national databases and additional informations collected from web mapping, Geographical Information Systems store, manipulate, analyse and manage all data under a table form that work with Structure Query Language (SQL) spatial language and which is called geo-database.

1.4 Geographical Information Systems (GIS)

1.4.1 History and functionality

GIS is an old tool used to link data and spatio-temporal location. In 1854, Doctor John Snow was the first scientist to draw a map to reveal phenomenon, as report Kari McLeod [15]. Snow held a study on the epidemic of cholera in the Soho district of London, by locating his patients and where they drew their water. Thanks to this geographical method, he demonstrated that a well was the source of contamination. This anecdote, is far from the subject of this report but illustrate the potential of this information system. Nowadays, GIS are used in several cases as for instance in environment, transportation, energy, defence, health, safety or research. Information systems are not only automatic mapping system, there are more decision supports.

Nowadays, lots of GIS are spread on the market; ArcGIS, Arcmap, Mapinfo, AutoCAD for the most renowned and they all have their specificities. OrbisGIS is a Geographical Information System, developed by the Institute on Urban Sciences and Techniques, dedicated to scientific

modelling and simulation in urban context. This software done in Java is capable of displaying, manipulating and creating vector and raster spatial data [16]. Information systems stock rasters, vectors and alphanumeric data as thematic layers, they can be compared, combined or analysed in new relevant layers of a particular problematic with particular attributes.

According to Church [17] five components are essential to have functional GIS. In addition to data we presented on the previous section, an efficient software and computer are fundamental to avoid bugs and to have efficient compilations. Moreover, the operator should be a specialist and methods should be followed to succeed in any project.

1.4.2 Structure Query Language (SQL)

Databases are organized collection of data used to classify information and call attributes. To order these attributes, there is a special purpose programming language, SQL created in 1974, able to data insert, query, update, delete and data access control. This language permit to deal with tables more conveniently than Excel files.

In the field of buildings in a neighbourhood, databases have initially a minimum of two attributes; a number of identification and a valid geometry. Thanks to the SQL language other attributes can be get as perimeters and areas. Then, databases inform the GIS of others attributes as the height of buildings and so new other attributes can be computed as the volume for instance.

1.4.3 Projections

Projections are mathematical transformations that take spherical coordinates (latitude and longitude) and transform them to a planar coordinate system able to make geometrical calculations on SIG. According De Floriani et al. [18], in the handbook of computational geometry and its chapter on applications of computational geometry to GIS, there are 3 main kinds of map projections, the cylindrical (Mercator projection), the conical (Lambert 93) and the azimuthal (Gnomonic projection). Coordinates from different projections cannot be compared without post-transformation.

1.4.4 Possibilities

Geographical Information Systems are used in a wide variety of applications as in history, hydrology, transportation, crime, renewable energy and all activity sector that can be localized.

In the energy field several experiments with various objectives have been lead. In her work Dorfner [14] used GIS to determine the annual energy demand for heating rooms on 200×200 m^2 grids. The originality of her work is to integrate different heating technologies to the yearly energy demand in order to design a district heating. GIS were also used by Mavrogianni et al. [19] to evaluate the impact of urban built form and heat island effect on the levels of domestic energy consumption. Heiple and Sailor [6] compare two approaches, top-down and bottom-up, and combine annual building energy simulation for city specific prototypical buildings and available geospatial data in a GIS framework. Finally, hourly results can be extracted for any day and exported as a raster output at a spatial scale as fine as individual parcel.

Whatever is the project, Geographical Information Systems are used as automatic map systems but are chiefly a tool able to generate results exploitable for decision support of project.

1.5 Approaches and models

1.5.1 Top-down and Bottom-up strategies

Top-down and bottom-up are families of strategies of information processing and knowledge ordering. They are adapted from districts to international scales and to several study domains. Each modelling technique relies on different levels of input information, different calculation or simulation techniques, and provides results with different applicability (Swan and Ugursal [7]). The following sections detail the top-down strategy and the bottom-up strategy. The Figure 1.2 summarize the classification of modelling approaches of the energy demand for the residential sector.

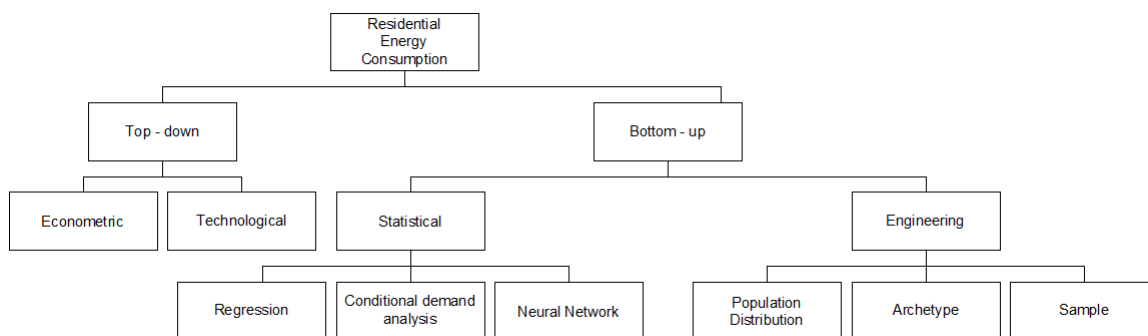


Figure 1.2: Hierarchical classification of approaches of residential energy consumption modelling. Source: Swan and Ugursal

- Top-down techniques are adapted to determine the impacts on the energy consumption after a change on a long time scale based on economics parameters. They treat the residential sectors as energy sinks and are used for supply analysis based on long-term projections of energy demand by accounting for historic response. This strategy implies simple data and models but is limited face to sudden changes. The Top-down technique often use a statistical approach to model the energy demand.
- Bottom-up techniques model detailed consumption for a small scale, based on engineering data, as the geometries, materials and all physical parameters impacting the system. By extrapolating the estimated energy consumption of this representative set of buildings to a bigger scale a global estimation can be done. The limits of this strategy is often the difficulties to get the input data and the complexity of systems, this often lead to long time calculations. However, slight changes and local phenomena can be easily modelled. As for the top-down technique, the bottom-up method generally follows a statistical approach but which can be developed in parallel to an engineering approach.

1.5.2 Variety of models

The Table 1.1 presents a review of thermal models based on the bottom-up approach. It details for each example of model: an equivalent example which follow the general method, the basics which explain how models work, the inputs and outputs of each model and then the advantages and limits.

Steady state

The calculation method 3CL-EPC [20] is based on the energy balance of buildings that is to say that for a given period of time the energy entering in the building plus the internal production minus the energy leaving is constant. Sankey diagrams are specific types of flow diagram, to visualize energy transfers, in which the width of arrows shows proportionally the flow quantity. To estimate the energy needs of buildings, the method is first to calculate heat losses through the envelop (walls, windows, doors, thermal bridges and air renewal), then to determine the inertia, the environmental solicitations and internal gains. The last fundamental parameter for a static approach is the heating degree hour which depend on the location and so the external temperatures during the heating season. An algorithm organizes these input parameters to give the annual heating needs of the studied zone.

Equivalent nodal network

Davies [25] was a precursor and explained that electrical analogy draws a parallel between heat transfers and electrical currents. The thermal balance is equivalent to the electrical current conservation equation for each node. The Table 1.2 summarize the analogy between the electricity and the thermal.

In the equivalent node network method, the building is approximated to a set of nodes, that can be assimilated to homogeneous temperature zones or parts which have limited influence on the heat stored. The thermal coupling between nodes are represented by equivalent conduction where some nodes receive heat sources. The method can be considered as a method of finite differences, the whole building is divided into zones of elements of varying size. The development of an equivalent nodal network requires a good understanding of the physics building and clear objectives. Then the number and disposal of capacitors and resistors are determined in function of the building and objectives.

1.6 Modelling parameters

Databases help to feed the algorithm of useful data, but do not have parameters in link with geographical attributes. A preliminary step before the development of any algorithm is then to prepare input data that influence the study. The parameters presented in this part are the attachment, the orientation, the obstructions and some words explaining how to take into account the occupancy and appliances.

Categories of thermal models ^a	Example	Basics	Input	Output	Advantages	Limits
Steady State	3CL-EPC / French Diagnostic [20]	Thermal model to estimate the energy consumption over a year	Buildings characteristics (heat losses, inertia, average temperatures, heating systems)	Monthly or annual consumption ($kWh/m^2/yr$)	Easy use	Occupants not included No power profile
RC Circuit Analogy	5R2C / Kampf [21]	Building model assimilated to an electrical circuit (Resistances and Capacities)	Buildings characteristics (heat losses, inertia, hourly temperature)	Power profile	Good accuracy	Possible divergence if time step too long or inertia too low
Simple Dynamic	ESP-r / Strachan [22]	Based on a finite volume approach where it solves a set of conservation equations. Also relevant for other applications than energy	Buildings characteristics (shape, environment, installations, ventilation)	Dynamic output	Flexibility, Wide possibilities	Long learning time, Need lots of data
Response Factor	Hyama [23]	Calculation of a response at a unit excitation	Studied parameter. Powerful for single parameter study	Corresponding response	Fast calculation Easy use	Not flexible Approximated
Numerical/ Finite Differences	Crowley [24]	Representation by equivalent thermal networks, the solution is obtained by solving a system of equations representing the heat flow between the elements	Buildings characteristics (shape, environment, installations, ventilation)	2D or 3D visualization	High flexibility of the model	Needs powerful computers

Table 1.1: Categories of thermal models

^aThe steady state and RC circuit analogy thermal model are detailed in the current subsection

Thermal	Electrical
$\mathbf{J} = -\lambda \overrightarrow{\text{grad}}(T)$	$\mathbf{J} = -\gamma \overrightarrow{\text{grad}}(V)$
Thermal conductivity λ	Electrical conductivity γ
Thermal resistance R_{th}	Electrical resistance R_{el}
Thermal flux ϕ	Intensity I
Temperature T	Potential V
Heat Q	Electrical load q

Table 1.2: Electrical/Thermal analogy

1.6.1 Attached walls

The wall attachment is a very important aspect of the modelling because it strongly influence the energy demand of a building. Indeed, attached buildings have external wall surface smaller than isolated ones, then the total heat losses are lower. Theodoridou et al. [26] in his work argues that the attachment to other buildings can even influence more than the age of buildings, which is justify as the older buildings feature does not have efficient thermal insulation.

Single zone building thermal models consider identical temperature for every building of the studied area. The heat conduction is by definition the transfer of heat energy of particles within a body due to a temperature gradient. In case of attached houses and based on Fourier's law (Equation 1.1), the heat flux between attached buildings is zero, because there is no temperature difference.

$$\overrightarrow{\phi} = -\lambda \cdot \overrightarrow{\text{grad}}(T) \quad (1.1)$$

with:

$\overrightarrow{\phi}$: Heat flux density [W.m²]

λ : Thermal conductivity [W.m⁻¹.K⁻¹]

$\overrightarrow{\text{grad}}(T)$: Temperature gradient [K.m⁻¹]

The shape ratio of a building is defined as the external surface divided by the gross volume. To reduce the energy consumption it is fundamental to get a low shape ratio and a heigh wall attached surface with surroundings buildings. According to Caldera et al. [13] the shape ratio is a significant parameter for calculating the heating needs per square meter and per year. With reliance, models consider that the percentage of surface of attachment is proportional to the heating energy saved, while considering only walls.

1.6.2 Orientation

The orientation is a parameter that can be only treated thanks to a GIS, never a data base give directly a value a orientation. Elsewhere, scientists debates to give a definition and to determine if the notion of orientation is meaningful for irregular building shapes. Most of researches, as

Duchêne et al. [27], fixed the orientation as the direction of the larger wall area, being based only on buildings footprints. Whereas, in their work, Andersson et al. [28] defined the orientation of the building as the direction in which the larger area of glass is facing. After the consideration of the orientation, researches determined the impact on the energy consumption. Andersson et al. studied the heating and the cooling load over a year for several U.S towns according to eight orientations (the four cardinal and four intermediate directions). Figure 1.3 shows the comparison of the orientation for the U.S city Nashville where the referenced orientation is the south and for a mixed climate in term of temperature. The paper presents how impacts the orientation on the energy consumption. For the modelled building of 100 m^2 , the setted disposal of windows and other parameters, the orientation can lead to a maximum heat load difference of 1 MWh for the heating period, this difference correspond to 10 % of the final consumption.

To confirm Andersson's work, Zerefos et al. [12] assure that the external shape of a building change significantly its energy consumption, regardless of the materials and the usage in terms of schedule, because the geometry change angles of incidence from solar radiation.

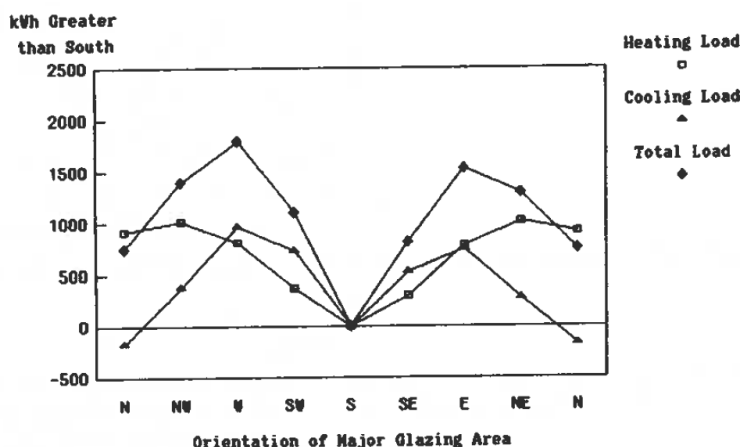


Figure 1.3: Relative variation of heating, cooling and total load according to the orientation of the building, in Nashville, Tennessee. Source: Andersson et al.

1.6.3 Obstructions

Obstructions are generally classified in two classes, the distant ones which are generally assimilated to the relief and the close shadows due to the direct surroundings environment as buildings or greeneries. For Nikoofard et al. [29] the orientation, size and distance of the neighbouring object determine the magnitude of the shading effect on the heating and cooling energy requirement. Some buildings can be totally bereft of solar energy, which implies heating needs much more high than without obstruction. Moreover, due to the lower altitude of the sun and its shorter azimuth arc during the winter months, a neighbouring object located on the south side of a house was found to have a larger impact on the heating energy requirement than that of objects located on the other sides. Planting trees around a house can give the advantage of reducing cooling energy requirement in summer and eliminate the disadvantage of increasing heating energy requirement in the winter.

Full studies of the thermal irradiation are possible with softwares as Solène². With this kind of software, spatial and temporal parameters are taken into account for the simulation of the solar irradiation of each façade of each building. A betterment would be to develop an urban 3 dimensions SIG able to work under OrbisGIS but with the functionality of Solène.

A sub-aim of the project is to use OrbisGIS, the corresponding difficulty is to consider the time and so the sun-path. A possible method to simulate obstruction is to draw the shadows of the building, and observe is the surroundings buildings are impacted. GIS, is able to get results as shown in Figure 1.4 where the shadow is drawn for a considered and fix time of the day.

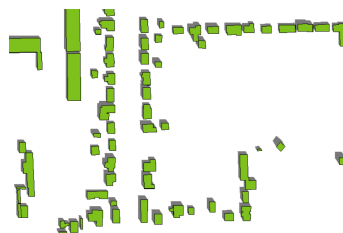


Figure 1.4: Buildings shadow get from a Geographical Information System

1.6.4 Occupancy and appliances

Richardson et al [30] modelled the domestic occupancy in order to estimate the energy consumption. Energy uses in homes is highly dependent on the activities of the residents. The timing of energy use, particularly electricity, is highly dependent on the timing of the occupants' activities. Figure 1.5, shows the proportion of houses with at least one active occupant over an experimental period of 50 days in an individual house. As expected, there is minimal activity during the night (00:00 to 07:00), some activity (at home) during the day and most activity during the evening. This example shows a tendency of the occupancy profile of a house but depends on numerous parameters often complex to model.

Activity	Metabolic rates [M]	
Reclining	46 W^2/m	0.8 <i>Met</i>
Seated relaxed	58 W^2/m	1.0 <i>Met</i>
Standing relaxed	70 W^2/m	1.2 <i>Met</i>
Car driving	80 W^2/m	1.4 <i>Met</i>
Domestic work	116 W^2/m	2.0 <i>Met</i>
Washing dishes standing	145 W^2/m	2.5 <i>Met</i>
Running at 15 km/h	550 W^2/m	9.5 <i>Met</i>

Table 1.3: Metabolic rates according to human activities, Source: INNOVA

However, the study of the domestic occupancy also lead to information about the internal gain in order to heat the space. Indeed, bodies produce energy, called thermal metabolism, due

²Solène is a software simulation of sunlight, illumination and heat radiation adapted for architectural and urban projects, developed by the CERMA laboratory

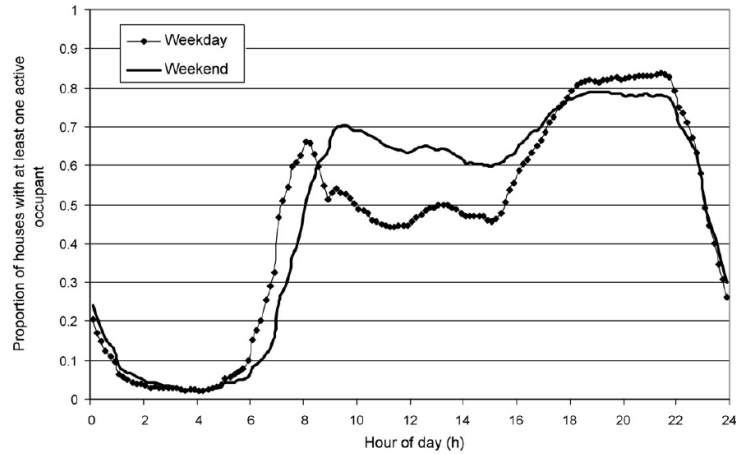


Figure 1.5: Aggregated individual active occupancy profiles for weekdays and weekend days. Source: Richardson

to the water and food oxidation, according to Denzer and Young [31]. The released energy is strongly function of the activity and its unit is the MET [M] ($1 \text{ M} = 58.15 \text{ W}/m^2$). The total metabolic heat for a body depends on his activity and its morphology. Based on Table 1.3 (INNOVA [32]), the total heat for a reclining person would be 82.8 W and for someone having a medium activity at home would be 208.8 W. According to FILOCOM' statistics [33], the average surface per person in households is 35.6 m^2 . Then knowing the occupancy profile it is easy to estimate the heat gain per square meter for a dynamic simulation. In addition to heat gain due to the metabolism, buildings equipments, as electrical appliances and lightings, also participate in the heating of rooms. The thermal power released by electrical appliances is nearly proportional to its electric power. Morel and Gnansounou in the EPFL's report [34] inform that to calculate precisely the energy gain due to appliances, a full study on devices is necessary in term of number and electrical power.

Finally, Morel and Gnansounou [34] conclude saying that the aggregation of the thermal power due to the metabolism and appliances leads to an average of $5 \text{ W}/m^2$ in households.

Conclusion

This state of the art permitted to present essential elements of the project, as databases, GIS, physics in buildings and energy demand models at local scales. Moreover, this bibliographic analyse presents a diversity of modelling approaches (physic, statistic, geographic, top-down, bottom-up ...) that can often be coupled between them. The objective of this Master thesis is to explore the bottom-up approach by integrating Geographical Information System to a statistical approach. The secondary objective is to get a flexible model, adaptable to different districts but also to different scales. However, the approach implies to have relevant data field (technical data of buildings for instance). To develop a new model and based on the existing works, input parameters should be operational to feed the algorithm, this is the main topic of the next chapter.

Chapter 2

Spatial analysis

This chapter presents the existing databases available at local scale, the prototypical approach selected and the preparation of input data using OrbisGIS queries. Limits and hypothesis of the model are presented all along the chapter. The simulation is done on Saint Félix, district of Nantes, and is associated to projects realized in *Ecole des Mines de Nantes* by Monteil [4] and Garcia [5] in order to compare approaches and results.

2.1 Data selection

2.1.1 Data base selection

The selection of the more appropriate database is fundamental for the following of the work. Indeed, it should contain the necessary attributes to be able to exploit it and to feed the algorithm. The available databases are:

- Topographic: Type of map characterized by large-scale detail and quantitative representation of relief.
- Cadastral: Type of map which includes details of the ownership, the occupancy, an accurate location and the dimensions.
- Plot (Parcel): Type of map which represents parcel of land owned by owners with buildings, yards, plots and names of streets.

In addition to differences in geo-localized data due to projections explained in the subsection 1.4.3, there are several differences between layers. For instance, topographic maps, got from Lambert II extended conic projection contains height attributes, but attached houses and buildings are considered as only one making this layer not exploitable for our project. Moreover, mismatches between two layers, as shown in Figure 2.1, cancel the possibility to merge two tables because none data are common between the two. These problems lead to manual and automatic update on OrbisGIS.

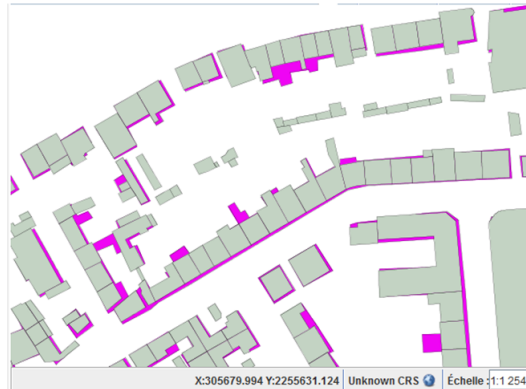


Figure 2.1: Displaying of mismatch between plot map (in grey) and topographic map (in pink)

The final selection is given to the plot database as a base of the work, because it has initially differenced buildings, that is to say, that attached buildings are not gathered in only one but separated.

The choice to be focus only on undifferentiated (residential and heated locals) buildings is done, deleting industrial and remarkable infrastructures. This choice is assumed in order to make a simpler model and because the district is mainly residential. Indeed, a typological approach is valid for buildings of the same categories and materials use to build factories are not the same than to build houses.

2.1.2 Prototypical approach

The fundamental requirement for the development of a statistical model is the selection and the evaluation of the most influencing parameters. A sensibility analysis is a solution to create representative classes. The initial choice of the IRIS_0409, Saint-Félix, is justify by an equilibrated distribution of houses depending on the period of construction (Figure 2.2), a representative number of persons per household and an average surface of households. The objective of the typological approach is to gather buildings by classes.

The first discrimination variable choose is the age of construction because material, urbanism and architecture significantly change during the last century. The following list presents the prototypical division by age of construction and a brief explanation of dates done by Graulière [35] and APUR [36]:

- **Class 1: Before 1915.** Construction with local materials (stones, terracotta or earthen). Thick and heavy walls leading to buildings with high inertia. Low efficiency of the envelop.
- **Class 2: Between 1915 and 1948.** Stones or bricks buildings make envelops buildings globally inefficient but generate limited thermal bridges due to a high compactness ratio.
- **Class 3: Between 1949 and 1974.** Period of construction very inefficient due to a fast construction post war. Thin walls, high glazing surface, untreated thermal bridges and so on.



Figure 2.2: Repartition of number of buildings according to their age and their type for Saint-Félix. Source: Monteil

- **Class 4: Between 1975 and 1989.** Establishment of the first thermal regulation after the first oil shock. The insulation is systematic.
- **Class 5: After 1990.** Date of the second thermal regulation which result in buildings less energy consumer. Creation of other classes after 1990, for thermal regulation of 2000, 2005 and 2012, is not done due to limited number of buildings even if performances still become better.

The second variable of discrimination concern the size of buildings and is called "Type" in calculations we have 4 types detailed in the following list:

- **Type 1-3: Collective buildings.** Collective is defined as buildings with a number of floors higher than 2. Type 1 means that the building is attached to another one while type 3 means that it is isolated
- **Type 2-4: Individual house.** Individual is defined as houses with a number of floors equal or lower than 2. Type 2 means that the house is attached to another one while type 4 means that it is isolated.

In most applications types 1+3 and 2+4 are gathered because the Geographical Information System, OrbisGIS, automatically computes the attachment of buildings. However the differentiation is interesting to study the impact of the attachment to the energy consumption.

2.1.3 St Félix district specifications

The Figure 2.3 shows the geographical limits of the district St Félix, N°441090409 of INSEE code [37], in the town of Nantes. It is located in the center/north part of the city beside the river Erdre and is inhabited by 3245 people distributed in 2015 households and 849 buildings. The neighbourhood is mainly residential and the two remarkable buildings kept for the simulation are the school (*Groupe scolaire Felloneau*) and the department store (*Intermarché*).

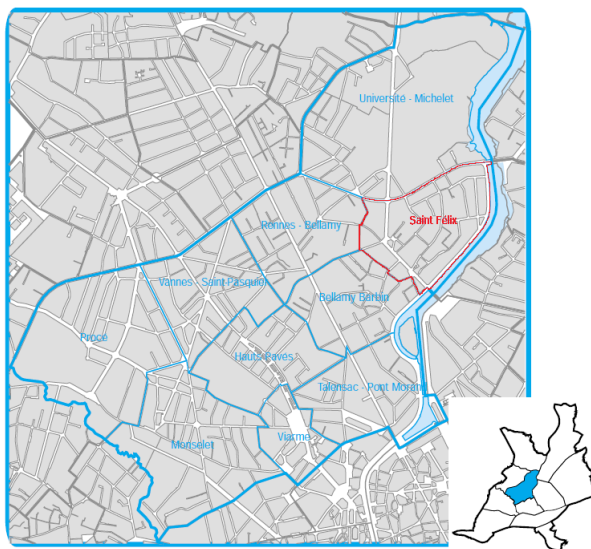


Figure 2.3: Location of Saint Félix in Nantes, Source: INSEE

The following work on OrbisGIS participate in the creation of the model of St Félix district. The plot database is a geographical layer which contains buildings footprints represented by polygons. Each polygon is associated to several data. First, a login is attributed to each geometry for manipulations. Secondly, the geometry of each polygon is stored to make the link between the maps and the database. The last information available and usable on the initial database is the kind of buildings (residential, remarkable and industrial). Queries on OrbisGIS and attributions of other data are detailed in the following section 2.2, they permit to get input data to feed the algorithm and consequently energy consumptions.

2.2 OrbisGIS

2.2.1 Classification by type

As presented in the previous section, the choice of data source is the plot (parcel) database. However, it was necessary to make some update and corrections as erasing garages and cabins of the layer, because they are not heated. Moreover, some invalids geometries of the layer as shows Figure 2.4 and 2.5 are edited and corrected to get valid input data.

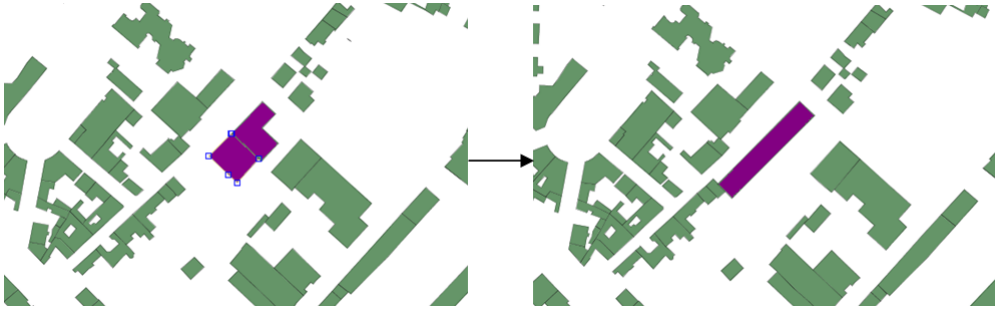


Figure 2.4: Geometrical modification of the building N°695, the left part is before and right one is after the modification



Figure 2.5: Use of Google map to modify the geometry of the building N°695

Thanks to the subsection 2.1.2 on the typological approach, the age is determined in accordance with the work of Monteil [4], Figure 2.6 and Google Street View. Classes of age are determined based on the morphology of buildings. Renewal of buildings, like changing aeration systems, installing double glazing or isolating the envelope of the building are not considered and so, effective energy consumptions and theoretical ones can have significant differences. These changes modify considerably the consumption but are not detectable on Street View. Direct field study on the district permits to see real situation and to confirm or infirm what is on map data bases.

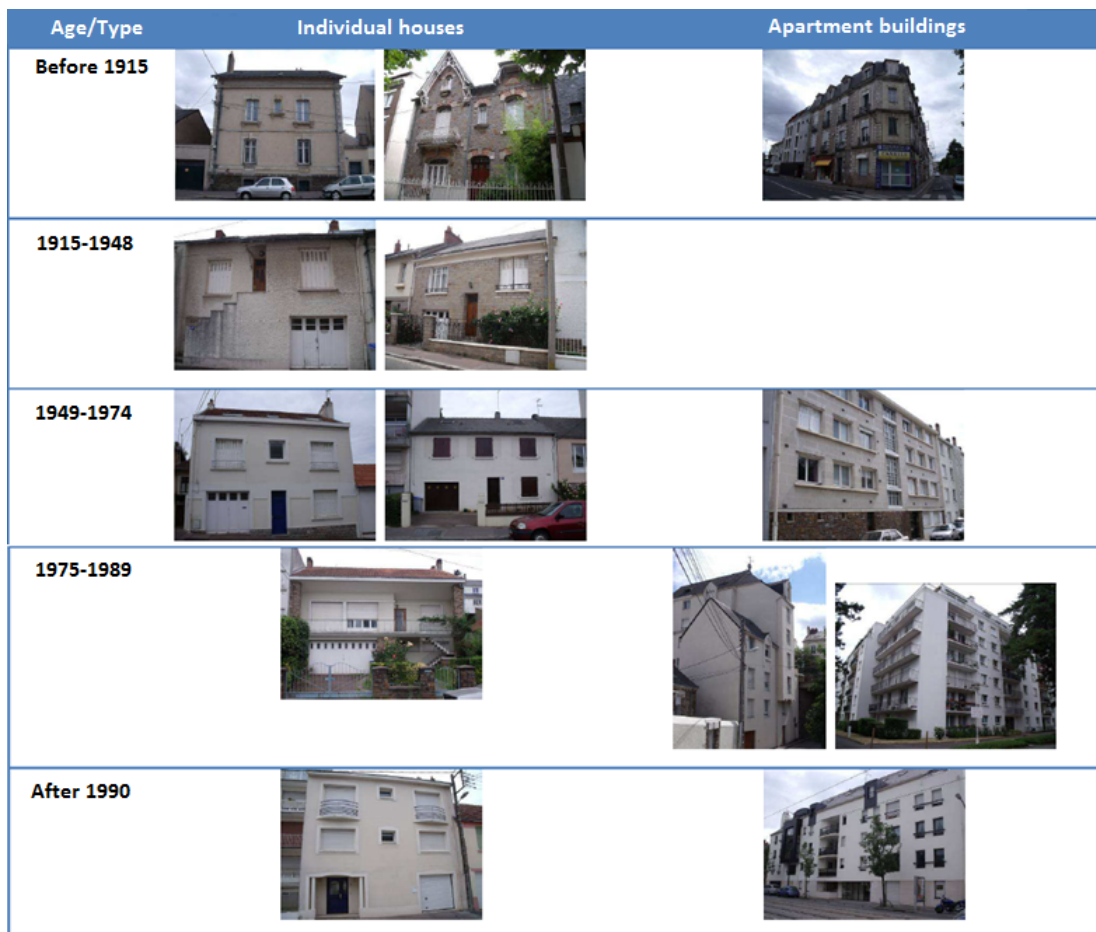


Figure 2.6: Buildings morphology according to their age and their type. Source: Monteil

2.2.2 Number of floors

First, it is important to know the height of buildings because it permits to identify the repartition of individual houses and apartment buildings. If the number of floors is lower or equal than two, then the buildings are considered as individuals, therefore buildings of more than two floors are considered as apartment buildings. Secondly, knowing the number of floors, it is easy to estimate the height of buildings by making the hypothesis that the height per floor is 2.5 meters¹. This information is essential to calculate the air volume to heat.

The initial topographic database contained the gutter height of buildings but after verification they did not feet with the reality and then attributes were considered as wrong. Instead of estimating the real height of buildings, the number of floors were counted and feed in a new database.

2.2.3 Glazing Ratio (GR)

The GR is defined as the percentage of glazing on a building side. This ratio is used for calculation of solar gains and conduction heat losses. To calculate it, a statistical study has been led, for each period of construction (periods 1, 2, 3, 4 and 5) and both types of buildings an average of 10 measurements are done on random façades (except attached walls) thanks to Street View. The results of the study are summarized on the Table 2.1. Despite the fact that the determination of the GR actually does not use OrbisGIS a program based on orientation (south/north and street/yard) of façades and the age could be programmed for further applications.

This statistical study led us to the conclusion that depending on the age of building, the evolution of the GR and so of the architecture is significant. Indeed, between the first and the last class of age the proportion of glazing is doubled for the individual houses and quadrupled for blocks of flats.

GR (%)	Individual houses	Apartment buildings
Before 1915	16.4	11.2
1915-1948	16.2	13.4
1949-1974	26.0	28
1975-1989	25.4	45.2
After 1990	32.2	43.6

Table 2.1: Glazing Ratio (%) according to age and type of buildings

2.2.4 Attachment

The study of attached houses is essential for the calculation of the heating energy needed. Indeed, in detached houses the heat which goes through the envelope is lost and released outside. However, in situations of attached houses, the heat transfer goes through walls but is given to the besides houses and in the same time the heat from surrounding buildings is recovered.

¹2.5 meters per floor is the general value used in civil engineering

The term attached perimeter on GIS informs on which side of buildings there is no heat losses through external walls. As illustrated on the Figure 2.7, there is the perimeter in black where the heat is not lost and in grey the perimeter where the heat is released in the atmosphere. In the developed model there is no distinction between external walls oriented to the dooryards and the ones oriented to the streets as APUR [36] did. Moreover, a limit of the actual model is that the height differences of buildings are not considered. Indeed, in the reality a 3 floors building attached with a 2 floors building, does not have the last floor which recover the energy from the second building, while in the model it does. This might be identify as an important limit but in Saint Félix there is very few discontinuity of building height, never an apartment building is attached to an individual house. The difficulty, on OrbisGIS is to discretize buildings to study only the one part of the perimeter or one façade.

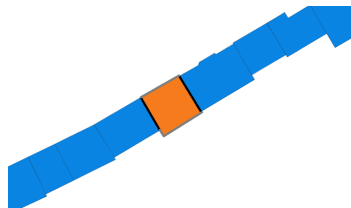


Figure 2.7: Visualization of the two kinds of perimeters

As explained in the previous paragraph the measure of the attached perimeter is fundamental for the calculation of the heating needs. Here below is method and the SQL code developed to get the attached length as output:

- **Step 1:** Measure of the common length between two attached houses. One building can be associated to several lengths.
SQL: CREATE TABLE perimetremitoyen AS SELECT a.*, ST_Length(ST_Intersection(a.the_geom, b.the_geom)) AS longueur FROM attributs a, attributs b WHERE (a.ID!=b.ID AND ST_Intersects(a.the_geom, b.the_geom));
- **Step 2:** We are interested in the length for each building so we gather results grouped by making the sum of the length. The result of this query is a table which contains the attached length of each attached building.
SQL: CREATE TABLE perimetermitoyen AS SELECT ST_UNION(the_geom) AS the_geom, ID, Sum(longueur) AS perimetremit FROM perimetremitoyen GROUP BY ID;
- **Step 3:** The next step is to merge these values to the table of all others attributes.
SQL: CREATE TABLE jointure AS SELECT a.*, b.perimetremit FROM attributs a LEFT JOIN perimetermitoyen b ON a.ID=b.ID;
- **Step 4:** Then we have to fix zero to detached houses that is to say buildings without attached length.
SQL: UPDATE jointure SET perimetremit=0 WHERE perimetremit IS NULL;

2.2.5 Orientation

As we saw during the literature survey, the general orientation of buildings is complex and the approach is debatable. First the orientation was define as the angle between the longest axis of the bounding rectangle of the building and the east-west axis, this method and the algorithm are explained in Appendix A.1. But this definition is not totally satisfactory because it does not take into account attachment and consequently glazings. The study of the orientation lead to coefficient that traduce the fact that façades ar not always oriented to the south and so does not benefit of the maximal radiation. The Table 2.2 lists the corresponding coefficients (C1) in function of the direction of one façade and not the orientation of the building according to [36].

Orientations	Coefficients (C1)
South	1
South-East / South-West	0.86
Est / West	0.55
North-East / North-West	0.3
North	0.2

Table 2.2: Orientation coefficients in function of the direction of one façade. Source: APUR

However the aim is not to associate a coefficient to façades but to the whole building. Having no informations on the repartition of windows on façades we make the hypothesis that they are equally distributed on external walls (by type and age of building as shown in the Table 2.1). Whatever is the shape of an isolated building or house, the overall orientation coefficient is always equal to 0.58. And the only parameter which changes this coefficient, is the corresponding attachment, that is to say the number of attachment (AP) for each building. The computation of the number of AP with a SQL query is very similar to the one presented in the subsection on building shadowing effects 2.2.6, since both queries count elements in a geometry. A link between overall orientation coefficient and number of attachment is done here below:

- **AP=0**: Calculated coefficients are comprised between 0.55 and 0.6 and finally fixed at **C1=0.58**.
- **AP=1**: Several situations are possible. If the attached wall is along the east or the west axis there is no impact on the final coefficient and the coefficient is equal to **0.58**. For all the other cases only 4 coefficients are attributed. If the south orientation is cancelled by a surrounding building then the corresponding coefficient is **0.48**. If it is north the corresponding coefficient is **0.68**. In addition two other intermediate coefficients are included where the shared walls have angles around 45°. The coefficient is equal to **0.53** for the south obstructions and **0.63** for the north obstructions. Currently this is a main limit because this has to be done manually, which is possible for a district but not for a city.
- **AP=2**: The study showed that buildings with two attachments have nearly always the attached wall at the opposite side. This means that the resulting coefficient is always close

to 0.58 because of the symmetry of the situation.

- **AP=3 and more:** No laws are found for these situations which represent 3.5 % of the buildings of the district. Therefore, coefficients are calculated individually and the Figure 2.8 presents an example of calculation:

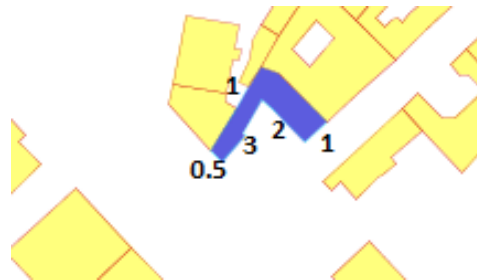


Figure 2.8: Example of calculation of the orientation coefficient for an attachment proportion equal to 3

$$C1 = \frac{3 \times 0.3 + 5 \times 0.3 + 3.5 \times 0.86 + 1 \times 0.86 + 1.5 \times 0.86}{3 + 5 + 3.5 + 1 + 1.5} = 0.54 \quad (2.1)$$

The convenience of this method is debatable since some attributes² should be feed manually, but the resulting orientation coefficients and the further solar gains associated are well-estimated. A possible update of this limit would be possible if and only if buildings façades are studied individually.

2.2.6 Greenery and building obstructions

Shading by neighbouring buildings and trees impacts the energy requirement of a building by reducing the amount of radiant energy absorbed and stored by its thermal mass. In this model, only close overshadowing are taken into account, distant overshadowing, due to mountains for instance are neglected. Clouds and aerosols are already taken into account in the solar gain of the external solicitation. The aim of this section is then to take into account the micro climate of the district, which significantly impact the building energy consumption.

Greenery shadowing effects

The consideration of greenery around buildings leads towards a model based on buffers³ of the vegetation layer. The model is static and the sun path is not include. In the developed model, the

²For the case of St Félix, 29 % of buildings have an attachment proportion of 1 and 3.5 % have an AP equal or higher than 3.

³Buffers in GIS are useful for proximity analysis, they create an area defined by a bounding region determined by a set of points at a specified maximum distance around a geometry

impact of the greenery shadowing is a coefficient which impact the solar gain when the considered buildings are included in the buffer of the layer vegetation. The Figure 2.9 shows the different kind of buildings, those which are impacted by the greenery (in red) and those which are not impacted (in blue). The chosen corresponding coefficient decreasing the solar gains is fixed at 10 % for the simulation but can be easily modify. To develop a more complete model a field survey could be lead to determine more parameters like the trees size or the kind of vegetation.



Figure 2.9: Impact of greenery on sun obstructions. The dark green is the vegetation, the light green is the buffer of 5 meters of the vegetation, red buildings are those into the buffer and the blue buildings are those which are not impacted by the greenery

Building shadowing effects

External obstruction influences the daylighting performance and the building energy consumption. The effect depends on the height of neighbouring buildings and the separations. When buildings are located close to each other, blockage of solar gain can be severe, particularly for the units on lower floors. The final effect on buildings overshadowed is difficult to estimate but

the impact seems to be limited since we consider only winter days in an region of low sunshine as Nantes area. The query is developed on OrbisGIS and here again based on the buffers. The method is to create buffers of size proportional to buildings high to represent the shadow of each ones that is to say when the declination of the sun is at 45 °. Then the number of buildings which impact the studied one is considered as significant to estimate the obstruction. Based on the work of APUR [36] and once the number of obstructions determined, the association to coefficients (Table 2.3) is necessary to feed the algorithm. The following list presents the necessary steps on OrbisGIS to link the building environment to building shadowing coefficients:

- **Step 1:** Creation of a table with the geometry of buffers of each building, where the size of the buffer is equal to the high of the building. The result of this step is exposed in figure 2.10.

SQL: CREATE TABLE bufferbati AS SELECT ST_Buffer(the_geom, 3*3*etages) AS the_geom, ID FROM attributs;

- **Step 2:** Link of the two tables where only couples which intersect themselves are kept.

SQL: CREATE TABLE join_intersect AS SELECT a.the_geom, a.ID, b.ID as ID_buff FROM attributs a, bufferbati b WHERE ST_INTERSECTS(b.the_geom, a.the_geom);

- **Step 3:** Count of buildings in the buffer zone, by pulling the studied building (minus 1).

SQL: CREATE TABLE final AS SELECT ST_UNION(the_geom) AS the_geom, ID, (count(ID_buff)-1) AS nb_bat FROM join_intersect GROUP BY ID;

- **Step 4:** Deleting of attached buildings.

SQL:

- CREATE TABLE buildingobstruction AS SELECT final.*, attributs.NB_MITOYEN FROM final, attributs WHERE final.ID=attributs.ID;
- ALTER TABLE buildingobstruction ADD COLUMN nb_obstruction DOUBLE;
- UPDATE buildingobstruction SET nb_obstruction=nb_bat-NB_MITOYEN;

Number of obstructions	0	1	2	3	4	5
Associated coefficient	1	0.9	0.8	0.7	0.65	0.6

Table 2.3: Associated obstruction coefficient to the number of building obstruction

As said, this method is improvable especially by taking into account the relative disposal of buildings. Indeed, a building can't obstruct another building situated to the south.



Figure 2.10: Visualization of virtual shadows (pink) around each building (green), useful for the estimation of the building obstruction impacts

Conclusion

We saw in this chapter the importance of the initial choice of the selected database and we presented the typological approach by age and type of building. The treatment of useful elements for the modelling of the building energy demand as the determination of the number of floors, the proportion of windows, the orientation and obstruction of buildings lead to computational algorithms that are presented on the following chapter.

Chapter 3

Energy models applied to St Félix

The aim of the project is to simulate the energy demand for a large number of buildings for which we have relatively few informations, so we need to ensure that we have compatibility between the available data and the selected modelling approaches. One of the interest of modelling at urban scales is the inexpensiveness unlike individual audits.

The model developed in this project uses meteorological data and building data but also interactions due to the environment. This chapter presents two types of physical models; a static algorithm based on the 3CL-EPC method and a dynamic algorithm based on the RC analogy (5R2C). The last section of this chapter is dedicated to the analyse, exploitation and comparison of results.

3.1 Additional input data

3.1.1 Meteorological

Depending on the objective of models, meteorological data are not the same. As presented in section 1.2.1, the temperature, the irradiation, the direction and the wind speed and the relative humidity are parameter that impact the energy consumption in houses. In this model, the weather parameters are limited to the outside temperatures and the direct irradiation for the referenced year of 2004. The temperature file, get from Météo France, contains the evolution hour by hour of the temperature in Nantes-Bouguenais. The direct irradiation is also given hour by hour and is get from sensors oriented to the south and inclined at 90° . The heating period in Nantes is set from October 1st to May 10th.

3.1.2 Buildings

Building data are the same for the static and the dynamic models. The approach is prototypical and the classification is realized by age and as explained in the subsection 2.2.1 contains 5 groups. For each class the performances of the envelops are different and the values of performances are summarized in the Table 3.1 and the detailed in the Table C.1 of the Appendices. Air renewal

values (Q_v) are from the technical report of Elisabeth Gratia [38], which gives a value of 2 vol/h for old buildings and 0.5 vol for recent ones, intermediate value are the result of the interpolation. The accuracy of the determination of performances of buildings is fundamental to get consistent results of consumption. The values of these tables probably are different than the real ones and are an average of available data. We make the hypothesis that available data for Paris, used by APUR [36], are also available for Nantes since thermal regulation are at least operative at the national scale. The internal temperature fixed for the modelling is 18°C and is identical for all buildings. This temperature set point has a significant impact on the heatings of buildings. In the final model, the air renewal is fixed constant, but nothing prevent to replace it by a model more detailed, where the air renewal changes depending on the occupation and the time for instance. As far as, the internal gains (occupancy and appliances) are simply fixed at $5\text{W}/\text{m}^2$ in this project, a more complete model as presented in the subsection 1.6.4, would also improve the modelling.

Age	U_{roof}	U_{floor}	U_{wall}	U_{window}	Air renewal (Q_v)
Before 1915	0.4	4.8	2.3	4.5	2
1915-1948	0.3	5.6	2.9	4.5	1.6
1949-1974	0.3	1.7	2.7	4.5	1.3
1975-1989	0.3	0.6	1	3.1	1
After 1990	0.2	0.4	0.5	1.9	0.5

Table 3.1: Values of heat transfer coefficients [$\text{W}/\text{m}^2/\text{K}$], and the building ventilation [vol/h] according to the age. Sources: Monteil, APUR and Calculation method 3CL-EPC

3.2 Static algorithm

Statics algorithms are developed to compute the energy needs over a long time period. The inputs are averages and are used to develop calculations or to elaborate certificates. The algorithm, inspired of EPCs (Energy Performance Certificates), is based on heat losses of buildings, the internal and external solicitations and the inertia. While full energy audits take into account intermittent factors and heating systems for the determination of energy used for heating. Static approaches, as EPCs, have been criticized by many professionals for their inaccuracy, and low reliability for old buildings but they have the advantage to give good overall estimations of the final consumption following a simple method.

The energy rating method is the index of a building's thermal performance, heating requirements, for residential homes. The model developed use the French legislation [20] and is partly inspired of the work of APUR [36]. The thermal behaviour of buildings is based on fundamental physical parameters: dimensions, materials, sunlight and attachment with surroundings buildings. APUR[36] treated Paris, that is to say around 96 000 residential buildings, the calculation of heating needs was computerized for each building with a prototypical approach by age and type. The algorithm developed in this part of the project follow mostly the path of the Parisian Urbanism Agency and is coded on MATLAB. The running time of the computation is about 10 seconds.

The aim of the algorithm is to calculate the theoretical needs for each building. The first step is to calculate the thermal heat losses (GV) [W/K] which is the sum of the heat losses through the envelop (DP) and the losses due to the air renewal (DR).

$$GV = DP + DR \quad (3.1)$$

The envelop heat losses are calculated knowing the area of façades (A_i) and their corresponding heat transfer coefficient (U_i). To simplify the algorithm thermal bridges are integrated into the coefficients U :

$$DP = \sum_i A_i \cdot U_i \quad (3.2)$$

and DR depends on ventilation rate (Q_v)[vol/h], the volume of the building (V) and the volumetric heat capacity of the air (c)[$0.34Wh/m^3.K$]:

$$DR = c \cdot V \cdot Q_v \quad (3.3)$$

To reach the theoretical heating needs BV in [W/K], GV reduced due to internal and external heat gains:

$$BV = GV \cdot (1 - F) \quad (3.4)$$

with F depending on the inertia of the building (n). According to 3CL-EPC standards [20], for a heavy inertia $n = 3.6$, for a light one $n = 2.5$ and for an average one $n = 2.9$. In the simulation the average value is chosen for all buildings. A possible improvement of the model is to attribute different values according to the type and the age of buildings, the tendency is that old buildings have a higher inertia than new ones due to thicker walls.

$$F = \frac{X - X^n}{1 - X^n} \quad (3.5)$$

In the previous equation X depends the living area (S_h) and on the internal heat gains due to the occupancy and appliances (Q_{in}) fixed at $22.9 kWh/m^2$ by APUR [36]. The vertical solar radiation (Q_{out}) is set at $599 kWh/m^2$ in Nantes, according to Météo France and is multiplied by the transparent area equivalent to the south S_{se} which depends itself of the glazing area, obstructions, orientation of façades and solar transmission factor as detailed in the Appendix B. DH is the degree hour base $18^\circ C$ in Nantes for the year 2004 which is the reference for the dynamic simulation.

$$X = \frac{Q_{in} \cdot S_h + Q_{out} \cdot S_{se}}{GV \cdot DH} \quad (3.6)$$

Then finally to get the annual heating needs Q_{heat} in kWh/yr for the building:

$$Q_{heat} = \frac{BV \cdot DH}{1000} \quad (3.7)$$

Once, the annual heating needs computed it is easy to extend this algorithm to the all set of buildings and to explore the potential of this work, this is the topic of the section 3.4.

3.3 Dynamic algorithm

Dynamic models can output all results that static ones can produce but with different inputs. The idea with an analogue model resistors/capacitors is to make a simulation at each time step. Dynamic energy consumption and power profiles are obtain with dynamic models, one interest being to know for each moment the energy needed, which is an essential element to design production and distribution energy systems for instance.

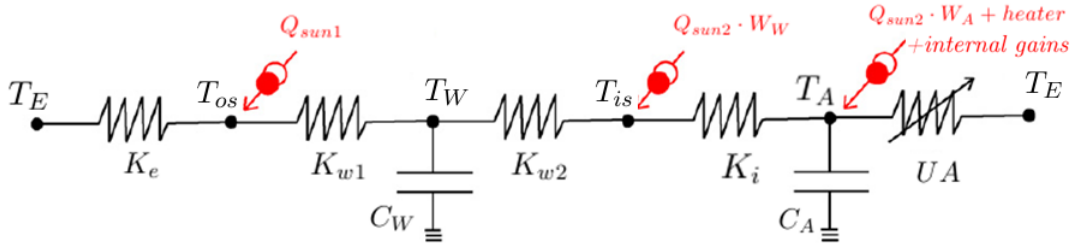


Figure 3.1: The thermal model for one zone building as an equivalent electric circuit

In the model 5R2C (5 resistors, 2 capacitors), inspired of the work of Kämpf and Robinson [21], the energy demand for space heating considers the heated space of a building as a single zone. The Figure 3.1 is the equivalent electric circuit where the nodes (air and walls) receive heat source as solar energy, internal gains or from a heating system. A simplified electric circuit 5R2C to simulate heat flows in buildings is enough accurate, as a starting point, and adapted for extrapolating the simulation to a set of buildings. This standard two-node resistance-capacitance model consider convective and conductive energy exchanges and permit to place a capacitance in the multi-layer wall. Free natural energy gains are the coupling of the thermal power released by inhabitants and the thermal power released by buildings equipments as the lightings and the electrical appliances.

K_e , K_i , K_{w1} , K_{w2} are respectively the conductances in (W/K) between the external part of the wall and the external temperature, the internal part of the wall and the ambient temperature, the external part of the wall and inside the wall and finally between inside the wall and the external part of the wall. Internal gains can be modelled according to EPFL [34] as gains of $5 W/m^2$. We consider here the accuracy of this parameter as sufficient and that a thinner model is not essential. UA is the conductance to the external environment through windows and ventilation. Nodes have thermal capacities, C_W of the heavy material (walls) and C_A ($W.s/K$) of the light material (internal). T_E , T_W , T_A are respectively the external temperature, the temperature inside the wall and the internal temperature of the air. T_{os} is the temperature at the external surface of walls and T_{is} is the temperature at the internal surface of walls. Q_{sun1} (W) represents the energy flux from the sun to the external wall surface. Q_{sun2} represents the energy flux from the sun that penetrates in the room, it is divided in two parts: W_W the proportion that goes on the wall surface node and W_A the proportion that goes on the air node. Lastly *heater* is the quantity of energy to add to the air node to keep the inside temperature at the setpoint temperature.

We respectively call K_1 and K_2 the equivalent conductances between T_E and T_W (left part of figure 3.1), and T_A and T_W :

$$K_1 = \frac{K_e \cdot K_{w1}}{K_e + K_{w1}}, \quad K_2 = \frac{K_i \cdot K_{w2}}{K_i + K_{w2}}$$

The general equation of energy conservation for each node is written as follow, with i and j representing two nodes of the electrical circuit and u the external excitation:

$$C_i \cdot \frac{dT_j}{dt} = \sum_{i=1, i \neq j}^n K_{ij} \cdot (T_i - T_j) + U_j \quad (3.8)$$

The equation (3.8) can also be expressed under a matrix form (3.9):

$$\frac{dT_j}{dt} = A \cdot T + B \cdot U \quad (3.9)$$

Where A and B are matrices of the equation system, in this model they do not depend of the time, their expressions are:

$$A = \begin{bmatrix} \frac{-(UA + K_2)}{C_A} & \frac{K_2}{C_A} \\ \frac{K_2}{C_W} & \frac{-(K_2 + K_1)}{C_W} \end{bmatrix} \text{ and } B = \begin{bmatrix} \frac{1}{C_A} & 0 & \frac{UA}{C_A} \\ 0 & \frac{1}{C_W} & \frac{K_1}{C_W} \end{bmatrix}$$

Based on this equation system the goal is to determine the temperature $T(t + \Delta t)$ knowing the value of $T(t)$. Δt being the time between two measurements, in this application it is fixed at 3600 seconds. We consider in the equation (3.10) the expansion of the Taylor series around the current value $T(t_0)$ only considering the first derivative:

$$T(t_0 + \Delta t) = T(t_0) + \Delta t \cdot T'(t_0) \quad (3.10)$$

To avoid the divergence that an explicit resolution scheme generate, due to a long time step of one hour, the equation (3.11) and the following present the implicit resolution scheme, the derivative is evaluated by backward derivative, with $\varepsilon(\Delta t)$ the error due to the derivative expansion.

$$T'(t_0) = \frac{(T(t_0) - T(t_0 - \Delta t))}{\Delta t} + \varepsilon(\Delta t) \quad (3.11)$$

By integrating it in the derivative expression of the equation (3.9) we can get the final implicit scheme:

$$T'(t_0 + \Delta t) = \frac{T(t_0 + \Delta t) - T(t_0)}{\Delta t} = A \cdot T(t_0 + \Delta t) + B \cdot U(t_0 + \Delta t) \quad (3.12)$$

That is to say:

$$T(t_0 + \Delta t) = (A \cdot T(t_0 + \Delta t) + B \cdot U(t_0 + \Delta t))\Delta t + T(t_0) \quad (3.13)$$

Which is equivalent to:

$$T(t_0 + \Delta t) - (A \cdot T(t_0 + \Delta t) + B \cdot U(t_0 + \Delta t))\Delta t = T(t_0) \quad (3.14)$$

We factorize $T(t_0 + \Delta t)$, with I the identity matrix:

$$T(t_0 + \Delta t)(I - A\Delta t) = T(t_0) + B \cdot U(t_0 + \Delta t)\Delta t \quad (3.15)$$

We finally have the expression of the implicit scheme:

$$T(t_0 + \Delta t) = (I - \Delta t \cdot A)^{-1}(T(t_0) + \Delta t \cdot B \cdot U(t_0 + \Delta t)) \quad (3.16)$$

The advantage of this scheme is the stability, but the calculation is more complex than in the explicit scheme due to the matrix inverse. This inconvenience become significant if thousands buildings are modelled. For Saint Félix, the calculation is done 5328 (number of hours of the heating period) times on each of the 622 buildings and lasts around 70 seconds while it is quasi instantaneous with the explicit model. Considering the Figure 3.1 and based on the implicit scheme (equation (3.16)) we get the equation (3.17), the full algorithm coded on MATLAB is presented on Annexe B:

$$\begin{bmatrix} T_A \\ T_W \end{bmatrix}_t = \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \Delta t \cdot \begin{bmatrix} \frac{-(UA + K_2)}{C_A} & \frac{K_2}{C_A} \\ \frac{K_2}{C_W} & \frac{-(K_2 + K_1)}{C_W} \end{bmatrix} \right)^{-1} \cdot \left(\begin{bmatrix} T_A \\ T_W \end{bmatrix}_{(t-\Delta t)} + \Delta t \cdot \begin{bmatrix} \frac{1}{C_A} & 0 & \frac{UA}{C_A} \\ 0 & \frac{1}{C_W} & \frac{K_1}{C_W} \end{bmatrix} \cdot \begin{bmatrix} u_A \\ u_W \\ T_E \end{bmatrix}_t \right) \quad (3.17)$$

With the external excitations on the air node and on the wall node:

$$u_A = Q_{sun2} \cdot W_A + heater + \frac{K_2}{K_{w2}} \cdot Q_{sun2} \cdot W_W$$

$$u_W = \frac{K_2}{K_i} \cdot Q_{sun2} \cdot W_W + \frac{K_1}{K_e} \cdot Q_{sun1}$$

The equation 3.18 gives explicitly the expression of the heating value for each time step:

$$heater = \frac{C_A}{\Delta t} \cdot (T_{setpoint} - T_A) - (-UA - K_2) \cdot T_{setpoint} - \frac{u_A + K_2 \cdot \frac{C_W \cdot T_W + \Delta t \cdot K_2 \cdot T_{setpoint} + \Delta t \cdot u_W}{\Delta t \cdot (-K_2 - K_1) - C_W}}{\Delta t \cdot (-K_2 - K_1) - C_W} \quad (3.18)$$

Implementing this algorithm on loops in MATLAB, heating demand hour per hour and for each building is computed and lasts 70 seconds. From the heating power needed throught exploitations are feasible as detailed in the section 3.4.

3.4 Comparisons and exploitations of results

The objective of this section is to present results of the static and dynamic models in term of consumptions, according to types, location and time. The results are get following hypothesis and choices, presented all along the report. As explained before, the test district is Saint Félix in order to compare outputs with the work of Garcia-Sanchez [5] and to verify relevancy of results and so of models.

3.4.1 Comparisons

Classifications of heating needs by age are summarized in table 3.2 for apartment buildings and in table 3.3 individual households. Heating needs got from static and dynamic models, are compared with MEDUS (Modelling Energy Demand at Urban Scale), model applied in Saint Félix developed by Garcia-Sanchez [5], APUR [36] applied for Parisian collective buildings and Dominique Braye for PREBAT [39] which are statistical studies based on data consumption ratios.

Results for apartments buildings relatively have interesting results, except for the first category of age which have important differences between the 3CL and the 5R2C. Moreover, estimation of heating needs for recent buildings seems to be underestimated in both models.

Results for individual houses are slightly more scattered. For all classes the dynamic model seems to underestimate energy consumption, indeed for all ages the consumptions are almost three times lower than in the PREBAT study. In addition, we can note that results get with statics and dynamics algorithms are quite similar especially for recent buildings.

Due to low energy consumption for buildings built after 1990, it is likely that the heat transfer coefficients were underestimated. A further update would be to differentiate the overall heat transfer coefficients between apartments and houses, this was not made due to a lack of data. Comparisons with PREBAT are not fully significant since buildings were not those of St Félix and experimental conditions are unknown. The comment for apartments is the same even if results are more comparable. Uncertainties appear mainly in two steps of the work and explain differences of final consumption. The first one is transformation of physical phenomenon to physical model and the second one, less significant, is the transformation of this model to the algorithm.

3.4.2 Exploitations

The originality of the work is to link physical results (consumption) to OrbisGIS. This subsection presents possibilities that the model can output. The figure 3.2 displays the results of energy consumptions with the static model. The consumption per square meter is a good indicator to consider the performances of buildings. The comparison of the map on figure 3.2 with real estates etiquettes has to be done with prudence, since the model developed in this project does not consider cooling, ventilation and domestic hot water contrariwise to classic EPCs. Another difference concern the period of measurements, in classic EPCs the consumptions are calculated on a full year, while the simulation of this project is based on the heating period. These differences






Geo-localized				MEDUS		APUR		PREBAT	
Period	Examples	HN(3CL)	HN(5R2C)	Period	HN	Period	HN	Period	HN
Before 1915		178	101	Before 1949	126	Before 1949	130	Before 1975	143
1915-1948		152	106						
1949-1974		134	80	1949-1974	144	1945-1967	176		
						1976-1981	90		
1975-1989		64	67	1975-1989	121	1982-1989	77	1975-1989	105
After 1990		19	47	After 1990	99	1990-1998	39	1990-2000	74

Table 3.2: Heating needs (HN) of apartments buildings in $kWh/m^2 \cdot yr$ for the static and dynamic models developed in this report, compared with MEDUS, APUR and PREBAT

seem to imply overestimation of energy consumptions, but it is actually not wholly true because few houses are equipped of cooling system in Nantes, the heating systems are rarely used between May and October. However, the most impacting difference concern the energy supply for DHW and ventilation which represent respectively about 20 % and 5 % of the final energy consumption depending on the age of buildings, according to CAUE [40] (Thermal efficient buildings have a larger part of domestic hot water consumption than energy intensive buildings).

The map, figure 3.2, permits to identify type of buildings that are energy intensive. Some geographical parameters seem to impact significantly the consumptions:

- Buildings with large footprints seem to consume less than buildings of small **size**.
- Some energy intensive buildings have a general **shape** elongated.
- It is rare to see buildings with lots of **attachments** consuming a lot of energy.

Geo-localized				MEDUS		PREBAT	
Period	Examples	HN(3CL)	HN(5R2C)	Period	HN	Period	HN
Before 1915		205	110	?	?	Before 1975	314
1915-1948		172	108				
1949-1974		175	97	1949-1974	178		
1975-1989		95	86	1975-1989	136	1975-1989	160
After 1990		32	45	After 1990	74	1990-2000	131

Table 3.3: Heating needs (HN) of individual households in $kWh/m^2 \cdot yr$ for the static and dynamic models developed in this report, compared with MEDUS and PREBAT

Actually, these parameters permits to define the shape ratio (m^{-1}) of buildings. In their work Caldera et al. [13] considered the shape ratio between the external surface and the gross volume as significantly influencing the consumption. This ratio is defined for one building as the external envelop area divided by the volume of the building. To confirm the impact of the shape ratio on the energy consumption, figure 3.3 links the two parameters and separates buildings by their age, where each point is one building.

Figure 3.3 confirms that the global energy consumption for recent buildings (age 5) is lower than for old buildings (age 1) but overall that the shape ratio strictly impact the consumptions. This graph also permit to conclude that it is important to get a good (small) shape ratio and that new buildings are less vulnerable to high shape ratio than old buildings. It is relevant to notice that small shape ratio are interesting for the energy consumption but that the comfort of occupants is often limited. Indeed, high ratio often implies large glazing and few neighbourship. Hence, the importance for town planers and architects to find equilibrated shape ratios.



Figure 3.2: Displaying of the yearly energy consumption for heatings of St Félix buildings. Green buildings are more efficient than red ones

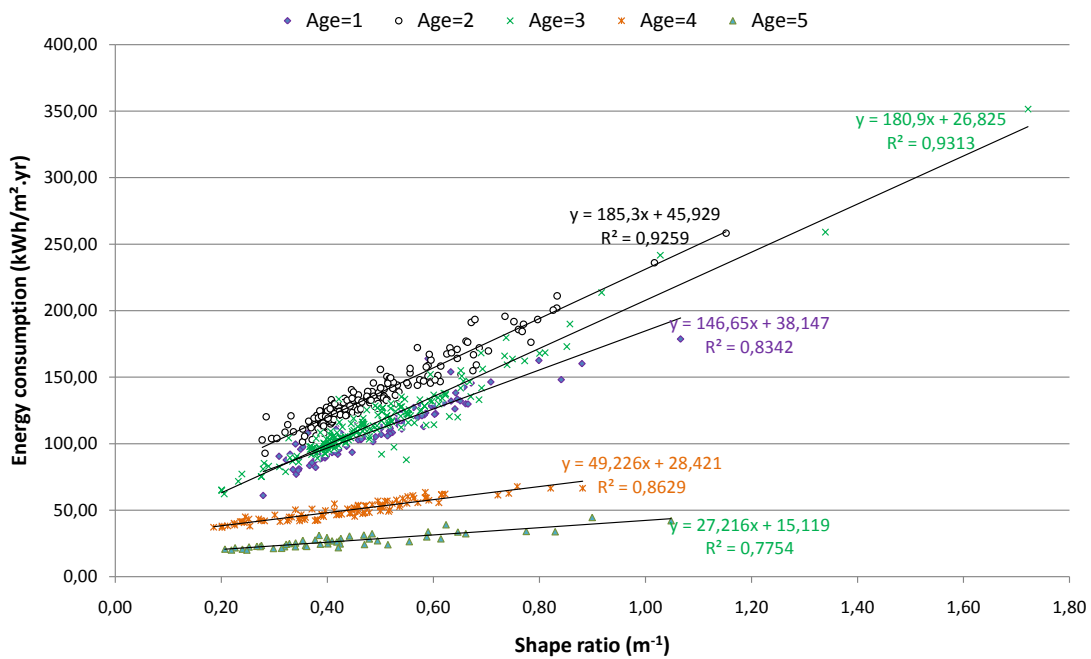


Figure 3.3: Energy consumption according the shape ratio and the age of buildings

Results presented figure 3.4 got with the 5R2C algorithm on MATLAB permit to display the influence of the external temperature on heating needs. The power needed is for the whole district, but the same kind of graphs can be displayed for individual buildings. The fluctuations of energy needs are important due to significant differences between days and nights, in term of free gains and so due the multitude number of abscissa points (5328). The graph in figure 3.4 shows as expected, that the energy needs are less important when the temperature is high and that the tendency of the curve rise from October to February then decrease till the end of the winter. This interaction temperature/power is confirmed by the figure 3.5 which is an zoom in of the month of December. One of the limit of the model are the slight fluctuations (end of December and beginning of January) which seem to appear randomly on the curve. The reasons of these curiosities are not determined at this step of the project but likely do not impact results.

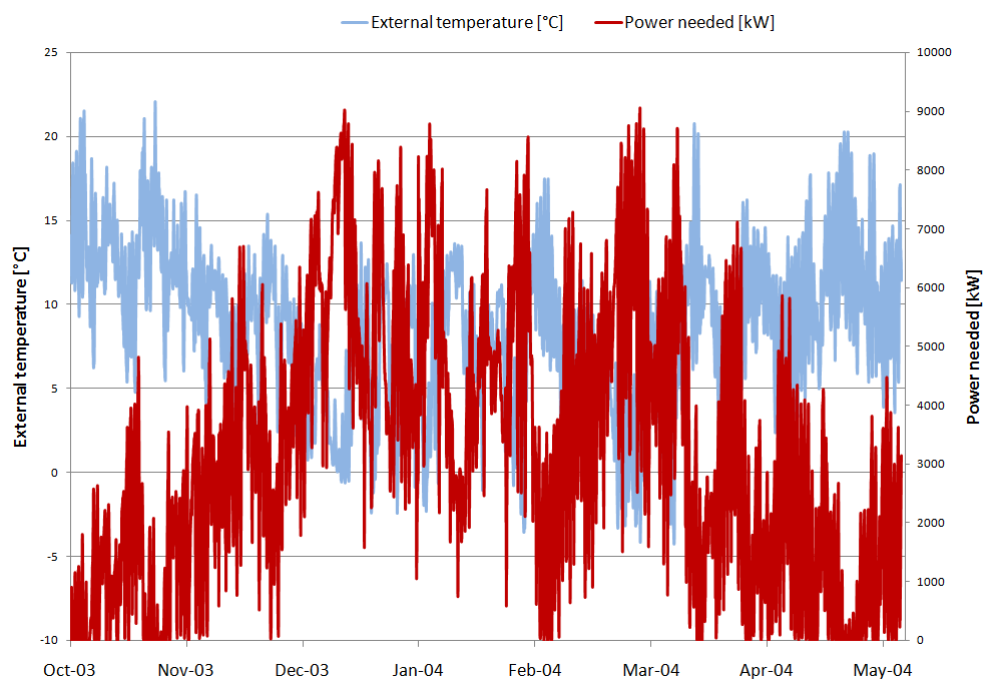


Figure 3.4: Temporal profile of simulated heating needs for the district of Saint Félix and the external temperature for the heating period 2003-2004

The applications of the dynamical thermal simulation at urban scale offer for instance the possibility to know the energy demand at each time of the winter. Dynamic models also give monotonic power graphs, obtained by classifying power needed, which are useful to design energy systems as district heatings. Figure 3.6 shows the monotonic power graph of a building (ID=88: 28 m^2 - older than 1915), where the base power is fixed at 60 % of the maximal one. On this graph the energy can be read as the air under the curve. To design and dimension heating systems monotonic curves are fundamental, in general operators try to supply the base energy (green) with renewable or fatal sources of energy and to complete the energy needs (grey) with gas or oil. These choices are often done at urban scale, thanks to the monotonic power curve of a set of building.

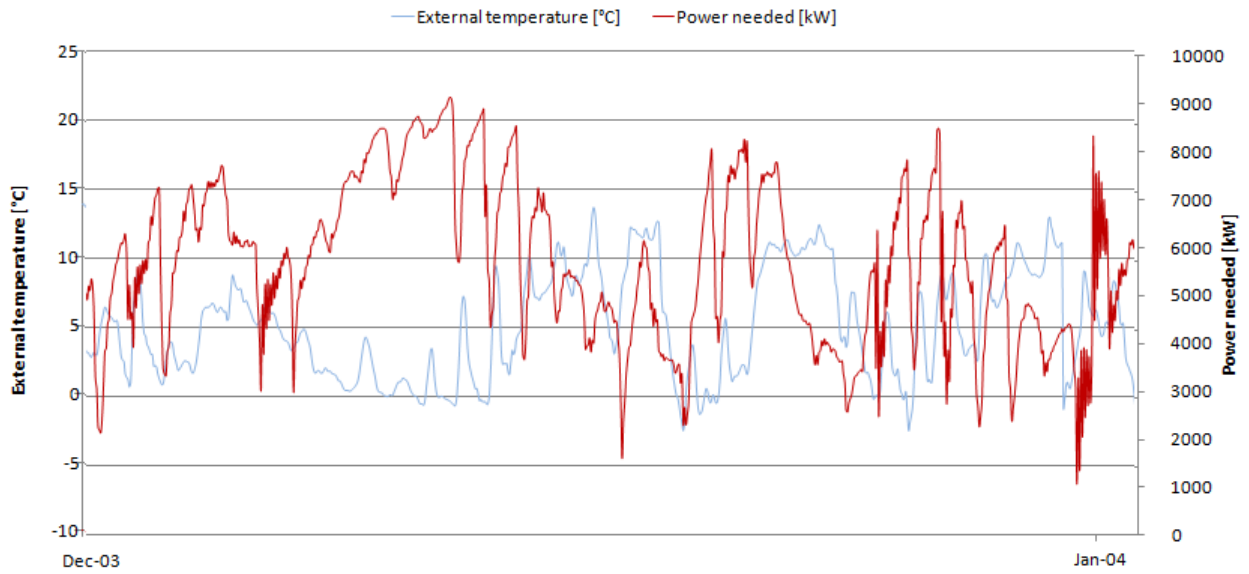


Figure 3.5: Zoom in of the figure 3.4 on the month of December

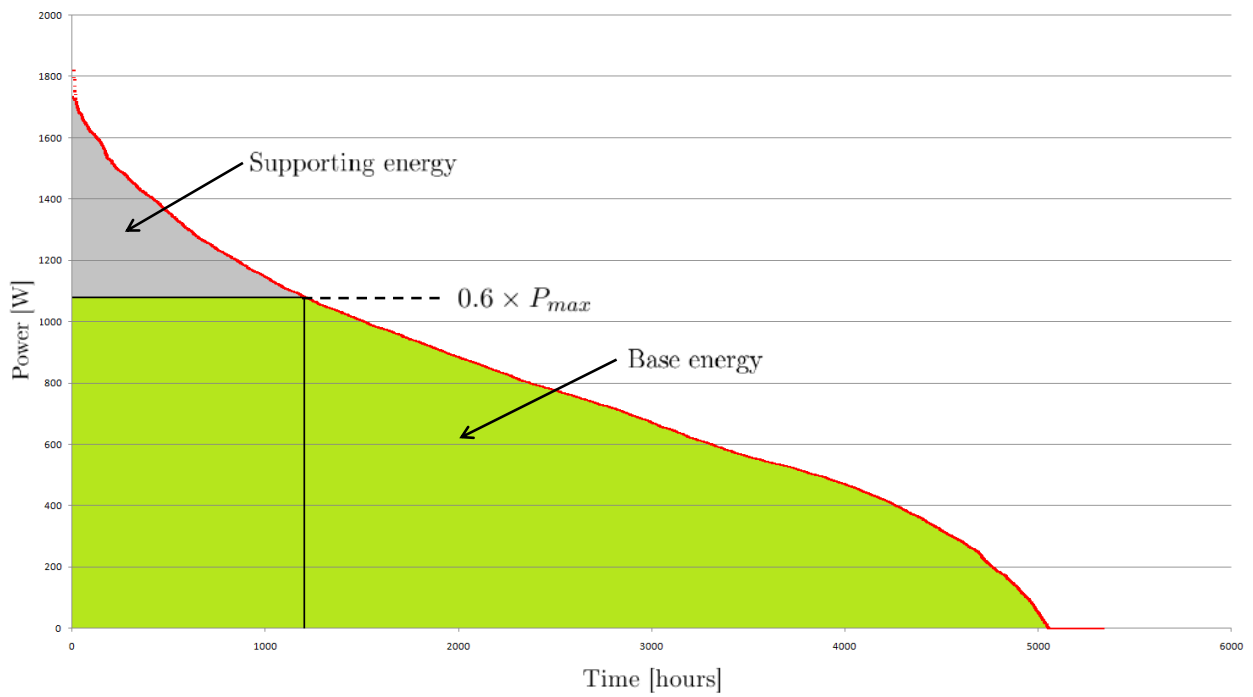


Figure 3.6: Classified power curve of the building number 88 and repartition of the base and the supporting energy for a separation at 60 % of the maximum power

Figures 3.7 and 3.8 illustrate the potential of the tool for operators in term of location of needs and details of consumptions. Figure 3.7 displays the thousandth maximum power value, reported by square meter for Saint Felix, needed during the heating period. This thousandth power is considered as relevant to dimension the maximum power of the heating system instead of considering the maximal power. The analyse of the map permit to note that collective buildings need a maximum power per square meter less important than individual and old buildings. These results on power are consistent with the tendency of heating energy consumption and similarities with figure 3.2 are evident. Figure 3.8 is get following another method, which consists in evaluating the needs of base energy and supporting energy by splitting both at 60 % of the peak power. As an example of the potential of the method, the map displays the percentage of supporting energy per building of the district. Here again, this information might be a decision aid for designers, operators and even urban planers. The results show a global homogeneity of the indicator and the majority of percentage are comprised between 6 and 7 % of supporting energy.

The tool informs on the quantity, the time repartition and the location of the heating energy consumption, these elements are fundamental for the management of needs/offers and in fine for the development of smart grids on urban areas.



Figure 3.7: Classification of the thousandth maximum power needed per square meter of floor

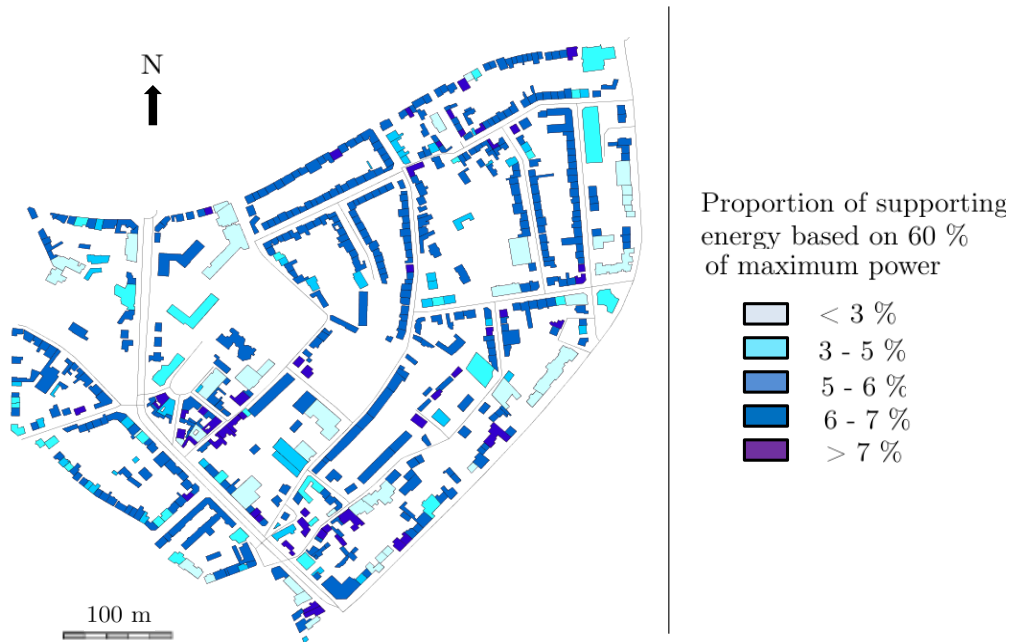


Figure 3.8: Percentage of supporting energy consumed by buildings considering the maximum based power at 60 % of the maximal power needed during the heating period

Some remarks should be exposed for a better understanding of the results. The theoretical consumptions and the measured ones are never identical. The difference between the two is due to several factors: The inaccuracy of the determination of parameters based on thermal regulations, the climate differences between years and the occupants behaviour faced to heating which is influenced by the energy price the billings mode (individual or collective). Knowledge on the equipments of heating systems could be something to think about to determine the carbon emissions and in fine display a similar map than the figure 3.2 where each building is associated to $CO_2/m^2/yr$ emissions. Indeed, knowing the heating energy emissions factors (gCO_2/kWh) of the systems, the illustration of the spatial repartition of carbon emissions would be persuasive tools for policy makers.

3.5 Conclusion: Project path

The figure 3.9 conclude this chapter and summarize the steps of the project and the overall approach, from the choice of the IRIS, to the algorithm detailed in appendix B which displays results.

In this Master thesis the estimation of the energy demand at urban scale follow a modelling strategy bottom-up. This strategy is an inductive reasoning, which lead to a sequence of processes produced from basic elements and organized by a typological approach. The originality of the project is the add of spatial component and so the geo-localization of data.

The selection of the residential neighbourhood Saint Félix is justify by a typology which present heterogeneous buildings in term of age. The plot database contains the three kinds of buildings but remarkable and industrial ones are deleted. This information is not kept in the data base used on OrbisGIS since all buildings are considered as residential. The type of building depends on the number of floors, apartment buildings have more than 2 floors. The age of construction is determined by coupling the field survey and using Google Street View. In the same time number of floors are counted and so the types of building determined. Based on the geometry and disposal of polygons; the surface, the perimeter, the attached perimeter, the number of attached building, the orientation and obstructions are computed and stored in the database. Building data depends on the two discrimination variables the age and the type of building. In parallel external temperature and solar radiation data should be collected for each time step, one hour in this project. Then all these data are organized and two algorithms are developed. A static model which permits to compute the energy consumption during the heating period and a dynamic model which permits to compute the power needed at each moment of the day and so a wide exploitation of results, notably displaying on maps.

Although results of the project are hopeful, it contains limits and some updates would permit to get a model more efficient. As presented in the section 3.1.2 on building data, the hypothesis in term of input data (heat transfer coefficient and air renewal) strongly impact final consumptions. The second limit of the present model reside in the modelling of spatial parameters which are often approximated. Indeed, the attachment take only into account the building footprints while a more advanced model would consider the relative height of attached buildings. Moreover, orientation and obstructions could be modelled by specialized tools while in this project only OrbisGIS is used. Lastly, the RC model is also source of errors and thinner modelling would permit to get results closer to those of other studies presented in section 3.4.1.

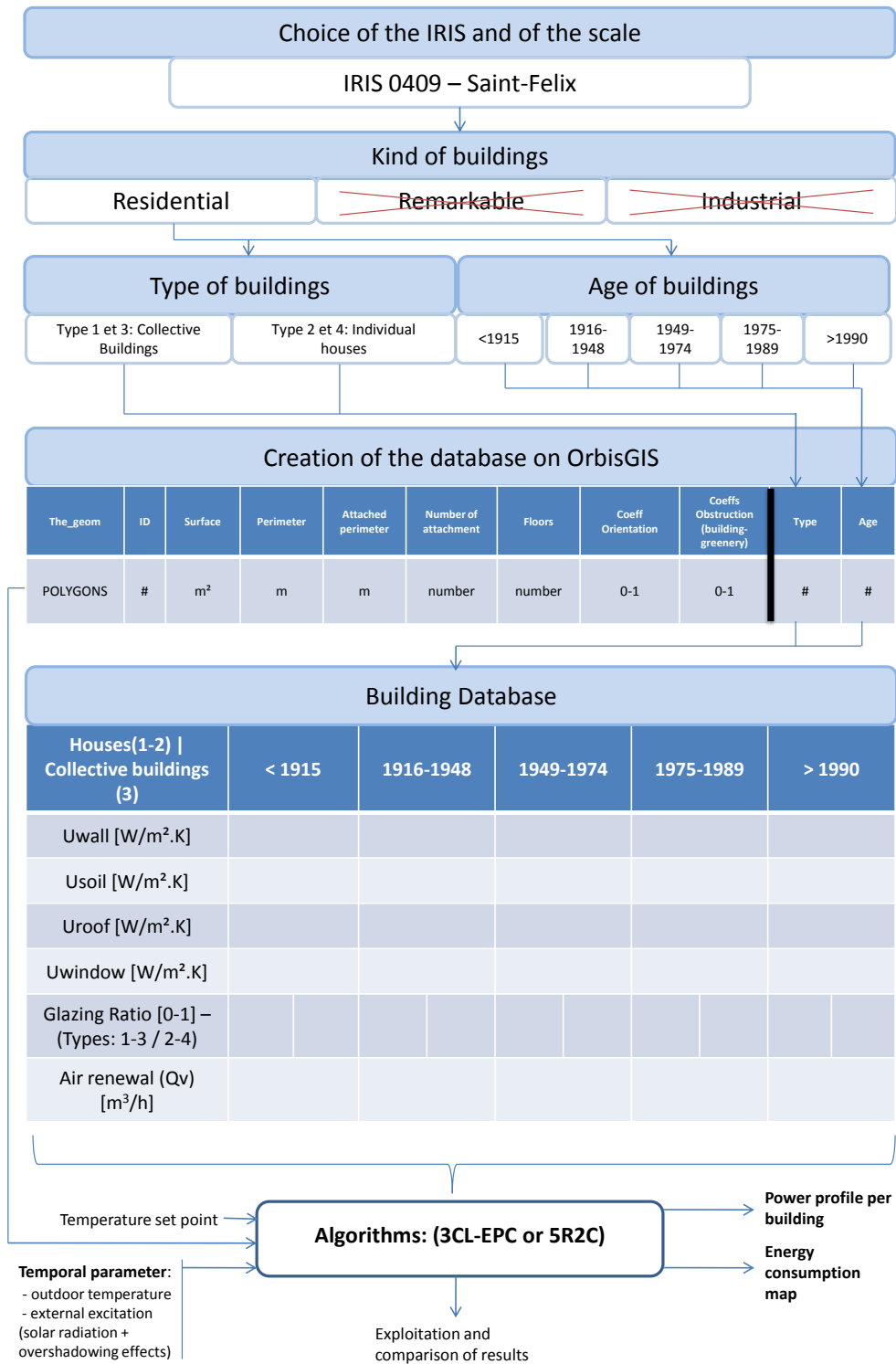


Figure 3.9: General scheme of the project path

Chapter 4

Conclusion

This Master thesis fits in the context of the energy demand modelling at the urban scale.

First of all, we gave in this report an analysis of the simulation objectives of the energy demand at urban scale. Then, we exposed the three main components of the project, namely informations on building engineering physics, the Geographical Information Systems and the precaution to take for an archetype approach.

Based on the software OrbisGIS, we proposed models to simulate complex phenomena as the impact of the orientation and the impact of obstructions in the context of dense urban area. In parallel to this work on GIS, it was important to consider the specifications of Saint Félix to organize a typological approach coherent with the housing stock.

Using the typological hypothesis, two models were developed, a static one able to output energy consumptions over a long time period and a dynamic one more powerful, which is able to generate power needed for each time step. For both models, every building of the district were studied thanks to algorithms coded in MATLAB. The flexibility of the model, which is often a limit in the problematic of energy modelling at urban scale, could be tested on other neighbourhood, even if it is likely that hypothesis valid for Saint Félix are also valid for similar French districts. The most important limit being the knowledge of ages of constructions, since most of parameters are given by the geographical database.

Results from this work are encouraging but improvements on the spatial modelling and on the dynamic model could permit to get very accurate results of energy consumption and operational for policy makers. One of the application of this tool is the identification of areas with high heat demand, which could be targets for renovation measures or for the designing of district heating networks. The logical following work to lead, appears to apply the tool to another district with concrete objectives to verify the flexibility and the accuracy of results. Moreover, combination with MEDUS [5] (approach by households) could generate another model able to work ether with buildings input data or households input data according to availabilities.

From a pure personal point of view, this Master thesis will stay as a rewarding experience, which permits me to discover the research environment. This project developed in me a strong interest of the theme of energy applied in buildings, which implied the desire unaccomplished to continue in Thesis; the industrial domain being also very attractive to me.

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Part II

Appendices

Appendix A

SQL code

A.1 Orientation

Another solution to take into account the orientation is to define the main orientation as the direction of the longest side of the bounding rectangle of the studied building. Here below is method and the SQL code developed:

- **Step 1:** Polygons are associated to the minimum encompassing rectangle as shown in Figure A.1

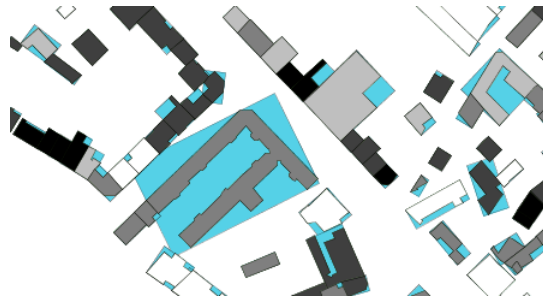


Figure A.1: Sample of buildings and their associated minimum encompassing rectangles (blue)

```
SQL: CREATE TABLE polygons AS SELECT ST_MinimumRectangle(the_geom) AS  
the_geom, ID from etude_street_view_2;
```

- **Step 2:** Selection of the smallest polygon side, minimum diameter
SQL: CREATE TABLE lines AS SELECT ST_MinimumDiameter(the_geom) AS the_geom,
ID from polygons;
- **Step 3:** Calculation of the azimuth
 - Add of a numeric field for the azimuth:
SQL: ALTER TABLE lines ADD COLUMN azimuth DOUBLE;

- Update of the azimuth (calculated between the start point and the end point of the segment and update of the azimuth):

SQL: UPDATE lines SET azimuth=ST_AZIMUT(ST_STARTPOINT(the_geom), ST_ENDPOINT(the_geom));

- **Step 4:** Conversion from radian to degree

- Add of a numeric field for the absolute azimuth in degree:

SQL: ALTER TABLE lines ADD COLUMN azimuth_degree DOUBLE;

- Update of the azimuth in degree:

SQL: UPDATE lines SET azimuth_degree= Abs(azimut*180/pi());

Once the orientations calculated on OrbisGIS, orientations are associated to coefficients impacting on the energy gains. If the main length of the bounding rectangle is oriented to the south the energy gains are more important than if it was toward the east.

After having generate one coefficient for each building a map can be drawn, Figure A.2 where buildings are coloured depending on their orientation (coefficient). Red buildings are those which have a favourable orientation and blue ones does not.



Figure A.2: Impact of solar gains depending on the main orientation of the encompassing rectangles of buildings

Appendix B

MATLAB codes

B.1 Static algorithm: EPC

```
% Opening of the xls file to get the input data
data=xlsread('C:\Users\qdarak12\...\attributs.xlsx','attributs');

% Setting of parameters
Qheat=zeros(622,1);
Qm2=zeros(622,1);
matriceconso = zeros(622,2);
c=0.34; % Volumetric heat of the air [Wh/(m3.K)]
n=2.9; % Building inertia (3CL). heavy=3.6, medium=2.9, light=2.5
DH=51382; % Degree Hour [K.h]
highfloor=2.5; % [m]
Qin=22.9; % [kWh/m2]
Qout=599; % [kWh/m2]
Fts=0.425; % 0.85(rideaux)*0.5(50% du rayon incident)

% First loop which simulate buildings one by one
for i=1:622

    % Meaning of each data(i,x):
    data(i,1); % ID
    data(i,2); % Surface
    data(i,3); % Perimeter
    data(i,4); % Attached perimeter
    data(i,5); % Attached buildings
    data(i,6); % Number of floors
    data(i,7); % Building type
    data(i,8); % Age
    data(i,9); % Coefforientation
```

```
data(i,10); % Greenery
data(i,11); % Number of obstruction
data(i,12); % Coefficient of obstruction (buildings)
data(i,13); % Compacity
```

```
% Features depending on the age of buildings
```

```
if data(i,8)==1
    Uwall=2.3;
    Usoil=4.8;
    Uwindow=4.5;
    Uroof=0.4;
    Qv=2;
elseif data(i,8)==2
    Uwall=2.9;
    Usoil=5.6;
    Uwindow=4.5;
    Uroof=0.3;
    Qv=1.6;
elseif data(i,8)==3
    Uwall=2.7;
    Usoil=1.7;
    Uwindow=4.5;
    Uroof=0.3;
    Qv=1.3;
elseif data(i,8)==4
    Uwall=1;
    Usoil=0.6;
    Uwindow=3.1;
    Uroof=0.3;
    Qv=1;
else
    Uwall=0.5;
    Usoil=0.4;
    Uwindow=1.9;
    Uroof=0.2;
    Qv=0.5;
end
```

```
% Features on the Glazing Ratio
```

```
if data(i,8)==1 & data(i,7)==2 | data(i,7)==4
    GR=0.164;
elseif data(i,8)==1 & data(i,7)==1 | data(i,7)==3
    GR=0.112;
elseif data(i,8)==2 & data(i,7)==2 | data(i,7)==4
    GR=0.162;
```

```

elseif data(i,8)==2 & data (i,7)==1 | data (i,7)==3
    GR=0.134;
elseif data(i,8)==3 & data (i,7)==2 | data (i,7)==4
    GR=0.26;
elseif data(i,8)==3 & data (i,7)==1 | data (i,7)==3
    GR=0.28;
elseif data(i,8)==4 & data (i,7)==2 | data (i,7)==4
    GR=0.254;
elseif data(i,8)==4 & data (i,7)==1 | data (i,7)==3
    GR=0.452;
elseif data(i,8)==5 & data (i,7)==2 | data (i,7)==4
    GR=0.32;
else
    GR=0.436;
end

% Facades losses deperdition [W/K]
DP=(data(i,3)-data(i,4))*data(i,6)*highfloor*((1-GR)*Uwall+GR*Uwindow)+
    data(i,2)*(Usoil+Uroof);

% Air renewal losses [W/K]
DR=c*data(i,2)*data(i,6)*highfloor*Qv;

% Thermal coefficient of heat losses [W/K]
GV=DP+DR;

% Transparent area equivalent south Sse [m2]
Sse=(data(i,3)-data(i,4))*data(i,6)*highfloor*GR*data(i,9)*data(i,10)*
    data(i,12)*Fts;

% Annual heating demand coefficient BV and steps to get it
X=(Qin*(data(i,2)*data(i,6))+Qout*Sse)/(0.001*GV*DH);
F=(X-X^n)/(1-X^n);
BV=GV*(1-F);

% Heating needs by building [kWh/an]
Qheat(i)=BV*DH/1000;

% Heating period consumption [kWh/(m2.an)]
Qm2(i)=Qheat(i)/(data(i,2)*data(i,6));

% Creation of a table displaying ID | Qm2
matriceconso(i,1)=data(i,1);
matriceconso(i,2)=Qm2(i);
end

```

```

% Energy use per square meter
matriceconso; % [kW/m2/yr]
% Calculation of St Felix heat consumption for the heating period
consotot=sum(Qheat(:)/1000); % [MWh]

```

B.2 Dynamic algorithm: 5R2C

```

% Opening of the xls files to get the input data on buildings and meteo
data=xlsread('C:\Users\qdarak12\...\5R2C\attributs.xlsx','attributs');
data2=xlsread('C:\Users\qdarak12\...\5R2C\metedata.xlsx','Feuill1');

```

```

heater = zeros(5328,622);
heaterm2 = zeros(5328,622);
consokWh = zeros(5328,622);
matriceconso=zeros(622,2);
tempW=zeros(5328,622);
tempA=zeros(5328,622);
tempext=zeros(5328,1);
floorhigh=2.5; % The average high per floor
Tsetpoint=18; % Setpoint temperature
dt=3600; % Time step [s]
hi=5; % Internal convection [W/m2.K]
he=6; % Internal convection [W/m2.K]
Ceff=500000; % Thermal capacity of the floor and walls [J/(K.m2)]
Cpair=1004; % Specific heat [J/(kg.K)]
rho=1.2; % Density of air [kg/m3]
Qh=5; % Internal gains (W/m2)
Fts=0.425; % 0.85(curains)*0.5(50% of incident beam)
Ww=0.5; % Fraction of solar radiation that impact internal wall
Wa=1-Ww; % Fraction of solar radiation that impact indoor air

```

```

% First loop which simulate buildings one by one
for i=1:622

```

```

    % Meaning of each data(i,x):
    data(i,1); % ID
    data(i,2); % Surface
    data(i,3); % Perimeter
    data(i,4); % Attached perimeter
    data(i,5); % Attached buildings
    data(i,6); % Number of floors
    data(i,7); % Building type
    data(i,8); % Age
    data(i,9); % Coefforientation

```

```

data(i,10); % Greenery
data(i,11); % Number of obstruction
data(i,12); % Coefficient of obstruction (buildings)
data(i,13); % Compacity

```

%Internal and external convection not taken into account U:

```

if data(i,8)==1
    Uwall=1/(1/2.3-1/hi-1/he);
    Usoil=1/(1/4.8-1/hi-1/he);
    Uwindow=4.5;
    Uroof=1/(1/0.4-1/hi-1/he);
    Qv=2;
elseif data(i,8)==2
    Uwall=1/(1/2.9-1/hi-1/he);
    Usoil=1/(1/5.6-1/hi-1/he);
    Uwindow=4.5;
    Uroof=1/(1/0.3-1/hi-1/he);
    Qv=1.6;
elseif data(i,8)==3
    Uwall=1/(1/2.7-1/hi-1/he);
    Usoil=1/(1/1.7-1/hi-1/he);
    Uwindow=4.5;
    Uroof=1/(1/0.3-1/hi-1/he);
    Qv=1.3;
elseif data(i,8)==4
    Uwall=1/(1/1-1/hi-1/he);
    Usoil=1/(1/0.6-1/hi-1/he);
    Uwindow=3.1;
    Uroof=1/(1/0.3-1/hi-1/he);
    Qv=1;
else
    Uwall=1/(1/0.5-1/hi-1/he);
    Usoil=1/(1/0.4-1/hi-1/he);
    Uwindow=1.9;
    Uroof=1/(1/0.2-1/hi-1/he);
    Qv=0.5;
end

```

% Features on the Glazing Ratio

```

if data(i,8)==1 & data(i,7)==2 | data(i,7)==4
    GR=0.164;
elseif data(i,8)==1 & data(i,7)==1 | data(i,7)==3
    GR=0.112;
elseif data(i,8)==2 & data(i,7)==2 | data(i,7)==4
    GR=0.162;

```



```

elseif data(i,8)==2 & data (i,7)==1 | data (i,7)==3
    GR=0.134;
elseif data(i,8)==3 & data (i,7)==2 | data (i,7)==4
    GR=0.26;
elseif data(i,8)==3 & data (i,7)==1 | data (i,7)==3
    GR=0.28;
elseif data(i,8)==4 & data (i,7)==2 | data (i,7)==4
    GR=0.254;
elseif data(i,8)==4 & data (i,7)==1 | data (i,7)==3
    GR=0.452;
elseif data(i,8)==5 & data (i,7)==2 | data (i,7)==4
    GR=0.32;
else
    GR=0.436;
end

% Conductances
% External convection [W/K]
Ke=he*(floorhigh*(data(i,3)-data(i,4))*data(i,6)*(1-GR));

% Internal convection [W/K]
Ki=hi*(floorhigh*data(i,3)*data(i,6)*(1-GR)+2*data(i,2));

% Conductance of the wall [W/K]
Kw=Uwall*(floorhigh*(data(i,3)-data(i,4))*data(i,6)*(1-GR))+data(i,2)*
(Usoil+Uroof);
Kw1=2*Kw;
Kw2=2*Kw;

% Equivalent conductances
K1=(Ke*Kw1)/(Ke+Kw1);
K2=(Ki*Kw2)/(Ki+Kw2);

% Windows exchanges and air renewal [W/K]
UA=Uwindow*(floorhigh*(data(i,3)-data(i,4))*data(i,6)*GR)+0.34*
data(i,2)*data(i,6)*floorhigh*Qv;

% Inertia (heavy wall and floors) - Thermal capacity [J/K]
CW=Ceff*data(i,6)*data(i,2);

% Inertia (air and furniture) - Thermal capacity [J/K]
CA=floorhigh*data(i,2)*data(i,6)*rho*Cpair;

% Equivalent useful surface that recover the solar radiation
Suseful=(data(i,3)-data(i,4))*data(i,6)*floorhigh*GR*Fts*data(i,9)*

```

```

data(i,10)*data(i,12);

% Internal gains
Qin=Qh*data(i,2)*data(i,6);

heater(1,i)=0;
consokWh(1,i)=0;
T=[Tsetpoint;Tsetpoint];
tempA(1,i)=Tsetpoint;
tempW(1,i)=Tsetpoint;

% Second loop to simulate every hour of the heating period
for j=2:5328

    % Meaning of data2(j,x):
    data2(j,1); % External temperature
    data2(j,2); % Solar radiation

    tempext(j,1)=data2(j,1);
    Qsun1=data2(j,2)*(1-GR)*Suseful/GR;
    Qsun2=data2(j,2)*Suseful;

    % Solicitations
    ua=UA*tempext(j,1)+(K2/Kw2)*(Qsun2*Ww)+Qsun2*Wa+Qin+heater(j-1,i);
    uw=(K2/Ki)*Qsun2*Ww+(K1/Ke)*(Ke*tempext(j,1)+Qsun1);

    % Temperature, T is a vector [TP,TA]
    T=( [1,0;0,1] - dt*[(-UA-K2)/CA,K2/CA;K2/CW,(-K2-K1)/CW] ) \ (T+dt*[
        1/CA,0,UA/CA;0,1/CW,K1/CW]*[Qsun2*Wa+heater(j-1,i)+(K2/Kw2)*
        (Qsun2*Ww);(K2/Ki)*(Qsun2*Ww)+(K1/Ke)*Qsun1;tempext(j,1)]);

    % Store and display temperatures of T
    tempA(j,i)=T(1);
    tempW(j,i)=T(2);

    % Heating needs
    heater(j,i)=(CA/dt)*(Tsetpoint-tempA(j-1,i))-(-UA-K2)*Tsetpoint-
    ua+K2*((CW*tempW(j-1,i)+dt*K2*Tsetpoint+dt*uw)/(dt*(-K2-K1)-CW));

    % Heatings needs per square meter
    heaterm2(j,i)=heater(j,i)/(data(i,2)*data(i,6));

    % There is no modelling of the cooling system:
    if heater(j,i)<0
        heater(j,i)=0;

```

```

        else
        end
        consokWh(j,i)=consokWh(j-1,i)+heater(j,i)/1000;
    end

    % Creation of a table displaying ID / Qm2
    matriceconso(i,1)=data(i,1);
    matriceconso(i,2)=consokWh(5328,i)/(data(i,2)*data(i,6));
end
% Energy use per square meter
matriceconso; % [kW/m2/yr]
% Calculation of St Felix heat consumption for the heating period
consotot=sum(heater(:)/1000000);

% Power needed for the whole district for each time step
district=zeros(5328,1); %kWh
tempmean=zeros(5328,1);
for j=1:5328
    district(j)=sum(heater(j,:))/1000;
    tempmean(j)=mean(tempA(j,:));
end
end

```

Appendix C

Detailed values of U

Here below is the detailed Table 3.1 of the overall heat transfer coefficients with data sources from Alexis Monteil, APUR and 3CL.

Age	U_{roof}	U_{floor}		U_{wall}			U_{window}	
Source	Monteil	Monteil	3CL	Monteil	APUR	3CL	Monteil	APUR
Before 1915	0.4	4.8	?	2.7	2	?	4.7	4.2
1915-1948	0.3	5.6	?	3.7	2.1	?	4.7	4.2
1949-1974	0.3	1.5	2	2.7	2.8	2.5	4.7	4.2
1975-1989	0.3	0.5	0.8	0.5	1.5	0.9	3.5	2.8
After 1990	0.2	0.5	0.4	0.4	0.6	0.4	2.6	1.2

Table C.1: Values of U [$W/m^2/K$], heat transfer coefficients of roofs, floors, walls and windows, according to the age

Spatial approach of the energy demand modelling at urban scale

Approche spatialisée de la modélisation de la demande d'énergie à l'échelle urbaine.

Abstract in english

In the European Union, the residential building sector is responsible for about 22 % of the total energy consumption. Over the last decades policy-makers recognized the high potential of this sector to contribute towards reductions of CO_2 emissions through the energy consumption reduction.

Thermal buildings models is the subject of several researches and several model tools resulted in. Diversity of local contexts, data availability and stakeholders goals lead to search flexible models, with ability to create information for different application. However, renewal of buildings are decided at urban scale, hence the interest to expend the knowledge of the energy demand at a local scale instead of single building.

The main goal of this stage is to link three well-known and complementary approaches: The physics of buildings, the typological approach and the Geographical Information Systems. By exploring the potential of bottom-up approaches, the models existing for single buildings are extrapolated for a complete set of households in a neighbourhood.

Two heating demand models at local scale have been developed and tested on the neighbourhood of St Felix in Nantes. The first one is static and mainly inspired of EPCs (Energy Performance Certificates) while the second one is dynamic and funded on an electrical analogy (5R2C). Both of them couple GIS, the typological approach and building physics. Results are analysed to check relevancy of the prototypical approach and to study energy retrofitting potential from different actions.

Keywords

Buildings, GIS, MATLAB, Thermal models, Urban scale

Résumé en français

Dans l'Union Européenne, le secteur des bâtiments résidentiel est responsable d'environ 22 % des consommations énergétique. Depuis plusieurs décennies, les politiques reconnaissent le potentiel de ce secteur à pouvoir contribuer significativement à la réduction des émissions de gaz à effet de serre grâce à la réduction des consommations énergétique.

La modélisation thermique des bâtiments fait l'objet de nombreux travaux de recherche et de nombreux outils de modélisation en ont aboutis. Néanmoins, les larges actions de rénovation se décident à l'échelle locale, d'où l'intérêt de connaître les demandes en énergie à l'échelle du quartier et non plus à celle du bâtiment individuel.

L'objectif de ce stage est de lier trois approches maîtrisées: La physique des bâtiments, l'approche typologique et les Systèmes d'Informations Géographiques. En explorant le potentiel des approches ascendantes, les modèles existants pour les bâtiments seuls sont extrapolés pour un ensemble de logements d'un quartier.

Deux modèles de demande en chauffage sont développés et testés à St Félix à Nantes. Le premier est statique et principalement inspiré des DPE (Diagnostiques de Performance Energétique) alors que le deuxième est dynamique et fondé sur une analogie électrique (5R2C). Les deux approches couplent les SIG, l'approche typologique et la physique des bâtiments. Les résultats sont analysés pour vérifier l'intérêt de l'approche typologique et pour étudier le potentiel d'amélioration du rendement énergétique de différentes actions.

Mots-clés

Bâtiments, SIG, MATLAB, Modèles thermique, Echelle urbaine