thesis

multiscale information management for historic districts´ energy retrofitting

a framework • a methodology • a model

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PhD Thesis

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MULTISCALE INFORMATION MANAGEMENT

FOR HISTORIC DISTRICTS´ ENERGY RETROFITTING

A framework

A methodology

A model

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ABSTRACT

European Historic Urban Districts are highly appreciated by their inhabitants and visitors and they can be considered as one of the most valuable collective achievements of the European culture. The preservation of our urban heritage requires the protection of the social context as well as the preservation of the authenticity and integrity of its physical materiality. That means to improve the quality of life of their inhabitants as well as the sustainability of the historic districts. This dissertation analysed the Historic Urban Districts as complex energy and informational systems in order to address the challenge to improve their sustainability and liveability while protecting their cultural values.

First, a methodological framework for energy retrofitting in all its phases has been defined based on a strategic information management and from a multiscale perspective. Secondly, a decision making methodology that allows the modelling of the historic city and the selection of the best strategies has been developed. In order to support the whole system a multiscale data model has been designed. Finally, the historic city of Santiago de Compostela has been selected for the implementation.

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List of Abbreviations

AEC: Architecture, Engineering and Construction

ADE: Application Domain Extension

AHP: Analytic Hierarchy Process

BIM: Building information Model

CAD: Computer Aided Design

CityGML: City Geography Markup Language

CMS: Content Manager System

DM: Decision Making

DSS: Decision Support System

EC: European Commission

EEIM: Energy Efficiency Improvements Measures

EP: Energy Performance

ES: Energy Saving

EU: European Union

GIS: Geographic Information System

HS: Heritage Significance

HUD: Historic Urban District

IFC: Industry Foundation Classes

INSPIRE: Infrastructure for Spatial Information in the European Community

IAQ: Indoor Air Quality

KPI: Key Performance Indicators

LCC: Life Cycle Cost

LIS: Low impact solutions

LiDAR: Light Detection and Ranging

LoD: Levels of Detail

LoDM: Levels of Decision making

NPV: Net Present Value

OGC: Open Geospatial Consortium

PE: Plan especial de protección e rehabilitación da cidade histórica
(Special Protection and Rehabilitation Plan for the Historic City Core of Santiago de Compostela)

RES: Renewable Energy Solutions

ROI: Return of Investment

TC: Thermal Comfort

TM: Transferable Models

UN: United Nations

WHS: World Heritage Site

XML: Extensible Markup Language

0 OBJECTIVES AND STRUCTURE

Ever tried. Ever failed. No matter.
Try Again.
Fail again. Fail better.
Samuel Beckett

European Historic Urban Districts (HUDs) are highly appreciated by their inhabitants and visitors and can be considered as one of the most valuable collective achievements of the European culture. The HUDs are an example of urban rationality and efficiency in plenty of their intrinsic characteristics: their density and mix of uses, their use (and reuse) of local and low embodied energy building materials as wood, stone or earth, their use of solar energy in form of natural lighting and thermal inertia or their walkable size among others. HUDs have a bioclimatic wisdom and a sustainable potential to be exploited.

They were built in a totally different technological and energetic context, in order to address different expectations of living quality and comfort. But they have evolved organically, adapting themselves to each era, in an attempt to answer to the needs of their inhabitants. Therefore, nowadays the sustainable conservation of the HUDs must be linked with the design of strategies to reduce maintenance costs, energy consumption and CO^2 but also to increase the comfort and the liveability. In order to support this decision making (DM) process, which will manage the evolution of the HUDs in a respectful and sustainable way, proper tools and technologies have to be found, adapted or created.

The contemporary sustainable urban planning and management can largely benefit from strategic information management. This informational approach, which is in the roots of the Smart City concept, can convert the urban environments into innovation ecosystems supported by information, technology, and collaboration among different stakeholders. The informational complexity of HUDs as urban systems due to their spatial, social and cultural richness, but also as results of their vulnerability, makes them exceptional beneficiaries of this approach. Information management technologies can be put at the service of renovation, regeneration and preservation processes of our urban heritage placing the historical environments in a central role in urban innovation.

0.1 Background

One of the antecedents of this research is the master thesis "Propuesta metodológica para una aproximación energética-patrimonial a la ciudad histórica" ("A methodological proposal for a heritage and energy approach to the historic city") (Egusquiza 2010) carried out in the framework of the Master's degree in Urban Management and Valuation of the Polytechnic University of Catalonia (UPC).

The research of this dissertation has been undertaken mainly within the on-going EFFESUS project[1]. EFFESUS (Energy Efficiency for EU Historic Districts' Sustainability) is a research project funded by the European Commission under its Seventh Framework Programme. The goal is to investigate the energy efficiency of European HUDs and developing technologies and systems for its improvement, especially the development of a methodology and a software tool to assess energy retrofitting interventions in HUDs. Parts of this research have been conducted also within another two projects: REACT[2] and FASUDIR[3].

0.2 Scope of the research

The main objective of this research is to develop a methodological framework in order to identify and implement the best energy retrofitting strategies for HUDs through a DM methodology and a multiscale information model. The scope of this research falls in the intersection of different domains as cultural heritage preservation, energy efficiency improvement and information management.

Cultural heritage preservation is a highly specialized sector in Europe with a long tradition that has to face the challenge of improving and updating historical buildings to modern standards while fulfilling very strict requirements of conservation principles. Consequently, it is a sector easily inclined to accept new technologies as long as the respect for the cultural heritage values is guaranteed. The cultural richness of historic urban environments and the obligation to document and disseminate this richness involve a great potential for new spatial information technologies. The analysis, visualization and processing of existing and generated data can support the DM for the improvement of the historic environments in different fields. If HUDs have to evolve to address the requirements of each era, the search for energy sustainability and the improvement of liveability has to be one of their contemporary goals.

Traditionally the cultural heritage domain has been focused in buildings with the highest heritage significance (castles, palaces, cathedrals…) in order to ensure their conservation. But when sustainability, energy savings and improvements of quality of life have to be addressed, the focus has to be established in the residential

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[1] EFFESUS Project (Energy Efficiency for EU Historic Districts' Sustainability. FP7/2012-2016 grant agreement n° 314678) http://www.effesus.eu/

[2] REACT Project (Resilience, Accessibility and Sustainability for Historic Cities), under reference number IPT-2011-0969-380000 within the MINECO INNPACTO programme

[3] FASUDIR Project (Friendly and Affordable sustainable Urban districts Retrofitting. FP7/2013-2016 grant agreement n° No 609222) http://www.fasudir.eu/

buildings for their impacts on the citizens but also for quantitative reasons as residential buildings represent the 75% (Economidou et al. 2011) of the built heritage. This research is focused on historic districts, mainly with residential function, composed by preindustrial buildings not necessarily protected by heritage legislation but with heritage significance (HS).

0.3 Motivation

Since the Charter of Leipzig [4] fomented the sustainable development of cities through the improvement of the energy performance (EP) of the existing building stock, the energy rehabilitation of existing buildings and districts has been within the EU main priorities. From another complementary perspective, the Amsterdam Declaration[5] established that the protection of the social context of a historic area is as necessary as the conservation of its buildings, turning the liveability of the historic areas into a requirement for their preservation. Within this context, in the last years, several historic district and cities have been aware about their role as opportunity zones for sustainability and urban efficiency and they have activated interesting initiatives to try to make their historic environments more sustainable and friendly while preserving their HS. But there is not a common generic framework that could support those projects from a holistic perspective. The motivation for the work done with this research was to provide a proposal for such a framework that would manage two crucial issues: the scale and the information.

Nowadays it is broadly accepted that the scale of the energy management cannot be just the building (Koch 2009). When reduction of energy consumption is sought, a district scale instead of single building approach is required. The district scale is the one that has to define the strategy, the tools and the objectives to be used in the energy retrofitting. But this strategic scale must be connected with the operative scales, the scale of the building and its components, where almost all the measures are going to be implemented. Consequently a multiscale approach is the answer to the question of the proper scale for HUDs energy retrofitting.

The need to acquire the proper information for diagnosis and DM purposes is not new for the cultural heritage discipline when it comes to preserve the historic buildings and districts. But this requirement has usually been addressed specifically for each project and moment without a strategic vision making data acquisition very resource and time consuming and limiting posterior reuses of the information. The use of Geographic Information Systems (GIS) supposes a big step in the direction of structured and georeferenced data but they are limited due to the lack of a multiscale approach. With this research a strategic information management is proposed that can reuse the existing information infrastructure and support the whole cycle

[4] The Leipzig Charter. Leipzig Charter on Sustainable European Cities adopted by the informal meeting of the Council of Ministers in Leipzig on 24 May 2007

[5] The Declaration of Amsterdam, Adopted at the Congress on the European Architectural Heritage, Amsterdam (1975)

of the renovation of the HUDs (including the analysis, DM, implementation, monitoring and also the necessary feedback) in a coherent continuity.

0.4 Research methodology

0.4.1 Hypothesis

The research is based on the following hypothesis:

- *Through the adaptation and enhancement of state-of-the-art multiscale 3D information models, in order to take into account historical, architectonic and energy characteristics of HUDs, affordable, scalable and flexible multiscale information management strategies can be designed to support the diagnosis, DM and management of energy retrofitting programs.*
- *A DM methodology for energy retrofitting strategies at urban level based on a tailored multiscale data model can improve the balance between the required information and the accuracy of the results if proper modelling strategies and flexible levels of DM are defined.*
- *A generic methodological framework, supported by a flexible DM strategy and grounded in a multiscale information management based on a single model that allows a continuous and iterative flow of information, can facilitate urban energy retrofitting processes in their whole lifecycle making them more comprehensive, systematic and holistic.*

0.4.2 Methodology

The research work developed in this thesis can be framed within the "use-inspired basic research" that was described by (Stokes 1997) using the following figure:

		Considerations of Use	
		Low	**High**
Quest for Fundamental Understanding	**Yes**	Pure Basic Research (Bohr)	Use-Inspired Basic Research (Pasteur)
	No	----	Pure Applied Research (Edison)

Figure 1: Model of scientific research. Source: (Stokes 1997)

This kind of research aims to converge the need for a fundamental understanding of the research problem with the need to apprehend the use considerations and can be classified as a mixture of basic and applied research.

None of the fields where the topic of this research intersects is new. The goal has been to take advantage of the work that has been developed so far in the different fields and ensemble it within a new approach. An analogy with a jigsaw puzzle can be made, where first the framework is defined and after the proper pieces are put together. Each piece of the puzzle is a relevant part of the system and has to be identified, understood and solved. The methodology to achieve this ("to solve each piece") has been analogue in all the cases and used in a fractal way:

- → First the problem or the need has been determined.
- → A literature review has been done to understand the problem and the work done in the field of solving it.
- → The requirements for the solution have been identified.
- → A solution has been designed, usually by the use or adaptation of existing methods.

This approach has been used both on the large and small scale: for the core topics of this dissertation (to establish the master framework in Chapter 1 and after to develop the other two big issues: the methodology of DM and the multiscale model) and also for the smaller pieces of each part.

The different elements of the research share this common approach, but each has a different combination of analytical, design, development and evaluation work.

Development of the framework: This chapter has the role to establish the scope, the structure and the frame for the rest of the research. Following research questions have been examined:

- 〉 *What are the requirements for a methodological framework that aims to articulate a comprehensive retrofitting process of a HUD?*
- 〉 *How the information is managed within this process in order to connect the different energy scales of the district?*
- 〉 *What is the logical structure of the process that ensures the reliability, feasibility and long term sustainability?*

The literature review established the requirements that guided the design of the structure and consequently the development of the methodological framework. The evaluation of the framework has been relied on the applicability of its principles in the rest of the chapters.

Development of the methodology for decision making: the main function of this chapter is to design the methodology of DM that enables the selection of the best retrofit strategies for a given HUD. Following research questions have been studied:

- 〉 *What are the elements, criteria and constraints that support the DM?*
- 〉 *What is the best urban modelling strategy that enables the balance between a realistic and feasible data acquisition and the accuracy of the results?*
- 〉 *How can be established different levels of decision making (LoDM) in order to address different levels of scenarios of information availability?*

Once again a literature review established the requirements. The elements, criteria and constraints have been adapted from the ones accorded in the EFFESUS project between the different experts involved. The best modelling strategy was selected through the comparison between different alternatives against the requirements previously defined. Those requirements allow also the design of the different LoDM and consequently the detailed development of the methodology for the levels where a data model is required. The methodology has been tested in the case of Santiago of Compostela in order to evaluate its validity.

Development of the model: the goal of this chapter is to develop the multiscale data model that will support the previously defined framework and methodology. Following research questions have been analysed:

- *Which are the requirements for a multiscale data model that will support the strategic information managements of the process of energy retrofitting a HUD?*
- *From all the existing data model formats, which is the one fulfilling those requirements?*
- *How this generic data model format has to be tailored to support the energy retrofitting of HUDs?*

Unlike in the previous chapters, the requirements for the model have been established by the previous chapters. The literature review allows the identification of the different alternatives for the format of the data model. The different alternatives have been compared and the one that fulfil the established requirements has been selected and adapted to the research purposes. Finally the validity of the model, along with the methodology, has been evaluated in the case study.

0.5 Main contributions

In short, the main contributions of this research can be summarized in the design of a **framework, a methodology** and **a mode**l. These three elements aim to support energy retrofitting processes of HUDs. In more detail the contributions are the followings:

- → To define a **methodological framework** for energy retrofitting of HUDs in all its phases based on a strategic information management from a multiscale perspective.
- → To design a **DM methodology** to identify the most suitable actions for energy retrofitting based on a modelling strategy for the generation of building typologies and in different LoDM according to different scenarios of information availability,
- → To develop a **multiscale information model** based on standards that include through extensions all the necessary information for the DM methodology and that supports the strategic information management.

0.6 Structure of the document

The thesis is structured in seven chapters. The first chapter (Chapter 0) deals with objectives and the structure of the document. Each of the next three chapters aims to tackle with one of the key subjects of the research as follows:

- → **Chapter I- Framework:** The goal of this chapter is to develop the overall framework that will articulate and structure the different phases of the energy retrofitting of a HUD.
- → **Chapter II- Decision making:** In this chapter a methodology will be developed in order to select the best strategy and actions for the energy rehabilitation of a given HUD
- → **Chapter III- Multiscale information management:** Once the methodological framework has been established and the DM methodology developed, in this chapter it will be designed the multiscale information model that will support them.

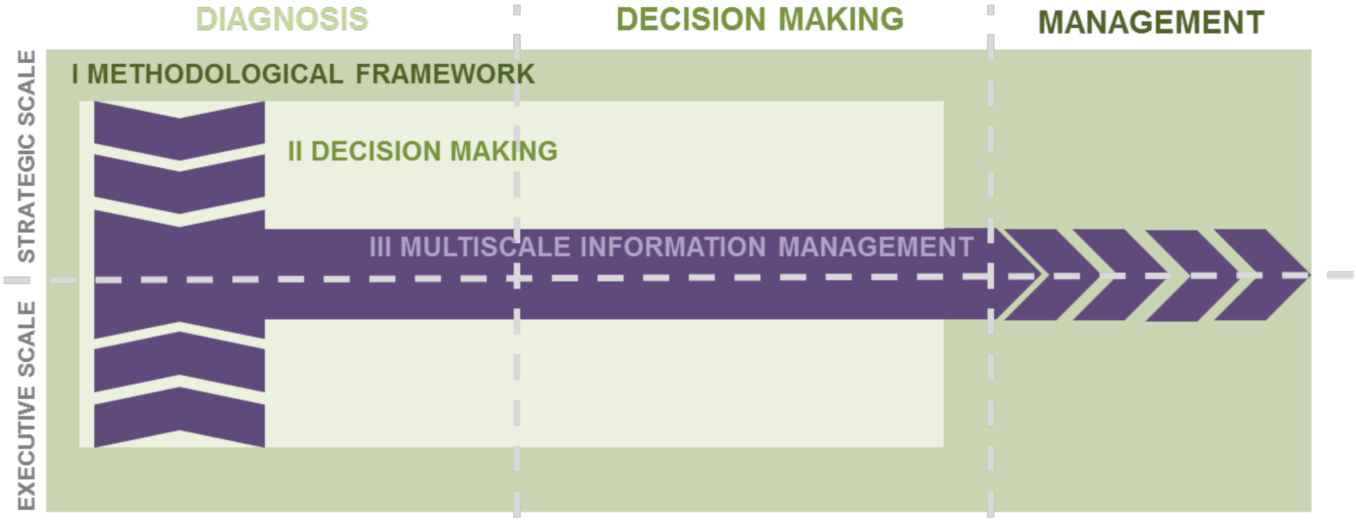

Figure 2: Structure of the document

The Chapter 4 develops the implementation of the methodology and the data model in the case study of Santiago de Compostela. The fifth chapter aims to summarise the conclusions and finally Chapter 6 discusses future perspectives, followed by the bibliography.

1 FRAMEWORK

Lively, diverse, intense cities contain the seeds of their own regeneration, with energy enough to carry over for problems and needs outside themselves
Jane Jacobs,
The Death and Life of Great American Cities

A Historic Urban District (HUD) is the best example of what Alexander described as a *natural city* in his classic "A city is not a tree" (Alexander 1966), where he described them as "*cities which have arisen more or less spontaneously over many, many years*". (Levine et al. 2005) compare the historic cities to natural ecosystems in their search of equilibrium by a continual process of dynamic rebalancing. The historic cities have grown organically through the years, adapting themselves to each era, assimilating the new technologies and trying to answer to the new requirements of their inhabitants. The results of this process are one of the mayor cultural achievements of the humankind as a collective, but the process itself also is an asset that has to be understood, appreciated, protected and continued. That means to find the knowledge and the tools to upgrade our historic towns to modern requirements while respecting their story and cultural values.

An approach from the energy could not only improve the sustainability and comfort of the HUDs, it can also improve the processes and protocols for the management and preservation of the HUDs from a cultural and technological perspective. The improvement of the energy efficiency and the levels of comfort of the city are two key aspects of a new way of understanding the architectonic conservation. The improvement of the liveability has to be an inherent factor in the process of preservation of the historic districts. Environmental and energy approaches, not limited to the mere protection and rehabilitation of the built heritage, are able to formulate innovative models of dynamic growth deeply grounded in sustainable development criteria (Panero Pardo 2009).

1.1 Sustainable rehabilitation of historic urban districts

"*Pero, ¿qué es el casco histórico? ¿Qué conservamos cuando salvaguardamos su estructura, sus edificios, sus espacios? ¿Cuál es el patrimonio que debemos conservar? Desde la sostenibilidad, el objeto de salvaguarda del*

patrimonio excede y atraviesa el concepto tradicional de conservación; lo amplía de escala, le da dinamismo y pone el acento en valores distintos que deben ser recuperados y salvaguardados" (Cuchí et al. 2008)
(But, what is the historical centre? What do we preserve when we protect its structure, its buildings, its spaces? Which is the heritage that we must preserve? From a sustainability perspective, the object to be safeguard exceeds and goes through the traditional concept of conservation; the scale is expanded and it gives dynamism and emphasizes different values to be recovered and safeguarded)

1.1.1 Preservation of historic urban districts through the improvement of their liveability

The preservation of our urban heritage requires the protection of the social context as well as the preservation of the authenticity and integrity of its physical materiality. The European Charter of Architectural Heritage and the complementary Amsterdam Declaration, both dated 1975 and promoted by the European Council[6] introduced the concept of integrated conservation where the protection of the social context is seen as necessary as the conservation of the fabric. Therefore, one of the main objectives of the preservation of HUDs has to be the improvement of the quality of life of the citizens.

If sustainability is critical for the preservation of HUDs, preservation is also fundamental for the sustainability as it maximizes the use of existing materials and infrastructure, reduces waste, and preserves the historic character (Todorović et al. 2014). The energy rehabilitation is within the priorities of the European Union (EU) since the Charter of Leipzig[7], which fostered the sustainable development of cities through the improvement of the EP of existing building stock. Moreover proper energy management is one of the key factors to improve the liveability of the districts in a sustainable way. But, regardless of this background, the relationship between historic preservation, environmental sustainability and liveability is a field that has not been enough studied from a systemic perspective yet.

Historically, traditional architecture has proved a great capacity of adaptation to the environment and the HUD can be considered as a model of urban efficiency in certain aspects. As (Salat 2011) stated "*the ecological city is a living system (…) its adaptability is what ensures sustainability*". A HUD traditionally has fulfilled the main requirements that Salat defines as design principles for an eco-district, i.e. high density and mixed used, walkability, a short density of strong connections, heterogeneous communities, the existence of public spaces, and the respect for the existing conditions of the site and the preservation of the relationship of people to space. The traditional architecture was bioclimatic by necessity, made by people in direct response to their needs and values, in a time when energy was really a scarce resource (Coch 1998) .

[6] *Ibid 5*
[7] *Ibid 4*

It can be said that the HUDs have the sustainability written in their genetic code. The process of updating our built heritage faces the challenge of balancing the requirements of the upgrading to the current standards of liveability and sustainability with the needs and constraints of the preservation of its integrity and cultural values. But the EP and liveability improvement and the protection of the heritage qualities do not have to be opposite criteria, on contrary, they can be considered inseparable processes of the preservation of the authenticity.

In the Charter of Washington[8] ICOMOS defined the criteria for intervention in historic centres. The charter includes, among the values to be protected, the need of preserving the various functions of the city that have been acquired in the course of history since the historical landscape is the complex result of changes in the use and development of the city. Equally to any other complex system, in HUDs, changes of its cultural context should bring a renewed recreation of its meaning (Funtowicz & Ravetz 1997). The European experience shows that one of the key values of the historic centres is its capability to mutate and adapt to meet the needs of different times[9]. The preservation of our built heritage in this framework is not a passive process, but rather a process of evolutionary improvement of historic urban systems. The HUD should continue the process of adaptation and improvement that has allowed surviving through the time. Integral functional rehabilitation strategies are required to update the HUDs to present time requirements (comfort standards, sustainability goals or energy efficiency objectives), but those strategies must be coherent and compatible with the technological, architectural and constructive characteristics of the HUDs.

The continuous process of preservation of HUDs cannot be limited to heritage preservation policies. It is necessary a second generation of rehabilitation policies that will update the role of the HUDs as technological systems to be inhabited answering to the need for improving the liveability of the built heritage. And this can only be feasible ensuring the technological coherence of the rehabilitation processes with the physical reality of the historical buildings (Panero Pardo 2009).

The functional wisdom of the city is also part of its cultural heritage (Fernández & Marat-Mendes 2010) and to lose its functionality means to convert its buildings in museum pieces. In almost all the HUDs its residential function has been preserved to the present. This gives us the opportunity to contribute to its evolution, reinterpretation and adaptation to modern requirements.

1.1.2 Energy retrofit of historical buildings and districts

In the detailed report "Europe's buildings under the microscope" (Economidou et al. 2011) about the situation in Europe in terms of the building stock characteristic, it is stated that over 40% of the European

[8] ICOMOS, The Washington Charter on the Conservation of Historic Towns and Areas (1987)
[9] Project PATUR I., "Metodología de regeneración y gestión de la conservación de la áreas urbanas históricas" resultado validado reunión de expertos Noviembre 2007

housing stock was built before 1960. This number varies depending of the region as it can be seen in the following figure:

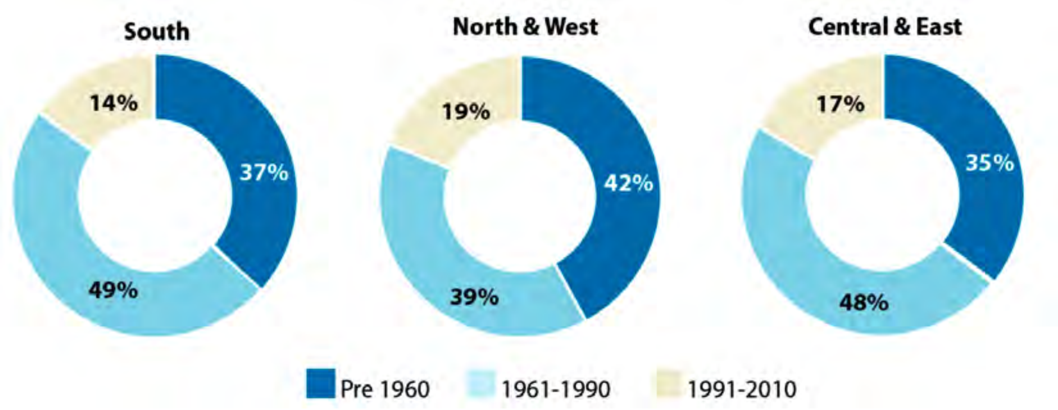

Figure 3: Age categorisation of housing stock in Europe. Source: (Economidou et al. 2011)

The Housing Statistics[10] in the EU shows that the 24% of residential buildings of the European building stock are pre 1945, and about half have some kind of HS. The majority of this building stock is clearly urban and residential as it can be seen in the following two figures:

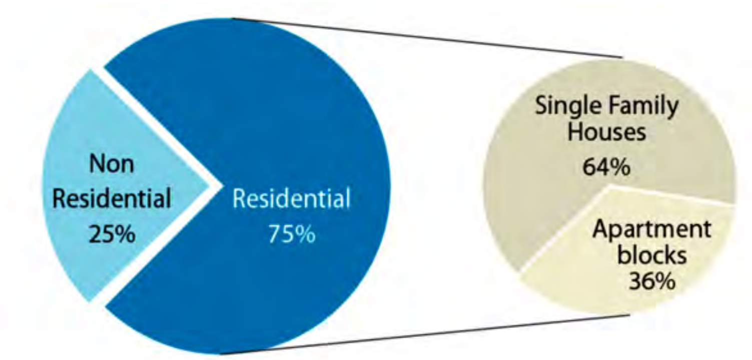

Figure 4: Europeans residential buildings. Source: (Economidou et al. 2011)

[10] Housing Statistics in the European Union 2010, Ministry of the Interior and the Kingdom relations. Sept. 2010

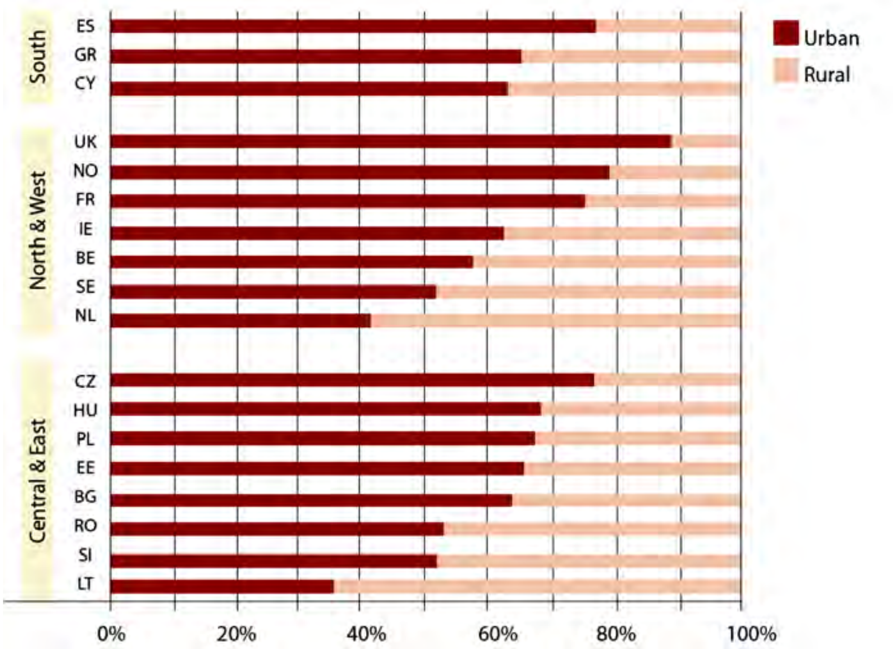

Figure 5: Location of residential buildings. Source: (Economidou et al. 2011)

Therefore the energy retrofitting of historic residential buildings and HUDs it is not only a cultural issue it also becomes important in terms of global environmental objectives in Europe.

The historic buildings and district are not only special for their cultural values, it have to take into account also their pre-industrial nature. (Cantin et al. 2010) differentiated three different periods regarding the thermal approach (see Figure 6) and states that the middle of the 20th century is the transition period that changes from a preindustrial construction period to a modern architectural design in residential buildings.

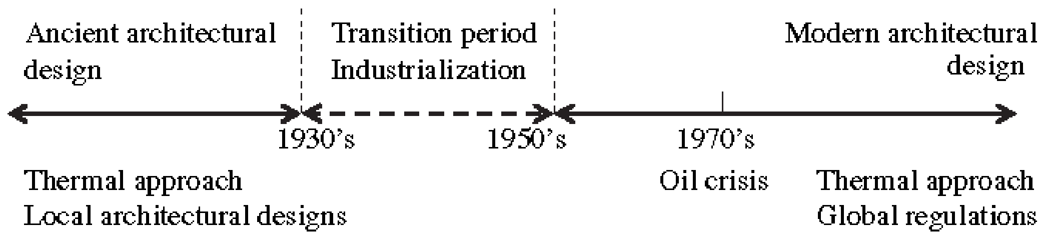

Figure 6: Different thermal approaches Source: (Cantin et al. 2010)

Some of the specific energetic features of preindustrial buildings regarding modern buildings are the followings:

- → Preindustrial building rely more in passive measures with bigger thermal inertia.
- → They have more heterogeneous envelopes: the stratification of different construction and re-construction periods generates heterogeneous fabrics, predominantly handcrafted, which are more difficult to be energetically characterized.
- → Presence of unique elements with a bioclimatic function as galleries or chimneys.

→ Embedded energy: historic buildings are a reservoir of embodied energy, an energy capital in the form of their materials (wood, stone, glass, metal, brick ...).

→ Local materials: the traditional architecture has always been made with low processed local natural materials. The energy needed to produce the materials used by traditional architecture (like wood, stone or adobe) is relatively low unlike the much more modern energy-intensive materials.

→ The hygrothermal behaviour of old buildings is different from modern buildings, since they have more interaction with the environment, the materials are more porous and permeable and react differently to air and moisture from the materials used in more modern buildings. In the following diagram from (English Heritage 2011)it can be seen the differences between traditional buildings and modern building regarding the moisture movement:

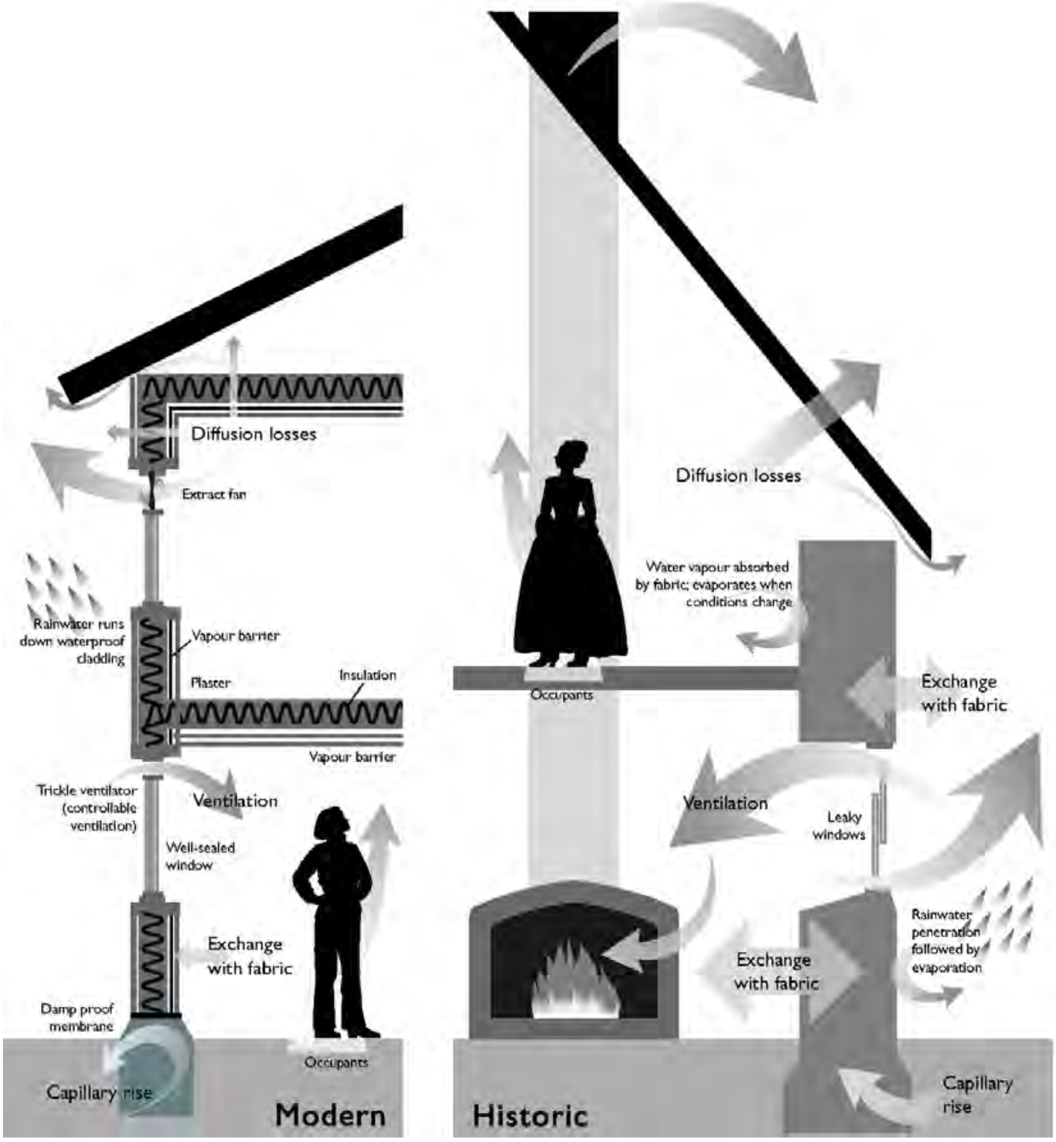

Figure 7: Comparison between modern buildings and older buildings. Source: from (English Heritage 2011)

It is worth to note the on-going work within the European Committee for Standardisation (CEN/TC 346/WG 8 "Energy efficiency of historic buildings"[11]) in order to develop guidelines for improving energy efficiency of architecturally, culturally or historically valuable buildings while preserving their inherent cultural heritage values. This standard aims to provide a normative working procedure for planning and selection of measures based on an in depth analysis of the information about the historic building and the assessment of the impact of the measures in relation to the preservations of the cultural values of the building. As in the case of this research, the use of these procedures will not be limited to buildings with statutory protection covering the whole range of building types and building ages.

1.1.3 Methodologies and approaches

Methodologies and approaches for the preservation of historic districts

There is a general interest translated into UN resolutions, EC directives and research projects on the need to structure the DM process in urban and regional planning in order to ensure sustainable development of local communities. This interest has focused on the integration of environmental issues as primary variable in planning, being cultural heritage one of the environmental factors to be protected. For example, in the Aalborg+10 Conference, European local governments united in the European Sustainable Cities & Towns Campaign confirmed a shared vision of a sustainable future for their communities, reflected in the Aalborg Commitments (2004)[12]. In the planning and design theme, among other working areas as the need of re-using and regenerating of disadvantaged areas or the priority of residential use in city centres, it was emphasized the importance of ensuring an appropriate conservation, renovation and use/re-use of the urban cultural heritage.

Despite of this interest, when it comes the time for implementation, there is a lack of methods and protocols for the effective inclusion of cultural heritage in these processes. The RehabiMed Method (RehabiMed 2007) is focused in Mediterranean traditional architecture and it aims to continue the task begun by Amsterdam Declaration[13], understanding the preservation of historic centres not only as the restoration of monuments but also on the promotion of actions to rehabilitate the fabric of dwellings and social measures. Therefore the interventions have to address on both the physical environment and the population it hosts, with the main objective of improving the living conditions of this population as well as the quality of the area and the built environment, maintaining and promoting its cultural and heritage values, and at the

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[11] Information about the standard at: http://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:36576,411453&cs=1C847D545393505B1B705B8122B6EC966 [Accessed 20 September 2015]

[12] Available at http://www.sustainablecities.eu/aalborg-process/commitments [Accessed 1 September 2015]

[13] *Ibid 6*

same time guaranteeing its coherent adaptation to the needs of contemporary life. The method is proposed for all actors involved in the rehabilitation process, but their main targets are the public authorities and technicians responsible for coordinating and managing the implementation of the process.

The method aims to identify the technical, administrative and legal tools to be used for optimum management and development, as well as to define the criteria that will allow reflection on the strategies to be established in order to guarantee the success of the process. But especially it intends to order and systematize the stages of the rehabilitation process. The process is structured in five phases of action and eight key stages as following:

1. Political backing: the process can only start with the political will to act. The preliminary decisions in order to appropriately organize and manage the rehabilitation process will be made in this phase.
2. Diagnosis: through multisectorial studies the prevailing legal conditions are studied and the area of action is established. During the analysis phase, it is possible to identify new problems not considered in the first phase, requiring a re-orientation. This analysis is the basis for the integrated diagnosis agreed by social consensus and with the corresponding political backing.
3. Strategy: based on the integrated diagnosis, and through strategic reflection, a series of hypotheses of action will be defined in order to evaluate its viability. The reflection process may reveal the need to complete the initial diagnosis requiring going back to the phase 2. Once the feasible target scenario has been decided, an action plan is designed. The plan will be agreed by social consensus and approved by the politicians.
4. Action: this phase includes the implementation of the actions foreseen in the action plan
5. Monitoring: the phase of continual evaluation of the actions will begin alongside the actions that are carried out. If the actions do not produce the expected results it will be necessary to return to the strategic reflection phase or even, if the conditions of the territory are seen to have evolved, to the diagnosis phase.

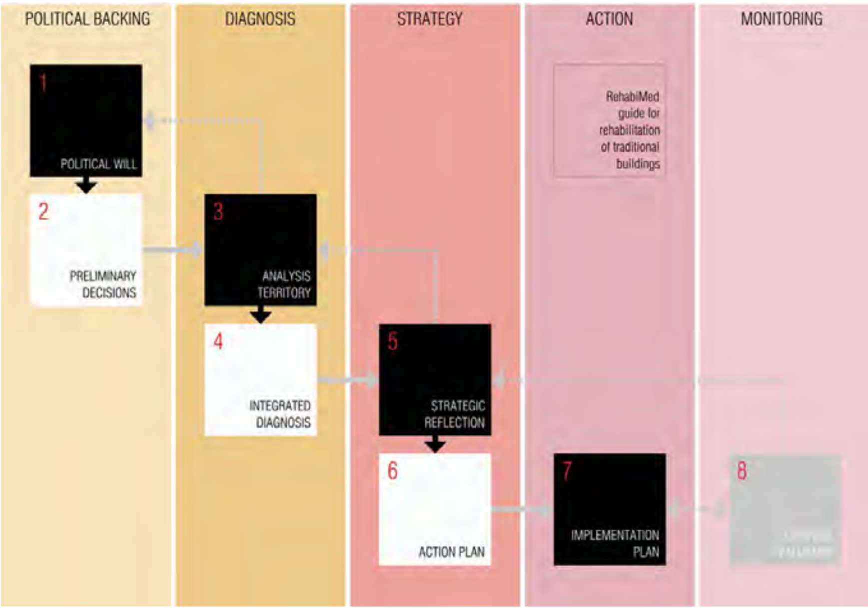

Figure 8: RehabiMed Method

Another initiative in this direction was the PATUR project [14]. PATUR had as objective the development of innovative methodologies and tools to support the DM and the management for the revitalization of historic centres. The project understood the participatory management of historical districts as a dialectical and continuous process between the definition of the intervention strategy (implementing plans and programs) and the monitoring as shown below:

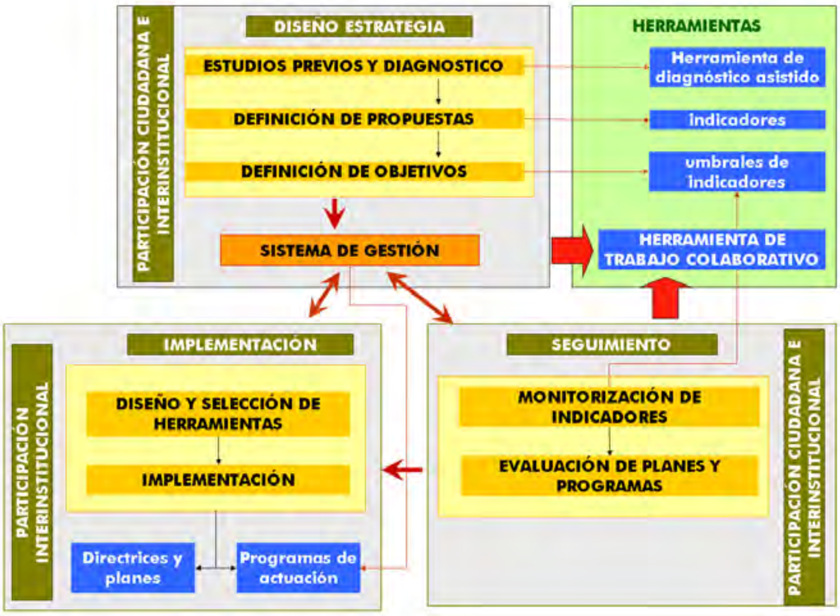

Figure 9: Methodology developed in the PATUR project

[14] Herramientas innovadoras de planificación urbana y toma de decisiones para incorporar y proteger el patrimonio cultural urbano (PATUR), 2007-2008, SAIOTEK program.

The PATUR methodology relied also in the structuration of the process in specific phases supported by a package of tools integrated within the system. Those phases or sub-processes of the process were the followings:

Sub-process 1: Design of the strategy. It is developed in 3 phases:

- → Previous studies and diagnostic studies will be developed for a comprehensive knowledge of the historic centre and the assessment of its conservation status. At this stage the first measurement of indicators is performed. The results of this first diagnosis will serve as a basis for the definition of the strategic objectives and their monitoring.
- → Definition of proposals: in this step specific proposals for measures that will support the regeneration of the historic districts are developed.
- → Definition of objectives: Once the proposals are selected, the specific objectives for each proposal are defined. A timetable for their implementation will be established. To ensure a reliable monitoring process the values to be reach will be defined (Ti).

Sub-process 2: **Implementation of the strategy.** It takes place in two phases:

- → Design and selection of the tools: based on the proposals and targets set in the previous phase, an assessment of the needs of each case will be made. The most appropriate tools for management, implementation and protection in a comprehensive and coordinated way will be identified.
- → Implementation: the implementation will be done through guidelines, plans and action programs:
    - The guidelines will develop the objectives, guiding and coordinating plans and action programs in a long term.
    - The plans will implemented the goals and the aspects whose programming is essentially medium term (four to eight years).
    - The action programs will implement short-term goals (immediate action) and correcting plans if the plans are suffering any deviation in its development.

Sub-process 3: **Monitoring strategy**. It takes place in two phases:

- → Monitoring indicators: periodic measurements (Tn) will be made as programmed. The system of indicators will be applied to monitor the performance, comparing the measurements (Tn) with respect to the predefined thresholds (Ti).
- → Assessment of Plans and Programs: each plan has to have its own system of monitoring and evaluation. Periodic measurements (Tn) of the indicators of each of the plans in accordance with its associated indicator system will be made.

From the analysis of the RehabiMed and PATUR initiatives it can be concluded:

- → The processes that intend to revitalize historic urban areas need to be clearly structured in phases.
- → It has to be considered the need of iteration and feedback among those different phases.
- → All the process has to be based on an integrated diagnosis and in a careful analysis of the existing information regarding the historic buildings.
- → The need of monitoring is emphasized.

Methodologies and approaches for the energy rehabilitation of HUDs

The building scale approach is not the most optimal in reaching significant and cost-effective improvements across both buildings and districts EP (Koch 2009). Moreover, in HUDs an urban strategic energy approach helps to overcome barriers and restrictions applied to individual historic buildings and optimisation of energy consumption and CO_2 emissions associated with historic urban cities infrastructure.

Although it is clear that the district retrofitting approach is frequently the most sustainable one, the complexity of DM grows exponentially when the intervention targets the district scale, due to the numerous additional aspects that have to be taken into account (the higher number of stakeholders involved in the process, the interaction between buildings and their environment, the bigger impact of the intervention in the infrastructure, citizens, urban landscape, the higher complexity of the retrofitting process, the bigger need of financial, human and material resources and the much higher scale of investment usually).This complexity can easily be visualized in the interactions reflected in the dEEP model that has been defined by the Retrofit2050 project[15]:

[15] http://www.retrofit2050.org.uk/

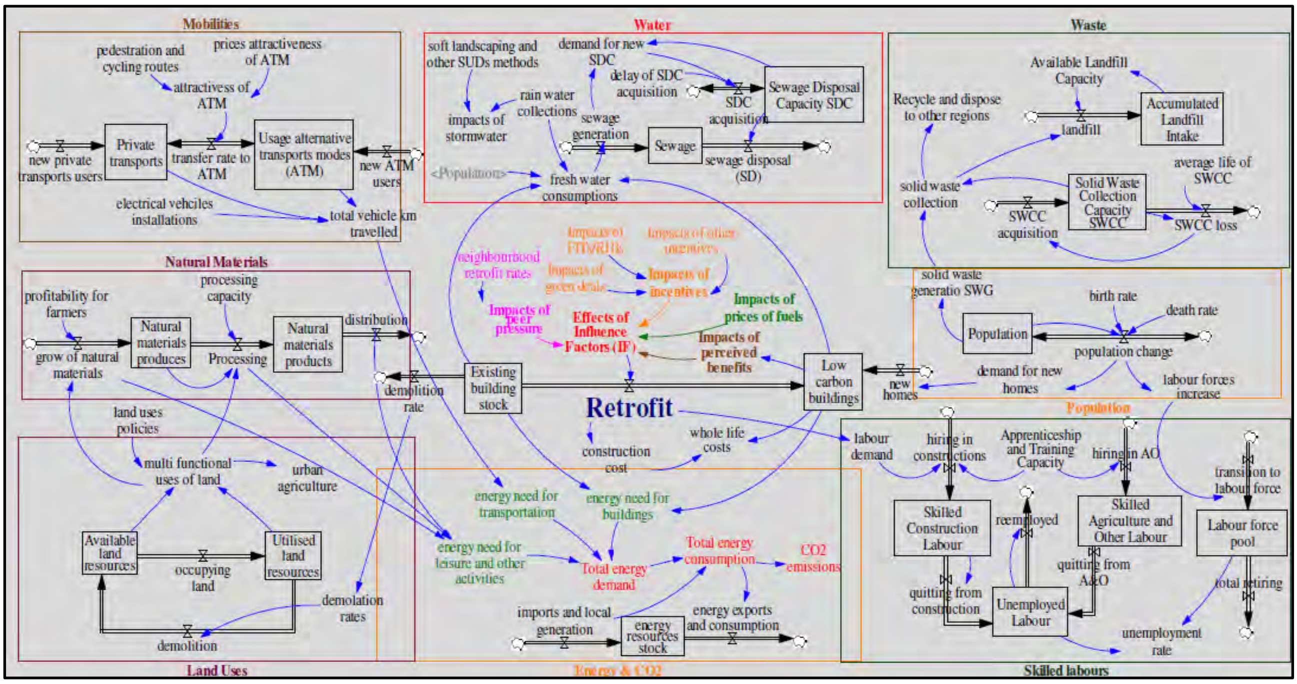

Figure 10: dEEP model. Source: Retrofit2050 project

The urban scale is the one where the decisions are made (i.e. the strategic scale) but the building scale still is the one where the main of the retrofitting measure are going to be implemented (i.e. the operative or executive scale). Both scales are necessary and, more important; both scales have to be interconnected. That is the reason why a multiscale approach is chosen for this research. This multiscale approach is going to be a constant during this entire dissertation but the interconnection between scales is going to be specifically addressed in Section1.4.

In the last years there have been a lot of cities trying to implement energy efficiency and sustainable measures at urban level. And the HUDs have not been strange to this trend, but there is a lack of literature on comprehensive methodologies covering the energy study of the historical districts at urban scale in a systemic way and with the aim of being generic and replicable. One of the few cases, was the research carried out by the Department of Architecture and Urban Planning at the Polytechnic of Bari (Vita Caivano & Fatiguso 2002) aimed at defining a methodological approach to the energy and environmental rehabilitation of historic heritage established for the identification of the interventions required for improving their EP. The general outline of this methodological algorithm was as follows:

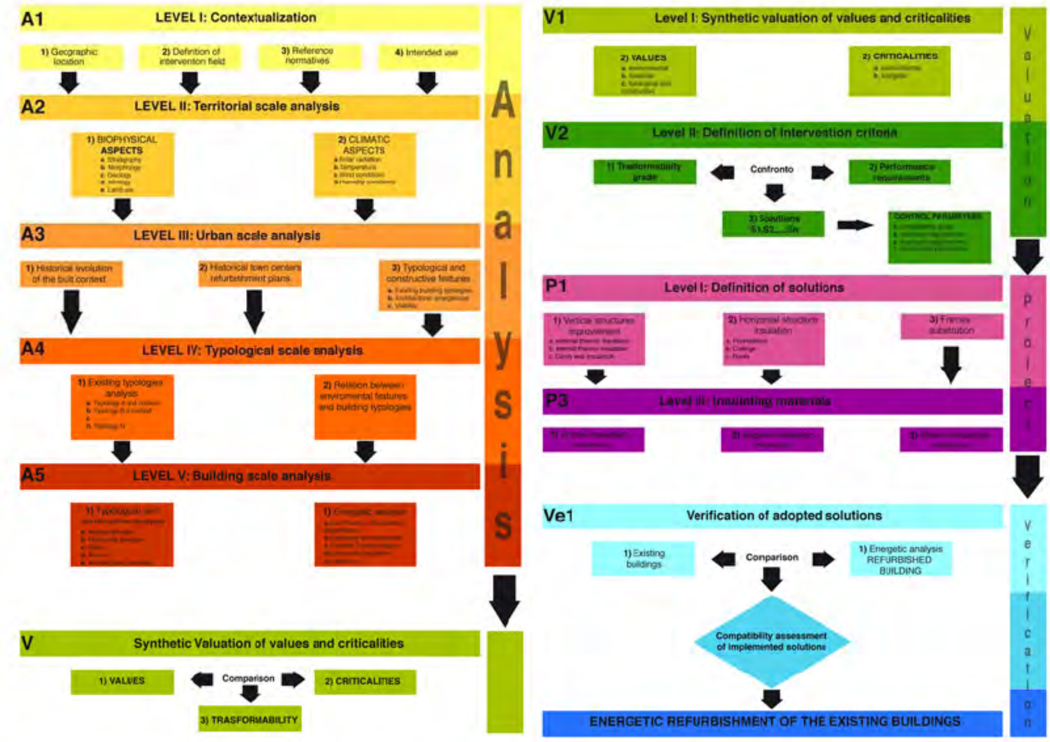

Figure 11: Methodological algorithm. Source: (Vita Caivano & Fatiguso 2002)

It was not intended to be a rigid methodology but an operational "route" articulated in consecutive stages, trying to cover from a broad framework to a deep knowledge of the building.

There are also valuable examples of initiatives thought for specific cities that could be extrapolated to similar cities. For example, Edinburgh model (Ronchini & Poletto 2014) is very interesting as model for the World Heritage Sites (WHS). UNESCO requires a *management plan* for all WHS as key document that sets out the vision for the Site. Edinburgh World Heritage, the independent non-governmental organisation set up to manage, to protect and to promote the WHS in Edinburgh, has created a management plan along with the City of Edinburgh Council and Historic Scotland that includes the climate change objectives and actions as an integral part of their management plan. Based on an intense consultation process and in a strong stakeholder's engagement, Edinburgh sets an operational framework focused on the reduction of carbon emissions and the fight against fuel poverty implementing energy efficiency programmes, community-led regeneration and innovative retrofitting projects. In order to ensure the success of the strategies "clear objectives, clear actions and clear monitoring strategies are defined by measurable indicators".

Another example is the initiative "Retrofitting Soho: Improving the Sustainability of Historic Core Areas" (Tony Lloyd-Jones et al. 2008) where a methodological model for retrofitting sustainability to historic centres was developed. In order to provide targeted advice and information to owners and occupiers the buildings of Soho were categorized and a "Whole Building Retrofit Strategy" for each *archetype* was developed.

Finally, it is worthy to mention the work that the Consorcio of Santiago de Compostela and Tecnalia made with the goal of establishing a program for the integral rehabilitation of Santiago de Compostela (Panero Pardo et al. 2009) and that can be considered as an antecedent for this dissertation.

From the literature review it can be concluded that there is a lack of generic methodologies to facilitate the energy retrofitting processes of HUDs. The existing methodologies either are too theoretical or too specific from a given HUD or city, and they do not take into account the multiscale information requirements.

1.1.4 Requirements for comprehensive methodologies

Sustainable urban development has been defined as the actions which steer urban development towards the moving goals of environmental sustainability (Ravetz 2000). Sustainability is a direction rather than a goal as urban environmental systems are constantly changing. The urban development, the evolutionary growth and restructuring of urban physical and human systems, in the global context is also non static.

The preservation of HUDs face the difficulty of reconciling the traditional view of heritage as something static, reluctant to the change, with the dynamics of transformation necessary for the liveliness and sustainability of the city. In the absence of universally accepted formulas, an interesting approach in the context of sustainability is to accept the *paradigm of complexity*. That means to understand the HUD as a superposition of strata where all periods have left a footprint. Everything is important and indispensable and the part that is known when planning is as important as what is unknown because it is hidden. The challenge is then to modify without destroying, adding our contribution in a contemporary and recognizable language minimizing the destruction of the historical legacy[16].

In the 70s, the majority of European historic districts went through important urban transformation processes with a big impact on their fabric and structure. This is the moment when the practice of urban rehabilitation as a form of built heritage conservation arises in Europe. In the World Heritage Convention of 1972[17] UNESCO urged all its member countries to establish and to activate measures for the protection, conservation and presentation of all of its cultural assets through the adoption of integrated policies and comprehensive planning. It should be emphasized the importance of the integration of the cultural heritage within the social and economic life of the city.

The concept of the *integrated conservation*, the conservation that takes into account the intangible aspects along with the conservation of tangible assets, was born in this context. The Council of Europe in 1975[18]

[16] Proyecto Patur II., "Guía de Gestión de las áreas urbanas históricas". Resultado validado en caso Piloto de la ciudad histórica de Segovia. Mayo-Noviembre 2008
[17] The World Heritage Convention was adopted by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) General Conference at its 17th session in Paris on 16 November 1972
[18] European Charter of the Architectural Heritage (1975). Adopted by the Council of Europe, October 1975

established the need to incorporate social factors and to ensure the continuity of the social and cultural diversity that is distinctive of the historic city. Since the plan for Bologna in 1969, the conservation and recovery of the HUDs is understood under policies of territorial equilibrium. That means to understand that the built heritage is not only the architectural richness. It encompasses also the productive activity, the population, the services and the infrastructure among others.

In 2007, the ministers for urban development of EU member countries reflected in the "Leipzig Charter on Sustainable European Cities" common principles and strategies for urban development policies. It was recognized the exceptional qualities of European cities: their unique architectural and cultural qualities, their strong forces of social inclusion and their great potential for economic development. It was accepted also the need to maintain their social equilibrium, by recognizing and protecting their cultural diversity and establishing high quality standards regarding design, architecture and environment issues. This view was particularized in the commitment to address the urban development from an integrated approach, with particular attention to disadvantaged neighbourhoods. The result was the recommendation of modernizing infrastructure networks and improving energy efficiency, in addition to the pursuit of strategies for improving the physical environment.

The need to include the participation in sustainable planning processes has been assumed directly by the European Community in the guidelines regarding the management of environmental resources. The "UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters" (Aarhus Convention)[19] was adopted on 25th June 1998 and "*establishes that sustainable development can be achieved only through the involvement of all stakeholders*". The recommendations of the Aarhus Convention are reflected in the development guidelines and methodological guides of the strategic environmental assessment procedures, plans and projects[20]. Strategic Environmental Assessment (SEA) is configured as a continuous process parallel to the life cycle of plans and programs, from the design phase to implementation and management phases. The process aims to integrate the environmental variable in urban and regional planning by the structuration of plans in specific and rational steps of participatory DM.

If HUDs are in constant evolution and development, their preservation has to be addressed as an ongoing and unfinished process of renovation. Consequently, current trends aim at identifying new management tools more flexible than the standard urban plans, tools and methodologies that also incorporate social and economic aspects characteristic of the historic districts. Those tools should facilitate also the participation of all stakeholders from the authorities to citizens.

The aforementioned PATUR[21] project established four requirements for this kind of methodologies:

[19] Available at: http://www.unece.org/env/pp/introduction.html [Accessed at 25 May 2015]
[20] SEA Directive 2001/42/EC
[21] *Ibid 14*

- → **An iterative approach for regeneration processes:** The management of historic districts has a life cycle that begins with the definition of the strategic approach, continues with its implementation into plans and programs and finally has a monitoring that ensures the follow-up of the proposed actions and their impact on the historic district.
- → **A participatory approach in DM:** the diversification of public and private stakeholders in the development of the city requires a greater understanding of the dynamics a synergies regarding their collaboration in order to include them in the regeneration process. Therefore specific tools and processes have to be identified to promote and channel their participation.
- → **A structured approach to the different stages of the process**: traditionally the regeneration plans have been the result of a personal idea constructed based on an unstructured assessment involving difficulties for a participatory DM. Consequently, it is necessary to rationalize as much as possible the generation of strategies and the proposal of actions in order to open and share the model.
- → **An open approach to the structuration of information: t**he shared information is the basis of all participatory projects. The baseline information compiled in the process must be open and available to all stakeholders involved in the DM. In the implementation phase also, mechanisms to expand and improve the information have to be provided.

The need for a clear structuration in phases and the requirement for the iteration and feedback among those different phases was also identify as requirements for the RehabiMed project (RehabiMed 2007). Moreover it was identify that the whole process has to be based on an integrated diagnosis emphasizing the need of monitoring mechanisms.

In the same vein, but referring to the entire building stock and focused in energy issues, (Ravetz 2008) stated the same need for a comprehensive approach that balances the costs and the social, economic and environmental benefits in order to get the full potential to improve the building stock. This management and strategic improvement of the building stock must facilitate the coordination of different stakeholders (designers, builders, users ...) and address an appropriate scale (from element to the neighbourhood). As (Crosbie et al. 2014) stated, in sustainable design the coordination and consistency between the different scales of intervention, from the macro (city and region) to the micro (buildings and components), is a requirement.

As summary, it can be said that the main requirements of a compressive methodology for the energy rehabilitation of and historic district are the ones that integrates the needs for the preservation of its cultural heritage with the improvement of its building stock. Based on this literature review in Section 1.3 the specific requirements for our framework will be identified.

1.1.5 Interscalarity and multiscalarity in the urban energy rehabilitation

In historic environments it can be very complex and even counterproductive to approach the energy retrofitting and management only from the scale of the building, since it is necessary to understand the building within a much larger system of relationships. The operational, historical and contemporary scale to address the implementation of energy improvements and subsequent management is the district (Koch 2009). For historic buildings, the district-level approach is even more necessary, as this scale could compensate the material and formal constraints of some listed buildings. Moreover, an urban approach enables the opportunity for the installation of some measures (e.g. RES) without compromising the protection of the urban landscape.

A review of the most recent literature carried out by (Pasimeni et al. 2014), showed that the international debate regarding the interaction between climate change, land-use and energy is focused on the identification of the suitable scale or scales for effective energy planning and that a growing number of papers have been dealing with the problem of suitable spatial and temporal scale in the context of energy planning during the last 10 years. (Cash & Moser 2000) among others argued that, global environmental changes are cross-scale phenomena, requiring multi-scale assessments for more effective political and DM processes. (Kates & Wilbanks 2003) noted that, although climate change is truly a global phenomenon, most of the specific adaptation actions can, and must, operate at different temporal and spatial scales, from local to global, and from local energy production policies to international agreements for generating improved outcomes at a global level.

Therefore, there is a wide and growing recognition of the importance of the local scale (e.g. municipal scale) and cross-scale dynamics (e.g. nested scales) to address and understand energy-environmental issues (Pasimeni et al. 2014). In particular, built environment studies ideally require analysis that is both fine-scale, to include buildings and streets, and large extent, to allow the study of city-wide processes (Smith & Crooks 2010).

The improvement of the sustainability of urban building environments is basically a spatial decision process. A comprehensive strategy for the sustainable improvement at urban scale has to take into account the executive scale (i.e. the building scale) in strategic decisions. In the same way the measures to be implemented at building scale had to be coherent with the global objectives at district and city scale.

Consequently the improvement of the sustainability of urban building environments is an interscalar problem that has to be addressed with a multiscalar and multidirectional approach, going from neighborhood downwards the building and upwards to the city. Multiscalar tools, methodologies and information models are needed to:

→ interconnect information at different scales (city, neighbourhood, block, building and elements)

→ integrate information at fine-scales to make calculations for large urban areas

→ visualize data at multiple scales

→ connect the strategic scale (urban) and the executive scale (building-component) to ensure a more integral diagnosis and the proper implementation of the strategies

→ connect different scale models and standards as City Geography Markup Language (CityGML) and GIS

Due to the complexity of studying urban sustainability, the first step has to be the identification of the different scales of analysis (Salat 2011). Within the FASUDIR project[22] in order to introduce the principles of interscalarity and multiscalarity a broad overview of the possible themes in the urban environment and their correlation across scales was provided (Barbano & Egusquiza 2015). The following figure highlights how some themes are transversal to all scales, while others only can be captured meaningfully in a specific dimensional subset:

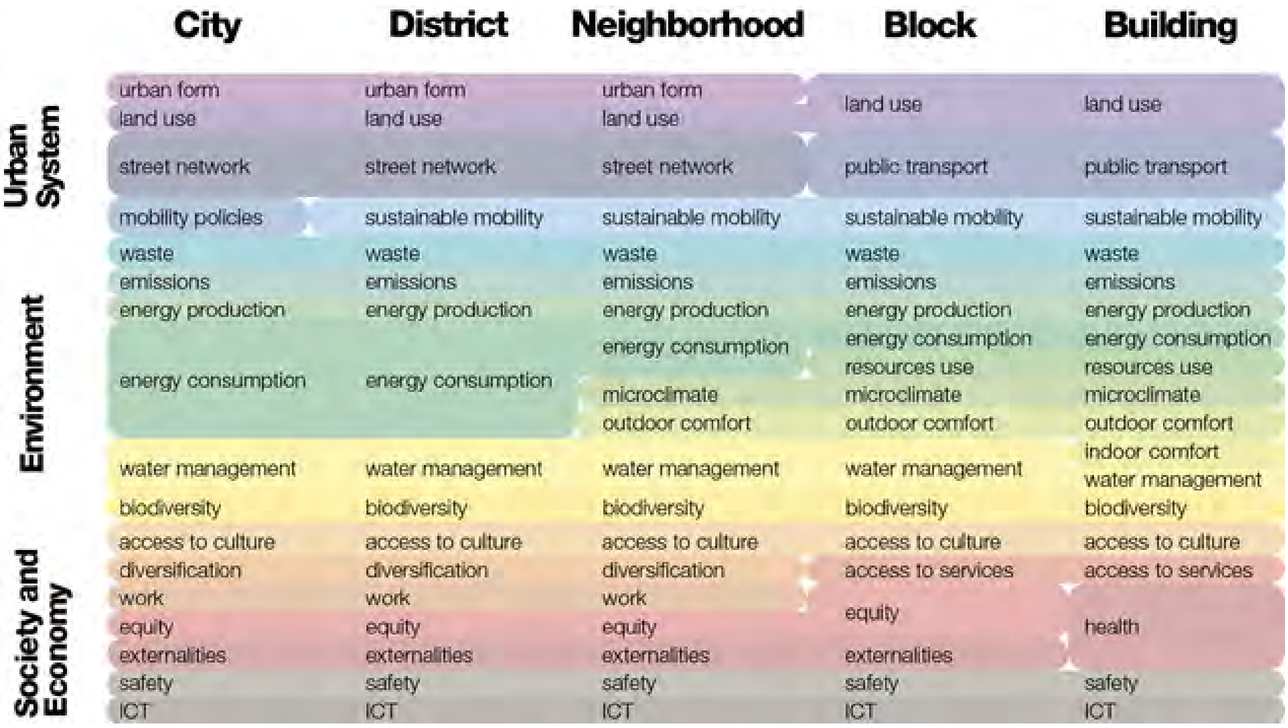

Figure 12: Sustainability themes at urban scale. Source: (Barbano & Egusquiza 2015)

In the figure, it can be seen the importance of the energy consumption but also its interscalarity as it can be analyzed at all scales if different levels of precision are used. This figure shows also the multiscalarity of the problem if elements are horizontally compared at the same scale. Some themes like indoor conditions or urban networks are constrained in one-two scales, but theme does not disappear beyond those scales, it is just the perspective that has to be changed. For example, networks cannot be studied at small scales such as blocks and buildings but the access to this networks has to be studied at these scales.

[22] *Ibid 3*

1.2 Scope of the methodological framework

Nowadays, there is not a common definition of concepts as historic districts, historic city or historic centre. Within this research, it has been decided to share the concept that it is used in the EFFESUS project and work with the broad concept of *historic urban district* (HUD). In the EFFESUS project, a HUD is understood as "a significant grouping of old buildings, built before 1945 and representative of the period of their construction or history, and comprising buildings which are not necessarily protected by heritage legislation". These buildings will be predominantly residential buildings, for which energy-related retrofitting is required in order to achieve Europe's policy targets of improving the energy efficiency of a large percentage of its housing stock.

As complement of this definition the description of traditional architecture that it is used by the aforementioned RehabiMed project (RehabiMed 2007) can be used: "*everyday architecture that is alive because it is inhabited, essentially civilian, domestic and of pre-industrial construction. It is a form of architecture built using local resources, which covers materials, techniques and the skills of its constructors, and it is the fundamental expression of the culture of the different communities and their relation with nature and the landscape*"

The (big) district scale is the best suited for the analysis of energy networks and some socio-economic issues, such as social mix of population and the distribution of human activities, the neighbourhood scale though is better to study the morphology of the buildings and their microclimate (Barbano & Egusquiza 2015). In the context of this research, the HUD will be understood between those two scales, depending of the city and country. Usually the HUDs are well delimited within the city due to protection purposes. Anyway it is important to ensure the continuity and test that a coherent and solid area is considered from the urban point of view.

1.3 Requirements for the methodological framework

Through the literature review carried out in Section 1.1 the requirements for the methodological framework can be established. In the next table those requirements are shown. Each of the requirements has a unique identifier and includes also whether the requirement is mandatory for the data model or is optional.

REQ. ID	REQUIREMENT	
FW_REQ_GEN_01	An iterative approach for regeneration processes that facilitates the feedback among different phases.	Mandatory
FW_REQ_GEN_02	A participatory approach in decision-making taking into account all the required stakeholders who are involved in the retrofitting process.	Mandatory
FW_REQ_GEN_03	A structured approach to the different stages of the process articulating all the phases	Mandatory

REQ. ID	REQUIREMENT	
	of the process: diagnosis, DM and management.	
FW_REQ_GEN_04	An open approach to the structuration of information establishing how the information flows and how the generated knowledge improves the DM process.	Mandatory
FW_REQ_GEN_05	The framework needs to address the multiscale nature of the sustainability of the HUD. The overall methodology should address both the strategic level and the executive/operative level.	Mandatory
FW_REQ_GEN_06	The framework has to facilitate the active coordination of different stakeholders (designers, builders, users ...).	Optional
FW_REQ_GEN_07	The framework has to take into account the patterns of users behaviours and the specific EP of preindustrial buildings.	Optional
FW_REQ_GEN_08	The framework has to be based on a diagnosis phase where the modelling has to be addressed.	Mandatory

Table 1: Requirements for the framework

1.4 Structure of the methodological framework

Once the requirements are identified the general structure of the framework can be outlined, a multiscalar structure is proposed, addressing the operational and strategic scale, which is articulated in the diagnosis (modelling and current state), DM (targets and strategy identification) and management (implementation and monitoring) phases. The following figure shows the basic structure of the framework:

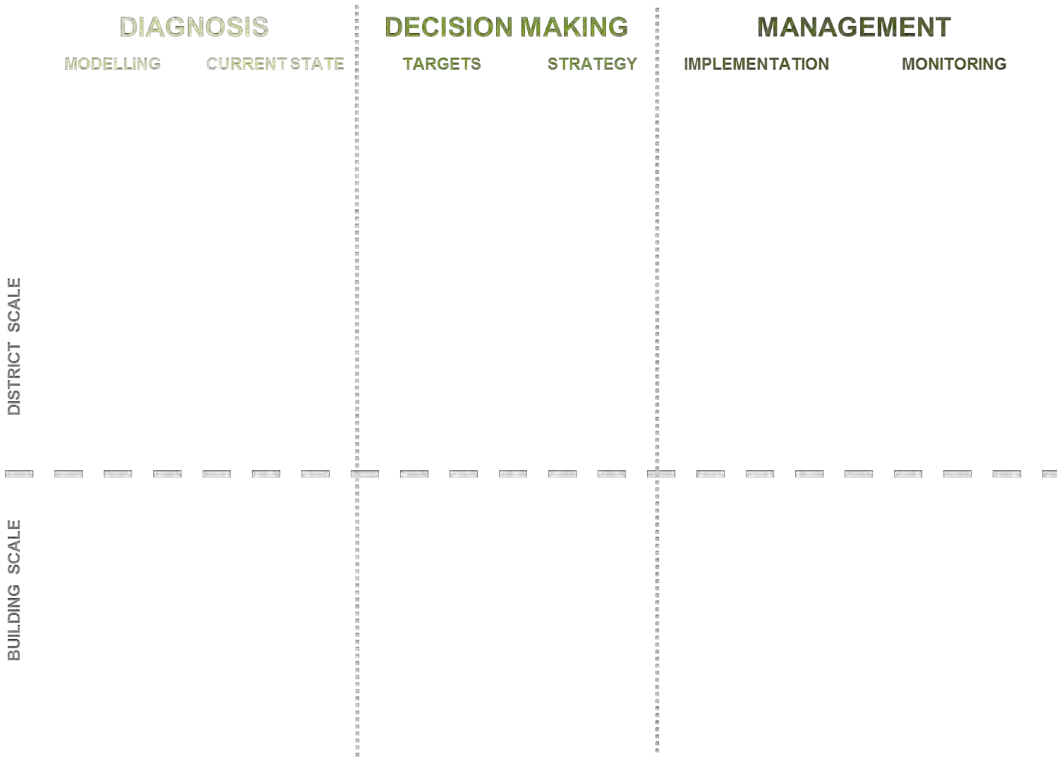

Figure 13: Basic structure of the methodological framework

1.4.1 Strategic information management

Nowadays is truer than ever what Jane Jacobs said in the 70´s regarding the future of the cities: *"The cities will not be smaller, simpler or more specialized as cities of today. Rather, they will be more intricate, comprehensive, diversified and larger than today's and will have even more complicated jumbles of old and new things as ours do"* (Jacobs 1970). In (Egusquiza et al. 2014) it was described that the districts as urban ecosystems generate a large volume of heterogeneous information (information at different scales, for different uses, of different natures, from different tools and formats and coming from different stakeholders) that will grow exponentially in the near future. Due to the growing complexity of the generated information a proper information management was identified as crucial for the comprehensive sustainable rehabilitation processes. It was identified also the following requirements for an information management strategy suitable to support the sustainable rehabilitation at urban level:

→ It must include the entire life cycle of information; from data acquisition, structuring harmonization and storage, to operation and maintenance.
→ It must include all stakeholders involved in DM.
→ It must include semantic and geometric information properly related and georeferenced.
→ It must ensure public access to information and allow 3D visualization since it facilitates the understanding for different kind of users (technicians or citizens).
→ It must enable the generation of tools and methodologies for DM.

- → It must emphasise the importance of the interoperability between different data models and other tools for management, analysis and DM.
- → It must be based on international standards that facilitate the use of public information (open data).

These requirements were defined for any urban environment but can be also applied when we are facing historic environments. However, after defining the requirements for the framework, other characteristics of the strategic information management can be added to the aforementioned:

- → The strategy has to design mechanisms to ensure the feedback of the information in the system among the different phases and scales.
- → The information strategy has to take into account the importance of the documentation of the cultural heritage values, understanding the energy as a new heritage asset.
- → The information strategy has to support the integrated diagnosis and the modelling phase.

Any information strategy that aims to be feasible has to play with an incremental use of information. Different LoDM can be established depending on the information availability and the stage of the process. The reuse of existing information structures will be mandatory and unnecessary costs in data acquisition should be avoided. Time consuming data acquisitions, especially the ones that need field work, will be considered very carefully, overall in the first stages, and when necessary, it will be planned very carefully in order to have the maximum usage of the generated information. The planning has to be especially careful with the structure and format of the information in order to ensure the interoperability and the reuse at maximum.

As established in (Egusquiza et al. 2014) a multiscale information model is the way to support this strategic information management. This model structures all the necessary information of the district in all the phases (from diagnosis to management including the DM) and that integrate information from different fields and scales. The following figure shows the role of the model and the flow of information on the framework:

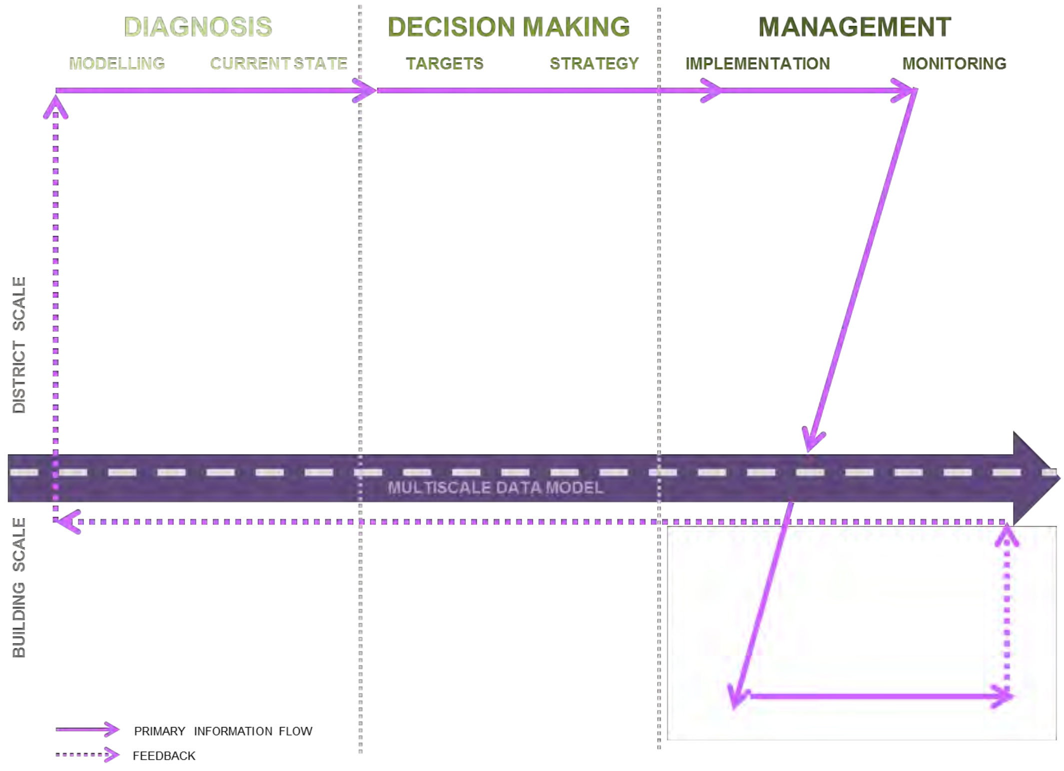

Table 2: Information flow in the overall framework

1.4.2 Interconnection between scales

Previously it has been concluded that multiscalarity is one of the main requirements for our framework. Therefore the different scales (city, district, building and component) have to be interconnected. Now the question arises, how can these scales be interconnected? Again, the information is the keystone here. The coherent and consistent flow of information between scales is the only way to ensure this link. The connection between the strategic scale (urban scale) and the operative one (building-component) can ensure:

- → Initially the information flow is sequential but multiscalar. It follows sequentially the three phases of the process. The first two phases, diagnosis and DM, although data for building level are used, are addressed at district scale. It is in the implementation phase when the connection between the operational and strategies scales is fully considered and implemented.
- → The required integral diagnosis (or current state identification) can be made by real data. At low levels of information, when information regarding HUD is scarce, the strategic level can target the data acquisition at building level by selecting proper modelling strategies. At higher levels of information, when databases containing information regarding the buildings are available, the data acquired at building level can easily be aggregated to form a complete urban level vision.

- → In the DM phase, the strategic decisions can be transferred to the executive level. The accorded global goals and the decided measures at urban level and actions can be translated to each building.
- → The implementation of the strategies at building level is a huge opportunity to feed again the model:
  - The diagnosis, DM and implementation phases at building level can update and complete the information regarding the building in the model with new information, with information that has been found that was not correct or with the information regarding the new strategies implemented. This new information could change the diagnosis of the HUD.
  - The monitoring phase at building level will feed the monitoring at strategic level measuring the real improvements of the implemented actions. This information will give the feedback that will refine all the system.

The following figure shows the interconnection between scales as described:

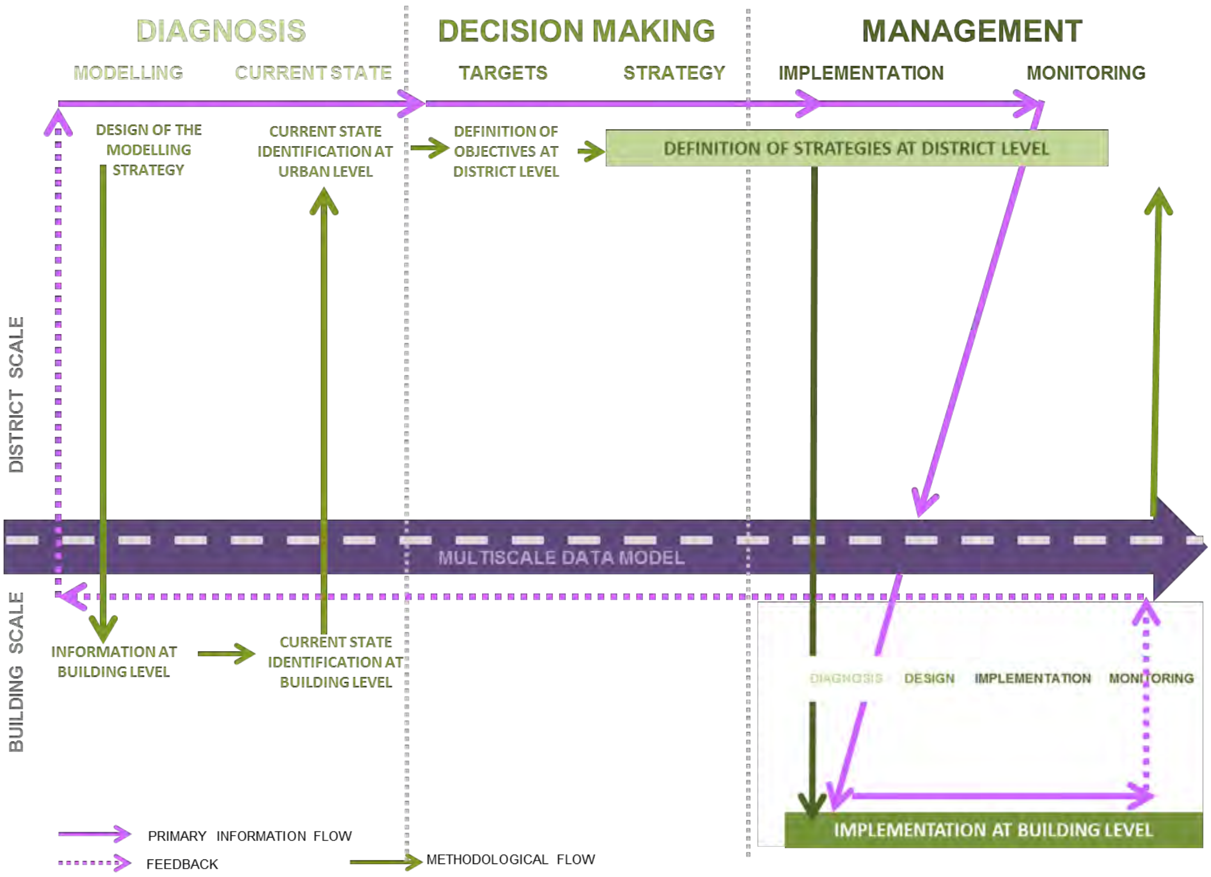

Figure 14: Interconnection between scales in the framework

1.5 Definition of the overall methodological framework

In order to facilitate the implementation of all the phases, the entire framework can be divided in two big stages:

- → A first stage: where the diagnosis and the selection of the best strategies is carried out (DM Methodology).
- → A second stage: where the Energy Rehabilitation Program is designed to develop the implementation and monitoring phases at urban and building level.

The next sections will describe this two stages and the second chapter of this document will develop in detail the first stage, i.e. the DM methodology.

1.5.1 Decision Making Methodology

The DM methodology covers the diagnosis (modelling and current state identification) along with the DM phase. The first step is to choose the modelling strategy that will allow the testing of the different scenarios and the assessment of the strategies. The modelling will be different according to the levels of available information:

- → **Low level:** the information is provided by the user and it is enough to characterize the HUDs in order to give general recommendations. No structuration of those data is necessary.
- → **Medium level:** information of the whole HUDs is available in low detail. This information will be sufficient for selecting a modelling strategy to target the acquisition of information at building level, which will allow the diagnosis at urban level with the minimum information required.
- → **High level:** when the data model can be completed in a higher level including information regarding a significant number of buildings of the HUD, the diagnosis at urban level is made by aggregation of real data.

The methodology will be structured in four different LoDM in order to give and answer to the four different scenarios of information availability in a HUD: no information (LoDM 0), low level (LoDM I), medium level (LoDM II) and high level (LoDM III). The LoDM and the DM methodology at medium-high levels of information will be developed in detail in Chapter 2.

A proper modelling will allow the current state identification, made at urban level but using the data from building scale. The definition of the objectives and the preferences of the users at urban level will be the first step in the DM process that will be translated to the selection of the best strategies at urban level (see Chapter 2). A Decision Support System (DSS) can be largely beneficial in this phase in order to guide the decision maker, implement a DM methodology and facilitate the calculations.

1.5.2 Energy Retrofitting Program

Once that the strategies are selected, it is necessary to design an *Energy Retrofitting Program* that will define the implementation and monitoring phases in long term. This program will develop a strategy at building level that will translate the urban objectives and strategies to the operative scale but also to ensure the mechanisms that will feed back the system with the information generated at building level. The whole methodology has to be able to articulate the structuration of all the new information and feedback generated during the whole process. All the phases of the intervention at building level (the diagnosis, the design of the intervention and its implementation) will generate new information about specific buildings that will complete the multiscale data model of the HUD and enable more accurate DM. A set of indicators at urban level can be used for the monitoring of the real improvement of the strategies and consequently the whole process will be refined. In section 3.4.1how this feedback mechanism is structured through the data model is detailed. The following figure shows the overall methodological framework and the different phases are described in the subsequent sections.

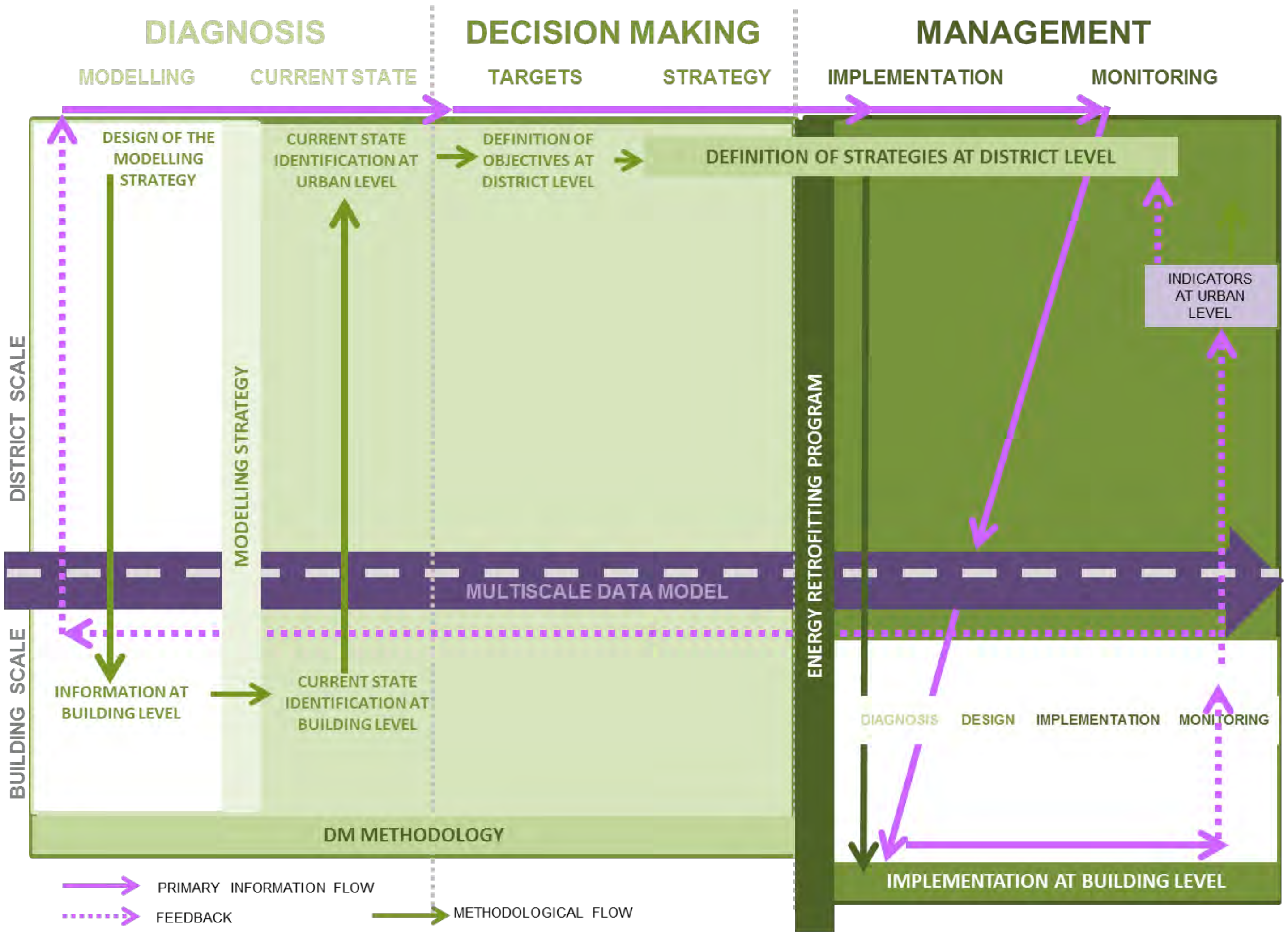

Figure 15: Methodological framework

2 DECISION MAKING

Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?
T.S. Eliot,
Choruses from the Rock

The previous chapter has developed a methodological framework divided in two main stages: a first stage where the diagnosis and the selection of the best strategies is carried out and a second stage where the energy retrofitting program is designed to develop the implementation and monitoring phases. This research is focused in the initial stage of the retrofitting process at district level, when the retrofitting framework is established, the strategies are defined and the technological solutions are selected. Within our multiscale approach, these strategies at urban level are constructed by the selection of highly replicable strategies at building level.

In this stage an optimal balance between the data required by the DM and the accuracy of the results is decisive. Methodologies that require big amount of data usually give accurate results but are too resource and time demanding, on the other hand, methodologies based on very simple data could give too generic results. In both cases, it is difficult to design and implement sustainable strategies based on methodologies that are either so stringent regarding data requirements or so unspecific about possible solutions. A flexible and incremental information strategy can overcome this problem. As seen previously, different levels of information available can be addressed by different LoDMs (Section 2.6 will discuss this in detail). In low levels of information the data regarding the HUDs can be provided directly by the user, but in higher levels a data model is required in order to structure the information. Although this research is focused in the levels when a data model is necessary, a methodology for lower levels of information availability was developed within EFFESUS project[23].

[23] EFFESUS (2014). Deliverable D5.2 – Transferable models. EFFESUS Project (FP7/2012-2016 grant agreement n° 314678), 2014

2.1 Decision making for improving energy efficiency of the built environment

The building, along with its environment, is a complex system from technological, ecological, social, cultural, anthropological, aesthetical and economical point of view. As (Keeney 1982) stated the upgrading of buildings is a proper subject to be treated by decision support models since they are usually developed for complex situations characterized by being interdisciplinary, long-range, uncertain, with multiple objectives and difficulty in identifying viable alternatives and where multiple decision-makers are involved and many groups are affected by the decision.

Several models and methods to support this DM have been developed, usually based on iterative processes: cost-benefit analysis (Goodacre et al. 2002), multicriteria analysis (Brandt & Rasmussen 2002), lattice method for global optimization (Saporito et al. 2001), prediction of the rate of occupancy (Kusuda 2001) or systems for existing building energy rating (Zmeureanu et al. 1999).

If the DM regarding the upgrading of the buildings is focused on energy rehabilitation, the task is specially complex to address since each subsystem influence the total energy behaviour and where interdependence between each subsystem plays a significant role (Kaklauskas et al. 2005). Therefore the decision maker can greatly benefit from decision-support models, which can be transformed to a computerized semi-automatic tool that can help support them to develop and execute reasonable and economic rehabilitations (Rosenfeld & Shohet 1999). According to (Diakaki et al., 2008) the state of the art has two different approaches:

- → After, an energy assessment of the building is made, based on its results the energy expert proposes several alternative scenarios that are evaluated and validated mainly through simulation. The selection of the final measures relies on the experience of experts.
- → Different techniques to support DM are used, such as multi-criteria methodologies that support the final selection from a list of possible actions.

(Kolokotsa et al. 2009) make a categorization based on the literature of the different methodological approaches for the improvement of energy efficiency in buildings as showed in the following figure:

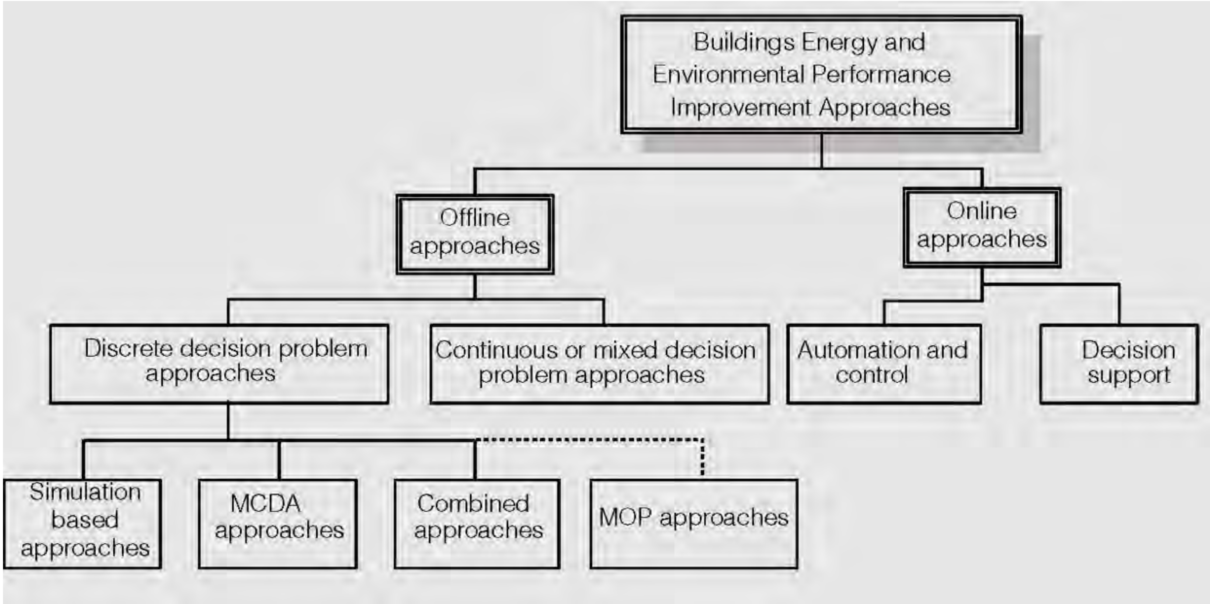

Figure 16: Categorization of methodological approaches for the improvement of energy efficiency in buildings (Kolokotsa et al. 2009)

As it can be seen in the figure, there are two big groups of methodologies: offline and online approaches. On the one hand, offline approaches aims to identify the best solution and measures while they are not interacting with the building in real time. On the other hand, at operational level, the goal of the online approaches is to identify particular parameters based on real-time measurements that improve the EP of the building during its real-time operation. The proposed methodology is focused on the first strategic stage of DM in a project at urban level therefore can be included among the offline approaches.

The fast technological development in the field of energy efficiency and renewable energy technologies is steadily increasing the range of solutions and decision alternatives. Even though the action and measures that the methodology will take into account are numerous they are countable and limited. Moreover they will come from a solution repository or data base; therefore it is clearly a discrete decision problem. Discrete decision approaches can be classified as following:

→ simulation based approaches
→ multi-criteria decision analysis approaches
→ multi-objective programming (MOP) approaches
→ combined approaches

The most promising ones are the multicriteria methods, which can be classified mainly in two categories: Outranking methods (pairwise comparisons between alternatives) and Utility-based models (single score for every alternative).

(Gero et al. 1983) were one of the first authors to propose a multi-criteria model to explore the trade-offs between EP of the building and other criteria such as investment cost to optimise cost, thermal load and usable area. (Wright et al. 2002) used genetic algorithms to optimise the design and thermal control of buildings and (Chen et al. 2006) proposed a multi-criteria model for lifespan energy efficiency assessment of intelligent buildings. (Alanne 2004) proposed a multicriteria *knapsack* model to support designers in the selection of the most feasible actions in the conceptual phase of a rehabilitation project. Under this approach a number of rehabilitation actions are developed and a utility score is assigned according to specific criteria. Then utility scores of all actions are used as weights in the optimization model to identify the actions that should be undertaken. In the literature there are several interesting reviews about these systematic approaches that rely on multicriteria techniques (Al-Homoud 2001) (Kolokotsa et al. 2009) (Wang et al. 2009) (Ferreira et al. 2013). A retrofitting scenario is a list of necessary task for the rehabilitation of a building. The evaluation of possible retrofitting scenarios through a multicriteria approach have been addressed by several authors: (Jaggs & Palmer 2000) (Flourentzou & Roulet 2002)(Rey 2004)

2.2 Elements for decision making

The selection of the strategies suitable for each district depends upon the own characteristics and restrictions of the specific HUD, the properties of the solutions proposed and the criteria that these strategies will serve. Consequently, the DM process for selecting the best strategies for the improvement of energy efficiency in HUDs has to be feed with data about those three aspects: data about the historic district, data about the technologies and solutions and indicators that will allow the selection of the best strategies. These data, and the structures that contain them, have to be coherent and compatible within a shared information strategy that will allow the matching of information and consequently the systematic assessment of the different alternatives.

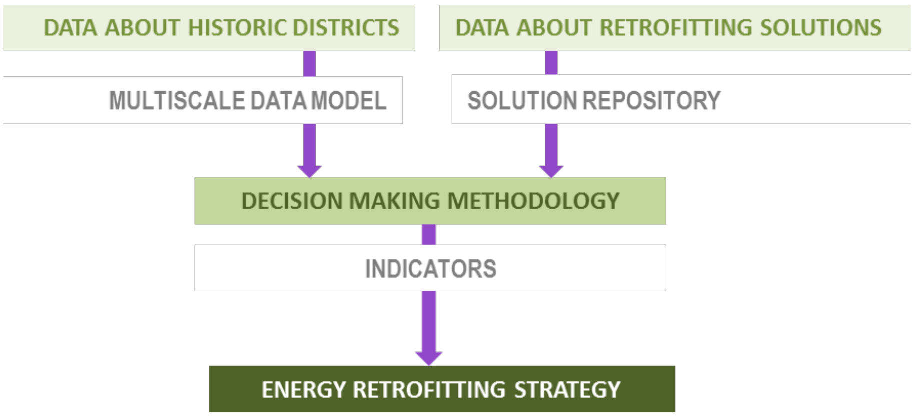

Figure 17: Elements for DM

2.2.1 Indicators

Reliable, measurable and specific indicators are needed in all the phases of the process: to obtain an accurate definition of the current state, to compare different alternatives and scenarios and evaluate their improvement in relation to the selected criteria in the DM phase and to monitorize those improvements in the management phase. The role of the indicators in DM phase is to facilitate the systematic assessment of the criteria that have been selected as significant. In case that the level of information that can be achieved at district level do not allow a quantitative assessment of the criteria a qualitative assessment for some of them has to be proposed.

2.2.2 Multiscale data model

A proper data model is a keystone element for a strategic information management and consequently for the entire methodological framework proposed. The Chapter 3 will discuss in detail the requirements of this data model and how it structures all the information regarding the HUD that is needed for the decision process. Some of the capabilities of the multiscale data model can be exploited through a categorization tool that would facilitate the modelling phase. This tool can support the categorization of the buildings of the HUDs according to some key parameters, clustering them and creating representative typologies. This process will be explained in more detail in Section 2.7.2.

2.2.3 Data base of energy efficiency improvements measures

The possible measures that would improve the EP of the HUDs have to be categorized and structured in a database compatible with the rest of the elements of the system. Plenty of work has been done in the last years analysing and classifying measures, technologies and actions for improving the energy efficiency of existing buildings. Some of the reviews of the literature can be seen in (Kolokotsa et al. 2009), (Ma et al. 2012) or (Boeck et al. 2013). Anyway, due to the topic of the present research, it is worth of mentioning the initiatives that focused in structuring and making accessible the retrofitting measures suitable for in historic buildings as "Responsible Retrofit Guidance Wheel"[24] developed by the Sustainable Traditional Buildings Alliance (STBA) or the repository already mentioned built within the EFFESUS and containing Energy Efficiency Improvements Measures (EEIM) are Renewable Energy Solutions (RES)[25]. Therefore it is not the aim of this dissertation to propose another repository or database but to identify the structure and information requirements that are necessary for the system.

In order to connect this database with the multiscale data model, and make the assessment location dependent, for each solution has to be clearly identify the element of impact. This element is the part of the building or district that would be modified in the case that the solution would be implemented. The list of these elements have to be the same that the elements considered in the multiscale data model, in this way, the information contained in the multiscale data model regarding the HUDs and its elements (levels of

[24] http://www.responsible-retrofit.org/wheel/

[25] EFFESUS (2013). Deliverable D2.5 – Energy efficiency solutions repository built up. EFFESUS Project (FP7/2012-2016 grant agreement n° 314678), 2013

protection, historic significance, energy and material characteristics…) can be match with the information contained in the solutions repository (improvement of the measure, impact on the fabric…) making possible a detailed assessment at element level.

Other requirements that the repository has to fulfil are the followings:

- → The solutions have to be classified according to the strategy that they address:
  - Solutions that intent to improve the management
  - Passive Solutions that aim the reduction of the demand (improving the airtightness of the building or the thermal performance of the envelope)
  - Active Solutions that pursue the improvement of the efficiency of equipment
  - RES
- → The solutions have to be characterized regarding the criteria of the DM, through the defined indicators.
- → The information describing the solutions have to contain the minimum data for the energy calculations and the HS assessment

2.2.4 Stakeholders: roles and responsibilities

In the retrofitting of historic districts, as in any other complex urban system, they are involved an increasing range of stakeholders with different needs and interests. A common 3D data model can support the collaboration between those stakeholders as a shared virtual space that facilitate visual communication between them as described in (Ross et al. 2009).

The first stage of the retrofitting process, where this research is focused, is usually led by **public administration** (municipalities and urban managers) who is interested in increasing the sustainability of the historic district and guiding the neighbours in this process. Although usually there is an internal department or an external organism that leads the strategy, all the process requires the coordination with the others departments and agencies within the public administration as crossthematic issues are involved (energy, social, economic, cultural and tourism issues among others). A shared spatial data model and an evidence based DM process can support and facilitate the necessary internal coordination.

But an integrated approach for the preservation of the urban historic environment has to involve also external and private stakeholders and a win–win situation for each and all of the stakeholders is decisive for the success of the programs. In order to be sustainable the solutions have to come from the understanding of the needs that are important to each of the stakeholders and have to be designed to address the issues salient for them (Khare et al. 2011). A proper stakeholders' engagement will imply a shared responsibility in which each stakeholder (i.e. decision makers, owners, citizens, and technicians) plays a key role. Some of those other stakeholders are the followings:

- → **Grant Managers** (Energy Agencies, European Comission, etc…): in common with the public administration, they could be interested in increasing the profile of sustainability of the HUDs through the launching of retrofitting programs, in which the different technologies and retrofitting strategies are considered, in order to invest in the most suitable one for a specific HUD.
- → **Owners**: they directly experience the performance and indoor climate characteristics of the building and consequently they are interested in reducing the costs and improving the value of the building through its upgrade.
- → **Investors:** they have the financial capacity to provide funding for the investment that is required by the retrofitting projects and to exploit the energy savings during the life of the buildings.
- → **Building Solution Providers:** they are interested in promoting their specific technologies for historic buildings and consequently they are looking for potential retrofitting projects of HUDs to supply their products.
- → **Building users:** although they are frequently not responsible for the choice of the retrofitting measures, they directly influence the needs of the building itself and provide funding through payments to the building´s owner. In many cases the building users are also the building owners (in 2013 up to 70 % persons in the EU-28 lived in owner-occupied dwellings[26]).
- → **Local/Regional authorities for building and heritage preservation:** they have the legal mandate to guarantee that the retrofitting projects are respectful with the HS of the HUDs.

Public administration can create an energy model of the HUDs for a better and integrated management of the city. Grants Managers provides incentives for investors and owners to boost the renovation activities and to make more attractive the investment opportunities. These incentives are often based on energy and environmental performance targets, assessed by means of evaluation/certification schemes/tools. Users benefit from the retrofitting activities obtaining at the end of the process more efficient buildings. The following figure shows the interaction between the results and the main actors involved in the retrofitting projects at urban scale:

[26] Distribution of population by tenure status, type of household and income group (Source: European Union Statistics on Income and Living Conditions (EU-SILC)). Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do

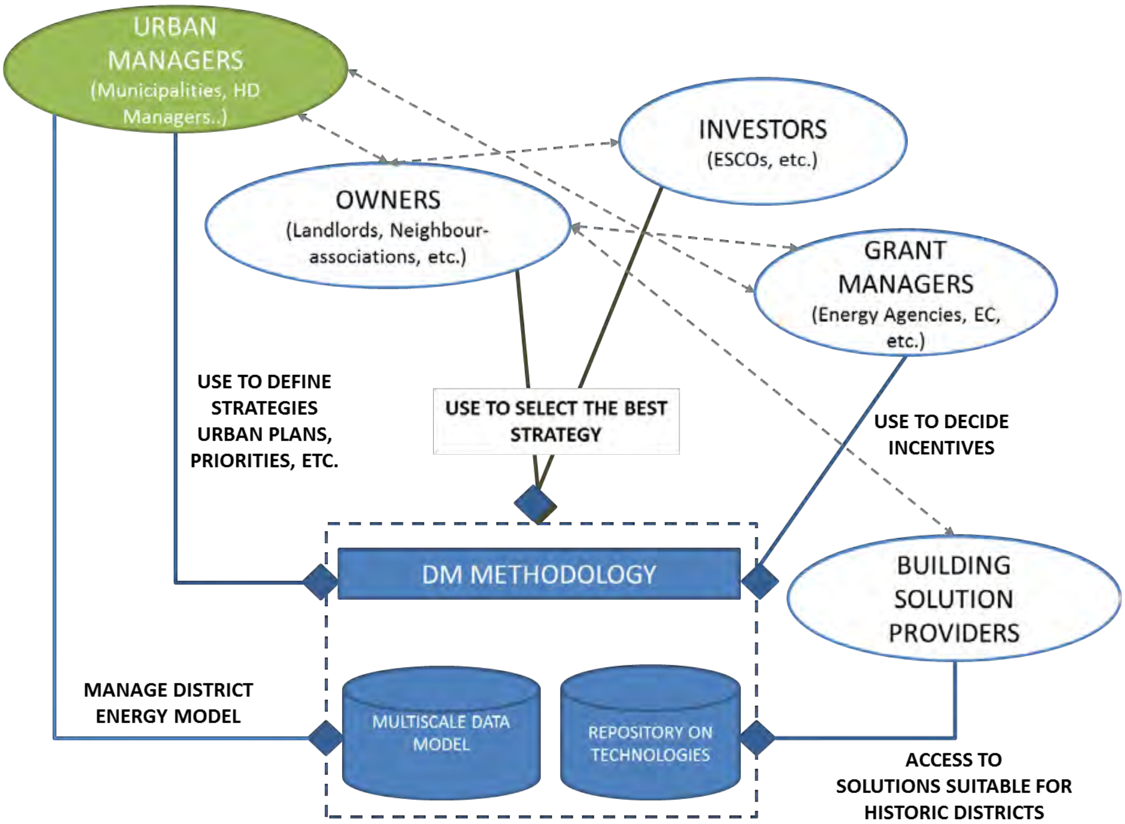

Figure 18: Stakeholders interaction with the DM methodology

2.3 Levels of Decision Making

The different levels of DM were first proposed in (Egusquiza et al. 2014) and they can be considered as one of the main requirements for the methodology (see Section 2.6.). If the methodology aims to be broadly applied it has to be able to deal with different scenarios of information availability. Keeping the information requirements flexible it will make possible to address the majority of the cases regardless of the information that is available or the effort that is intended to put in the information collection and structuration. It is important to stress out that the lower the information level is the lower of the accuracy of the results will be. According to the level of information provided for the DM four cases can be distinguished:

- → No information provided.
- → Low level of information provided: the information is provided through general questions which will help to characterize the historic district. No data model will be used.
- → Medium level of information provided: information of the whole HUD is provided in low detail. The information is enough for the implementation of a modelling strategy that will allow the evaluation of the different scenarios.

→ High level of information provided: the data model can be completed in a higher level; the strategy will focus in specific building groups that can be prioritized using the information from the previous levels.

Taking into account those possible scenarios, four LoDM can be defined:

LoDM 0

At this level, no specific information is required regarding the HUD. The user can obtain information, metrics, guidelines and recommendations to improve the sustainability of a HUD in a general way.

LoDM I

This level is intended to provide solutions and recommendations for different historic districts using low level information, rather than a full data model. The main characteristics of the HUD have to be identified and consequently it would be fit in a HUD typology. Using a simplified scheme for decision, this level is intended to be used at a very early stage in a planning process. The information is provided by the user through questions defined by the method called Transferable Models (TM). This research aims just to identify the role of the TM in the whole framework, but not further development has been done in this direction. The detailed development of the Transferable Models can be found in the EFFESUS project deliverables D5.2[27] and D 5.4[28].

LoDM II

At this level a multiscale data model is necessary but in a low level of completeness. The data model will have a low detail level, containing only limited information of the entire district and more detailed information of buildings selected as representative. The results can be extrapolated to the rest of the buildings of their category and establish the impacts of the selected retrofit strategies.

LoDM III

At this level, the strategy will focus in specific building groups (or single buildings) that can be prioritised using the information from the previous levels. Therefore, this level requires more detailed information about the district and its buildings. Consequently it will be necessary to develop the multiscale data model to a higher level of detail and to include buildings not considered in the previous level.

The choice of optionally using external tools or information will determine additional levels of accuracy within the II and III levels. The four LoDMs (and the six levels of accuracy) are included in the following figure:

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[27] *Ibid 23*

[28] EFFESUS (2014). Deliverable D5.4 – Methodological Framework. *EFFESUS Project (FP7/2012-2016 grant agreement n° 314678)*, 2014

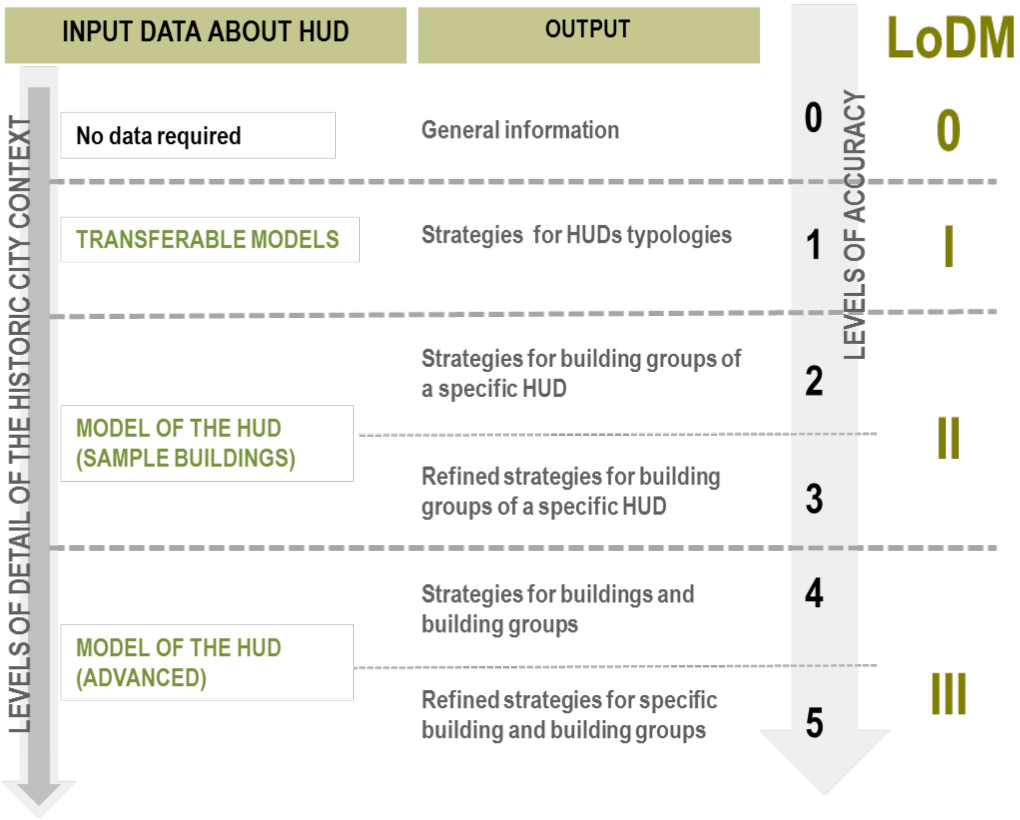

Figure 19: Levels of the DM and Levels of Accuracy

The next figure describes the different scales that are addresses with the different LoDM:

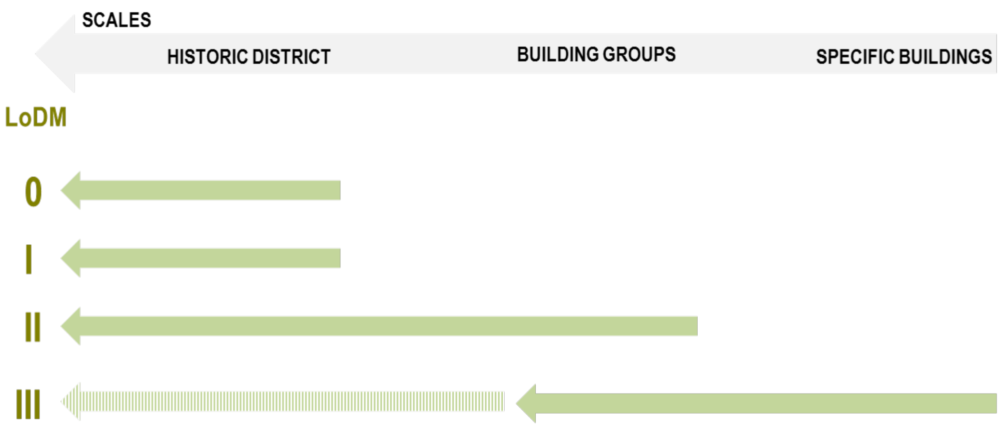

Figure 20: Scales according different LoDM

In addition to help to address different HUDs, the different LoDMs can also be useful to meet the requirements of the different stakeholders. The following figure describes this interaction between end-users, the different results of the project and the LoDM:

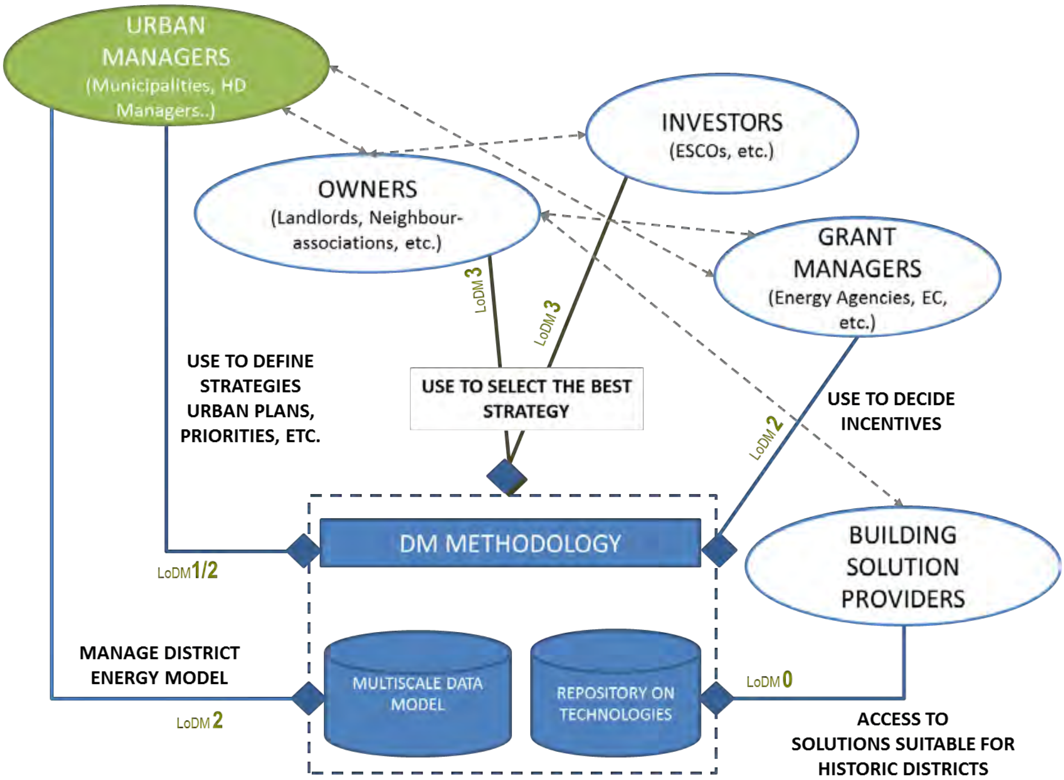

Figure 21: Interaction between DSS results, LoDMs and main stakeholders

2.4 Criteria, constraints and indicators for decision making

2.4.1 Definition of the criteria for the decision making

The first step in any decision is to identify the factors that are important. Three main axes influence the HUD´s energy sustainability: efficient resource management, improvement of the liveability and conservation of their cultural values. In the EFFESUS projects the followings six criteria were identified[29]: indoor environmental conditions, embodied energy, operational energy, economic return, HS and fabric compatibility. These six categories can be categorized among the three axes as it is shown in the following figure:

[29] EFFESUS (2013). Deliverable D1.2 - Establishment of impact indicators. *EFFESUS Project (FP7/2012-2016 grant agreement n° 314678)*, 2013.

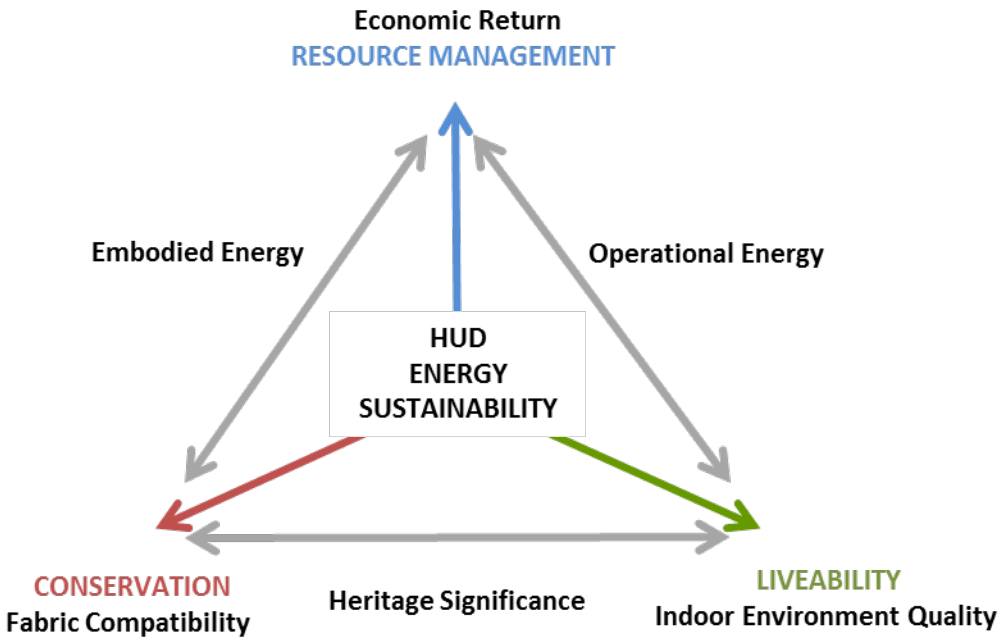

Figure 22: Criteria for HUD sustainability

Three of the categories are centrally linked to one of the axes as indoor environmental conditions with liveability, economic return with resource management and fabric compatibility with conservation. The other three, however, can be understood as contributors to two different axes.

To keep the embodied energy as low as possible is one of the priorities of the resource management that leads to urban sustainability. However, it is crucial also for the heritage conservation as the embodied energy is part of the cultural assets that have to be conserved. The strategy of minimum intervention is shared for both of the axes: the more is conserved the more embodied energy is saved. Analogously, operational energy has to be saved but it contributes also clearly to the liveability, therefore equilibrium has to be sought. Finally, the conservation of the HS is mandatory in a HUD, but it is also important in the improvement of the quality of life of the citizens as part of their identity.

2.4.2 Definition of the constraints for the decision making

The indoor environmental conditions, embodied energy, operational energy and economic return can be considered as competing or evaluating criteria for selecting the best solution and technologies, but HS and fabric compatibility are constraints in the DM. The conservation of historical values, the observance of conservation principles and the consideration of material compatibility are mandatory, therefore these aspects cannot be trade-off for other objectives.

These two categories will allow discarding the technologies that are not suitable for a specific HUD or, at least, will identify the possible risks. In order to develop a logic that will filter the solutions it has to be crossed the information regarding the building or HUD (about its HS or material characteristics) and the information regarding the potential impact of a retrofit measure in those categories.

In EFFESUS a method was drafted for this assessment based in a 0-4 scale to value the vulnerability/significance of the buildings and the potential impact of the measures[30]. This has to be done by, firstly, identifying the HS of building and urban elements, such as walls, roofs and urban spaces. Secondly, defining the various impact of retrofit measures on the elements, with regard to HS, technical compatibility etc.

Heritage Significance and Conservation Principles

Based on EFFESUS methodology for assessing the impacts of energy-related retrofit measures on HS (Eriksson et al. 2014), HS is assessed at three levels of the historical environment: HUD, external building envelope and building interior areas.

The scale that measures the degrees of HS of these elements is as following:

- → 0= Neutral or negative significance
- → 1= Minor significance
- → 2= Major significance
- → 3= Outstanding significance
- → 4= Exceptionally outstanding significance

Value	Description	Example for Wall Render	
		Illustrating Description	Potential Results
0	Negative or neutral significance (or assessment not applicable)	Recently applied cement render in a location which traditionally would have had a lime render	Loss or damage would not be considered problematic and might even be beneficial
1	Minor significance	Traditional render	Loss or damage might be considered acceptable
2	Major significance	Older traditional render or render with ornate decoration	Loss might be considered acceptable under special circumstances; damage should be minimised
3	Outstanding significance	Older, rare, traditional render with or without ornate decoration	Loss is considered unacceptable and damage should be kept to the absolute minimum
4	Exceptionally outstanding significance	Older, rare, and well-surviving traditional render with ornate decoration of outstanding quality, e.g. sixteenth-century pargetting	Any form of damage or loss is considered completely unacceptable

Table 3: An example of HS assessment for wall renders. Source: (Eriksson et al. 2014)

[30] *Ibid 29*

The proposed system distinguished between three types of HS: visual (e.g. appearance), physical (e.g. authenticity, materiality) and spatial (e.g. plan layout, space etc.). The second scale measured the degrees of impact / risk of the retrofit measure as follows:

- → 0=No impact
- → 1=Insignificant impact
- → 2=Minor impact on HS
- → 3=Major impact on HS
- → 4=Outstanding impact on HS

This information can be matched for specific elements to establish the suitability of a specific retrofit measure for that specific element. In order to enable this assessment, the information regarding the HS has to be stored in the multiscale data model for each element and the information about the impact of the solution in the database has to include the element in which the measure has impact. This assessment is explained in Section 2.7.4 of the methodology.

Building and urban fabric compatibility

The way to assess the *Building and urban fabric compatibility* is very similar to the assessment of the *HS and Conservation Principles*. In order to assess the compatibility between the proposed measure and the fabric of a specific building it has to be crossed information regarding the fabric as well as the potential impact of a retrofit measure. In a detailed assessment, this should be done in the fabric level checking in which fabric (and how) the solution is going to impact and which are the properties or vulnerabilities of this fabric. These assessments only can be done qualitatively, so the EFFESUS project[31] it was proposed a qualitative scale for the both of them. As in the HS case, the scales have been slightly adapted, changing the original *Not applicable* for the value of 0 to *No impact* in both cases. The first scale measures the degree of applicability to existing fabric and it is as following:

- → 0= Not impact
- → 1= Unlikely to occur now and in the future
- → 2= Might occur at some point in the future
- → 3= Occurs occasionally
- → 4= Occurs regularly and repeatedly

The second one measures the degrees of impact / risk of the retrofit measure as follows:

- → 0= Not impact
- → 1= Will not negatively affect the fabric performance in the concerned impact area short- and/or long-term

[31] *Ibid 29*

→ 2= Unlikely to negatively affect the fabric performance in the concerned impact area short- and/or long-term

→ 3= Might negatively affect the fabric performance in the concerned area short- and/or long-term

→ 4= Will detrimentally affect the fabric performance in the concerned impact area short- and/or long-term

The cross of this information in a specific fabric will provide the suitability/applicability of the measure for that fabric. In order to enable this assessment, the information regarding the fabric has to be stored in the multiscale data model for each fabric and the information about the impact of the solution structured in the database has to include the element in which the measure has impact.

2.4.3 Selection of indicators

The role of meaningful data and quality indicators is becoming increasingly crucial as sustainability is developing more into a procedural issue than a final solution (Crosbie et al. 2014). Plenty of work has been done in the last years regarding the gathering and harmonisation of the Key Performance Indicators (KPI) that are able to provide quality metrics to measure the sustainability at urban and building scales. It is worthy to mention the work done in OPEN HOUSE [32] and SuPerBuildings [33] projects funded under the FP7 framework and the review done in (Kolokotsa et al. 2009) about indicators used in literature regarding the categories that can affect the DM when energy retrofitting strategies are selected: energy use, cost, global environment, thermal comfort, visual comfort, indoor air quality (IAQ) or acoustic comfort.

The role of the indicators within this research has been explained in the Section 2.2.1. Six categories of indicators have been identified coincident with the six criteria for DM: indoor environmental conditions, embodied energy, operational energy, economic return, HS and fabric compatibility. In the EFFESUS a preselection of indicators was defined through a review of the existing literature and group discussions and their usefulness for the impact assessment of the implementation of new energetic retrofitting technologies and measures in HUDs was analysed[34]. An analysis has been made by studying each indicator according with the following criteria:

→ the type of data (unique or multiple values, if they are a predefined set of values…)

→ the element or scale that can be linked to the indicator

→ if the data is easily available or how it can be measured (measure with sensors or other means)

→ their priority for the DM

→ their link with the multiscale database and the database regarding technologies

[32] http://www.OPEN HOUSE-fp7.eu/
[33] http://cic.vtt.fi/SuPerBuildings/
[34] *Ibid 29*

In the Annex I the result for each indicator can be found, but the following sections will summarised the conclusions of that work.

Improvement of habitability and indoor environment quality

In this category 12 indicators were preselected structured in 4 different subcategories as following:

Category	Subcategory	Specific Indicator
Indoor environmental conditions	Thermal comfort	Temperature
		Relative humidity
		Predicted mean vote (PMV)
		Predicted percentage dissatisfied (PPD)
		Indoor ambient noise levels in unoccupied spaces
	Acoustic comfort	Mean maintained illuminance
	Visual comfort	Illuminance uniformity
		Colour rendering index (CRI) for lighting
		Daylight factor
		Pollutants
	Indoor air quality (IAQ)	Microbial pollution
		Ventilation rate

Table 4: Indoor Environmental Conditions Indicators

The majority of these indicators have to be measured through sensors and they are related with the room or dwelling scale.

Energy saving

Under the *Energy Saving* concept it has been included the categories of *Operational Energy* and *Embodied Energy*. The conclusion of the EFFESUS regarding energy efficiency indicators was that their development is limited by data availability and quality of data. As a consequence, the available indicators are generally more energy indicators than energy efficiency indicators, limiting the extent to which indicators can be used to actually follow trends in energy efficiency. They can to a certain extent be a proxy for energy efficiency (e.g. energy intensity indicators). The following table shows the indicators that finally were preselected:

Category	Subcategory	Specific Indicator
Operational Energy	Electrical energy use	Total use/year
		Electricity use per m^2 building area
	Thermal energy use (heating and cooling)	Total use/year
		Thermal energy use per m^2 building area
	CO_2 emissions	Total for a building or a district
	Peak power demand	Total for a building or a district
	% RES	Fraction of energy supply from renewable energy sources

Table 5: Operational Energy Indicators

The indicators regarding the embodied energy were classified between *Comprehensive energy consumption* and *Comprehensive (life cycle) energy saving*. The former are performance indicators and can be calculated for the current situation. They are connected to the operational energy indicators, but include the issues of maintenance and *end of life*. They are usually calculated by aggregation of information provided usually at lower level of detail (e.g. component or installation level). In the indicators regarding the comprehensive (life cycle) energy saving it has to be considered the fourth dimension too. These indicators are linked also to the "operational energy" indicators, as they consider the expected reduced operational energy need after the implementation of a measure, but take into account also the new embodied energy that is added with this measure as well as the changed energy need for maintenance and "end of life".

Category	Subcategory	Specific Indicator
Embodied Energy	Comprehensive (life cycle) energy consumption	Total Primary Energy consumption (over 100 years)
		Total Primary Energy consumption (over 100 years) per year
		Total Carbon emissions (over 100 years)
		Total Carbon emissions (over 100 years) per year
	Comprehensive (life cycle) energy saving	Total Primary Energy saving (over 100 years)
		Total Primary Energy saving (over 100 years) per year
		Total Carbon saving (over 100 years)
		Total Carbon saving (over 100 years) per year

Table 6: Embodied Energy Indicators

Economic feasibility

This category includes the impact indicators associated with the economic return on an investment into energy efficiency in HUDs. They can be estimated, in a first approach, using simple relative values on a scale of 0 to 4 for the economic impact with 0 meaning *zero impact*, 1 meaning *low impact* and 4 meaning *high* *impact*, but values could be calculated with detailed information using specialist tools, professional advice, contractors' estimates or more detailed research (i.e. external calculations).

Category	**Subcategory**	**Specific Indicator**
Economic Return	Cost of Retrofit Measures	Cost in euros
	Value of energy saved	Value in euros
	LCA (Life Cycle Analysis)	Combined Environmental Impact Indicator LCC
	NPV (Net Present Value)	Value over time
	ROI (Return on Investment)	Efficiency of investment
	Public Domain Benefits	GDP
		Health care costs
		Health benefits
	Overall Payback Period	Payback time taking account of all benefits
	Energy Payback Period	Payback time only taking account of cost of energy

Table 7: Economic Feasibility Indicators

Basic set of indicators

The key factors influencing the selection of indicators are the availability of data for their estimation, the meaningfulness of the inferred information, the easiness of their calculation (whether complex tools are necessary or not) and their priority for the DM. As seen in Section 1.5, within a strategic information management frame, it is not necessary to renounce to any indicator if an incremental complexity in the use of the indicators is adopted. In a first stage, it will be used the indicators that can be calculated/estimated semi-automatically and the indicators estimated by sensors, sophisticated tools or in need of detailed information will be postponed for a higher levels of accuracy. The following table shows the final set of indicators considered in the first stage for the levels of Accuracy 2 and 4 and how they are calculated:

Level		Accuracy		Scale		Category	Current state DSS: Subcategory	Current state DSS: Specific Indicator	Current state DSS: Calculation	Decision making DSS: Subcategory	Decision making DSS: Specific Indicator	Decision making DSS: Calculation
II	III	2	4	building		Habitability				Thermal comfort		REPOSITORY
				building						Acoustic comfort		REPOSITORY
				building						Visual comfort		REPOSITORY
				building						IAQ		REPOSITORY
				building	district	Energy saving				Energy Saving		REPOSITORY
				building	district		Thermal energy use	Total use/year	EE ADE + EN ISO 13790:2008	Thermal energy use	Total use/year	EE ADE + EN ISO 13790:2008+ REPOSITORY
				building	district		Thermal energy use	Thermal energy use per m^2 building area	EE ADE + EN ISO 13790:2008	Thermal energy use	Thermal energy use per m^2 building area	EE ADE + EN ISO 13790:2008+ REPOSITORY
				building	district		Electrical energy use	Total use/year	DSS ESTIMATION	Electrical energy use	Total use/year	REPOSITORY
				building	district		Electrical energy use	Electricity use per m^2 building area	DSS CALCULATION	Electrical energy use	Electricity use per m^2 building area	DSS CALCULATION
				building	district		CO_2 emissions	Total for a building or a district	DSS CALCULATION	CO_2 emissions	Total for a building or a district	DSS CALCULATION
				building	district	Economic feasibility				Cost of Retrofit Measures	Cost in euros	REPOSITORY
				building	district					Value of energy saved	Value in euros	DSS ESTIMATION
				building	district					Energy Payback Period	Payback time only taking account of cost of energy	DSS ESTIMATION

Table 8: Basic set of indicators for the first phase

As conclusion, the following decision tree is proposed, where the different criteria with the different category of indicators are showed, classified by the level of accuracy where they are used:

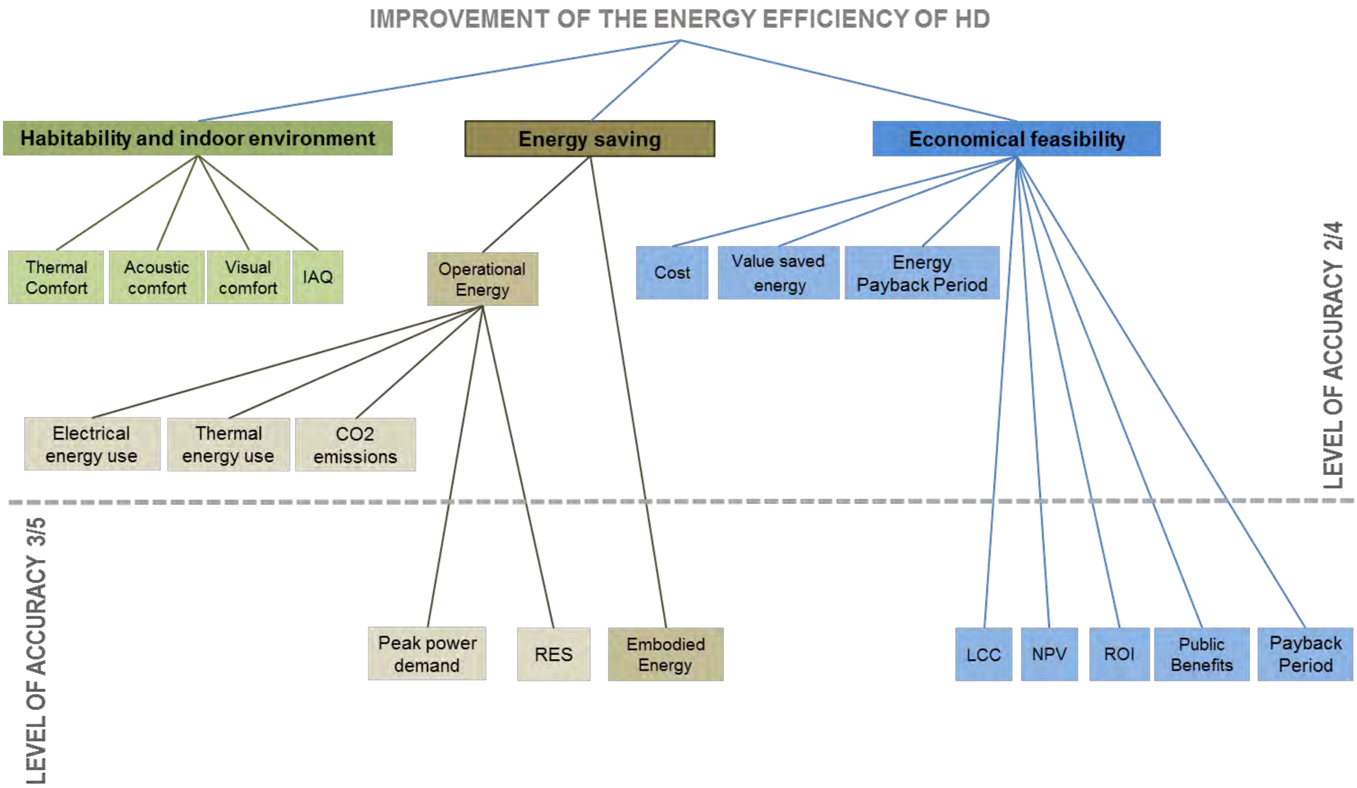

Figure 23: Decision tree for the improvement of energy efficiency of the HUD

In the Annex 2 it is included the table with all the indicators in the different LoDMs and different phases.

2.5 Modelling strategies for decision making in historic urban districts

DM processes are about managing and exploiting the right information in the proper way. The DM regarding improvements of the sustainability of HUDs has to take into account information that is spatial, multiscalar and crossthematic:

→ **Spatial** as the EP of the buildings is a function among others of the geometry and orientation of the building and its surroundings. Moreover the measures to improve the EP impact in specific buildings and components that could or could not be compatible with those actions and could be protected due to their HS.

→ **Multiscalar** as the goal is to improve the whole district addressing individual buildings and building components.

→ **Crossthematic** as the information from different knowledge domains is involved (cultural heritage, energy, indoor environment…). This information will be store as the semantic information of the model.

Urban models are digital environments used for testing the consequences of physical changes in the built environment of the cities. Urban modelling is a necessary tool for planning and development of policies (Kavgic et al. 2010) as they can support from the design of policies to the implementation of specific strategies. In order to be effective and feasible, the urban modelling has to fall between the search for simplicity in articulating the urban structure and the need to translate their complexity (Batty 2009). Moreover, for the purposes of urban scale simulation, the accuracy of the model has to be balanced with the computational overheads and data availability (Robinson et al. 2009)

Consequently, if a model is a simplified version of the reality, the modelling strategy that decides the way the complex reality is abstracted into a manageable, accurate, coherent, comprehensible, predictive and low cost model is decisive for testing purposes. This section discusses the implications of different modelling techniques in the DM. Chapter 3 will address in more detail the specific requirements and the development of a multiscale urban data model able to support the DM.

Georeferenced 3D models represent an increasingly accepted solution for storing and displaying information at urban scale. The energy improvement of the built environment at urban scale is a spatial phenomenon where the third dimension is crucial for the DM. The majority of the essential variables that influence in the energy demand and comfort of the buildings as building shape, orientation, building mass, glazing ratio or shading (Gero et al. 1983) have to be analysed in a 3D environment.

The generation and updating of 3D urban models can be very costly in terms of time and money (Döllner et al. 2006), especially if high quality and realism is necessary. Thus, a balance between the available data and the required level of accuracy of the results is determinant for the success. It is necessary to use a progressive and flexible information management strategy regarding the modelling that allows starting with a very low level of information. The purpose of the LoDMs described in Section 2.3 is exactly this, to have first results with basic information that will allow to identify the buildings or areas that have to be described in more detail in order to improve the accuracy of the model in a cost effective way.

As stated before, cross-thematic information will be necessary. In a HUD is imperative to contemplate the constraints that a cultural heritage context imposes. Accordingly, the proposed modelling strategies have to integrate energy planning and cultural conservation approaches. When it comes to assess the improvement of the EP due to retrofitting strategies the energy modelling is necessary. It allows quantifying the energy requirements as a function of input parameters, and can be used at macroscale scale or microscale scale. The quantification of the impact of the retrofitting measures, new technologies or materials, enable us to make key decisions regarding the energy management of a district (i.e. power supply, investment in retrofitting plans, prioritization of actions, the most suitable measures, possible regulatory changes ...).

There are several techniques to address the urban energy models. (Swan & Ugursal 2009) developed this scheme of different energy modelling techniques regarding the residential building stock:

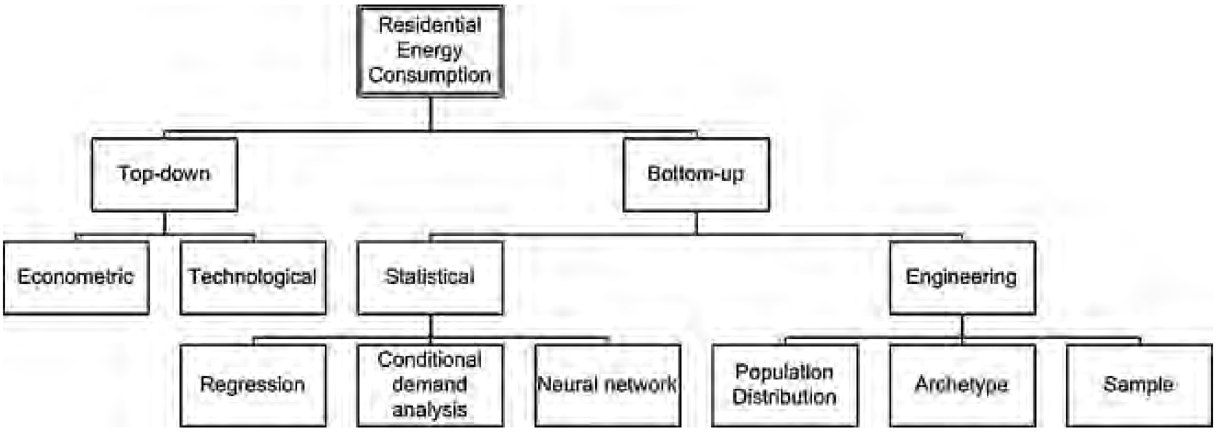

Figure 24: Energy modelling techniques of residential energy consumption. Source: (Swan & Ugursal 2009)

The techniques can be grouped mainly into two categories: *top-down* techniques and *bottom-up* techniques. According to the authors, the first approach considers the building stock as an energy sink and does not differentiate individual consumption. It allows determining the effect due to long-term changes in consumption in the residential sector in order to determine supply needs. The variables that are commonly used for these models include macroeconomic indicators (GPD, employment rates ...), weather conditions, construction and demolition rates, energy rates, and the estimation of the number of devices in households.

The *bottom-up* models use input data from a hierarchical level below, so they can explain the consumption of individual buildings or groups of buildings. These techniques are subdivided into *statistical methods* and *engineering methods*. The *statistical methods* are based on historical information and regression analysis. Once the relationship between the end use and the energy consumption is established, the model can be used to estimate the energy consumption. The *engineering methods* take explicitly into account the use and the characteristics of the systems and the heat transfer and thermodynamic relations in order to calculate the demand. This high level of detail makes possible to model the different technological options, and to determine areas for improvement.

Therefore, in order to estimate the impact of retrofitting strategies, a modelling based in an engineering method is necessary. These models have to be extrapolated to represent the building stock. This can be accomplished using a weight for each reference building or group of buildings on the basis of their representativeness. This can be done through different strategies: *distribution of the population*, *archetypes* or through *sample buildings*.

The *distribution method* is based on the use of the distribution of equipment and its use in order to calculate the final energy consumption. End uses are usually calculated separately and the interactions between them are not taken into account. In the method of *archetypes*, the building stock is classified according to representative parameters. Thus archetype definitions for most representative building types are developed and these descriptions are used as the input for the energy modelling. If real buildings are used as representative buildings they are called *sample buildings*.

As stated before, the energy modelling has to be combined with a representation of the cultural assets of the HUD in order to balance HS with the heritage impacts and compatibility of retrofit measures. Within the EFFESUS project a methodology for assessing the impacts of energy-related retrofit measures on HS has been developed (Eriksson et al. 2014). This impact assessment on HS is a location-specific one (see Section 2.4.2). That means that the HS and the impact of the measures are linked to a specific component and scale within the districts. The modelling strategy therefore needs to structure the spatial data on the HS of the buildings and district under consideration.

The main drawback of a 3D model based on a bottom-up approach, that considers energy and HS data, can be its complexity and the huge amount of data required. The use of a multiscale data model with real data of buildings could efficiently facilitate this task if a proper modelling strategy is chosen. The next chapters will detail different strategies of modelling that could be adopted when using such a model. The choice of approach will depend on factors like the availability, accuracy and level of detail of the existing data, the objectives of the analysis or the spatial scale of the analysis.

2.5.1 Large scale energy assessment

(Nouvel et al. 2013) described an automatic *large-scale assessment* of building energy behaviour based on a CityGML model using data available from public sources as cadastre. It is based on the hypothesis that strong correlations exist between information about residential buildings and their energy consumption values (Krüger & Kolbe 2012).

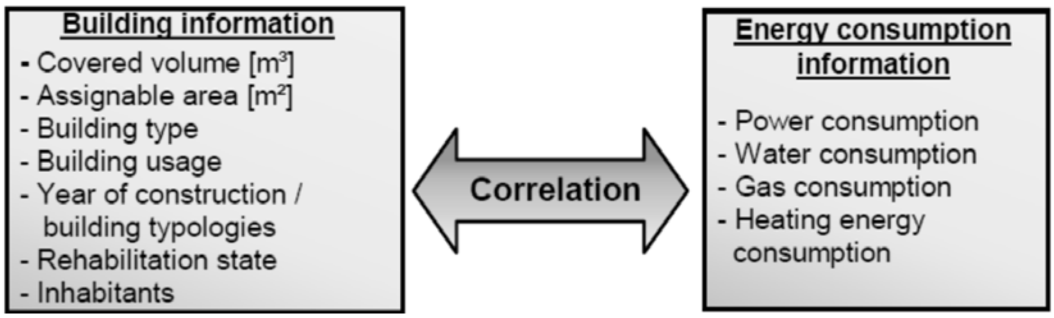

Figure 25: Correlation between building characteristics and consumption values. Source: (Krüger & Kolbe 2012)

In order to get some of the required energy characteristic of the buildings a building typology database can be used. One of those databases is the outcome of TABULA project (Ballarini et al. 2014). Those typologies are quite generic as they were developed at nation scale, but a map between the buildings of the analysed city or district and the typologies can be made through the geometric characteristics and the year of construction. An Application Domain Extensions (ADE) can be used to store the specific information of each building as in (Carrión et al. 2010) (Kaden & Kolbe 2013)(Krüger & Kolbe 2012). This method doesn't take into account the HS of the buildings so its use for HUD is limited.

2.5.2 Identification of priority areas

A very effective approach, in urban areas with low level of information, is to *identify priority areas* for energy efficiency interventions and to focus data acquisition on the buildings within this area. In the REACT project[35] a methodology using a multiscale data model has been developed for this purpose. Based on a low level of information, blocks or groups of buildings can be prioritized according to their conservation state, their EP and the concerns of the citizens. The basic data for the prioritization are provided automatically by the cadastre or from low cost sources.

The first step is to characterize each building in terms of the following categories:

- → The **conservation state** is inferred by the year of construction plus the data about whether it has been previously retrofitted or not. Both data are automatically extracted from the cadastre for all the buildings in the districts.
- → A simplified **EP** can be derived by the geometry of the building (orientation, exposed surface, compactness…), the year of construction or rehabilitation and the installations. The geometry is obtained directly from the model and the year and the installations from the cadastre.
- → The **concerns of the citizens** are translated from the number of problems reports by the users regarding each building and their seriousness. This data is provided by a platform for *digital citizenship* that allows the users to report problems regarding the buildings within the HUD.

Each building is assessed in each category through a 0-4 scale. Then, each block is represented by the percentage of buildings with the lowest scale in each category and a map of colours according to these percentages (for example: 80% of buildings with very bad EP, 50% of very old buildings and 60% of buildings with many problems) is develop. The level of protection of the building (municipal databases) and the private or public use (cadastre) is provided as additional information. This information can be used also as constraint in the DM process.

This method provides a vulnerability map based on basic data very easy to obtain in an automatic or semi-automatic way. If the data regarding the vulnerability are weighted with the information regarding the density of those buildings (also provided by the cadastre), an opportunity map is obtained. This map will show the

[35] *Ibid 2*

priority areas, that is, the building blocks more vulnerable and with higher impact due to their density. The next step is to broaden the information regarding identified priority areas in order to carry out more detailed analysis.

2.5.3 Modelling through sample buildings

One procedure used to analyse large building stocks is to examine and categorise a sample of the stock according to some parameters as climatic area, dimension and age. For each category, a reference building can be defined using a suitable procedure (Ballarini et al. 2014) as shown in the following figure:

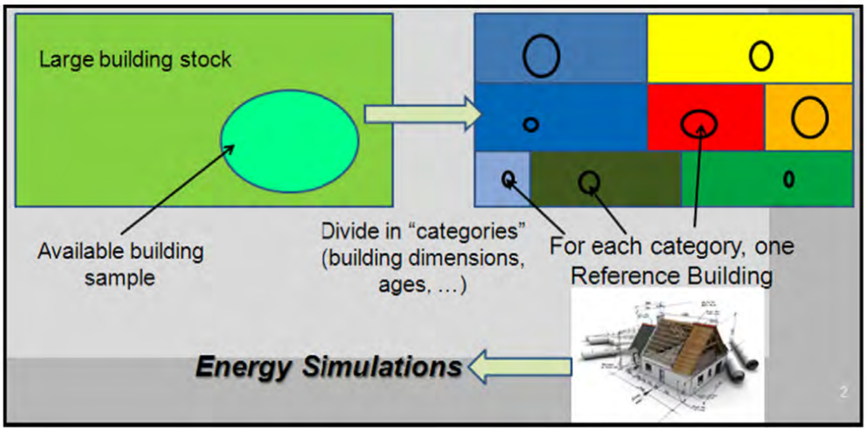

Figure 26: Categorisation process to determine reference buildings. Source: (Ballarini et al. 2014)

As explained before, those reference buildings could be real buildings (*sample buildings*) or ideal buildings constructed with the statistical characteristics identified as representative (*archetype buildings*). (Parekh & Eng 2005) described the process of developing archetypes for energy simulation. The authors identify three basic criteria to generate the archetypes: the geometric characteristics, thermal characteristics and operating parameters. The method of archetypes is used by "The Canadian Urban Archetypes" project at urban level in order to investigates the relationship between urban form, the lifestyles of its residents and energy consumption associated with urban scale (Webster 2007).

An European level initiative using the typology approach for building stock energy assessment is the TABULA project[36] (Ballarini et al. 2014). A harmonised structure was used in order to create and compare typologies among different countries. The two critical parameters used for the classification, besides the climate, were the size and the age of the constructions. The age was characterized through nationally defined construction periods. But, the building size categories were selected to be enough representative and generic to cover the residential building stock of the 13 participant European countries. The categories were the following: single family house, terraced house, multi-family house and apartment block.

[36] http://episcope.eu/iee-project/tabula/

Three different methodological approaches were used in TABULA for the definition of building types belonging to each specific climatic area, construction age and building size. Two of these methodologies identify real samples for representing building types and the third one use constructed archetypes. When real buildings were used, these sample buildings were selected analysing a large building sample to find out a real building showing characteristics similar to the mean geometrical and construction features of the statistical sample, but when statistical data were not available this selection was done by expert judgement. In (Dascalaki et al. 2011) building typologies based on construction and electromechanical installations were used to model the national energy balance in Greece. The categorization parameters were: construction period (pre-1980, 1981–2000 and 2001–2010), type of the building (single family and multifamily) and four climate zones.

(Jones et al. 2001) developed an energy and environmental model for prediction using GIS techniques and broadening the information provided by archetypes using "drive-pass" studies. They proposed a cluster analysis for energy and environmental prediction based on statistical methods to identify properties with similar energy consumption and emissions. This cluster analysis classifies properties into a group based on selected built form characteristics and age of the properties. The five parameters used for the clustering were: heated ground floor area, facade, window to wall ratio, exposed end area and age.

Therefore, the literature review shows that typologies are a powerful tool for the energy modelling of the building stock at European, national or regional levels. But, this approach could be useful also when smaller scales are addressed. Information that is already available on building stock can be used to select the sample buildings through a statistical approach that will represent the entire building stock. Once the sample buildings are selected the information regarding those buildings can be completed for more detailed analysis. (Dall'O' et al. 2012) used the data regarding the construction period of the buildings (provided by the national census) to categorise the building stock of a medium sized town in the Lombardy region of Italy. Approximately a 7% of the buildings were selected as samples and energy audits were carried out in those buildings. The results regarding their EP were extrapolated to the entire city.

2.5.4 Modelling building groups

This strategy is intended to be used in a second phase, after a prioritization phase has been carried out. Once a group of buildings have selected, by means of the identification of priority areas strategy or the sample buildings strategy, the semantic information regarding those buildings can be completed allowing much more detailed analysis as building and urban fabric compatibility.

2.5.5 Conclusions regarding the modelling strategies

The following table summarized the characteristic of each modelling strategy that has been described in the previous chapters:

	LARGE-SCALE ASSESMENT	IDENTIFICATION OF PRIORITY AREAS	SAMPLE BUILDINGS	BUILDING GROUPS
Required data	Low	Very low	Low	Medium/High
Assessment	Yes	Yes	Yes	Yes
Simulation	No	No	Through the sample building	Yes
Prioritisation	No	Yes	Yes	Yes
Historic Significance	Not taken into account	Taken into account	Through the sample building	Taken into account
Use of typologies	Just for semantic data	No	Yes	No
Semantic data	Public (cadastre) or generic (TABULA)	Public (cadastre)	Real data for samples	Real data
Scale	Buildings	Blocks	Buildings	Building/dwellings
Accuracy	1	1	2/3	4/5
Advantages	Good balance between needed data and result.	Low level of data required	Very good balance between needed data and result. Real semantic data (just for sample buildings). Historic significance is considered	High accuracy. Real semantic data. Could be used as a second phase after a prioritization.
Disadvantages	Accuracy of the results. Not real semantic data. Historic significance is not considered.	Limitation of the results. Not real U a values are used.	Uncertainty of the extrapolations.	Time demanding

Table 9: Summary of modelling strategies

It can be concluded that the four strategies can be useful depending on the circumstances, the objectives and the data availability. However in a DM process regarding a HUD, the constraints regarding HS are mandatory. That means that the most proper strategies are the ones that take into account these parameters, i.e. *sample buildings* and *building group* strategies. These two strategies can be used consecutively as two phase modelling. In the following section these two strategies will be integrated in the different LoDM that can be considered within our methodology.

This is also a good strategy for an efficient information management since it makes more targeted the process of acquiring real semantic data for the data model. It allows starting with basic information about all the buildings of the district in order to identify homogeneous groups of buildings. But, after the clustering process, more detailed semantic information (for example information regarding HS) can be acquired just for those representative buildings in order to extrapolate the results. In order to facilitate this process a categorization tool can be used as described in Section 2.2.2.

2.6 Requirements for a decision making methodology

The following table shows the identified requirements for the DM methodology:

REQ. ID	REQUIREMENT	
DM_REQ_GEN_01	The methodology has to deal with different scenarios of availability of information offering different LoDM	Mandatory
DM_REQ_GEN_02	The methodology has to allow that external calculations can be introduced to provide more accurate results (levels of accuracy)	Mandatory
DM_REQ_GEN_03	The methodology has to be feed by easily acquired data and has allowing an incremental use of it	Mandatory
DM_REQ_GEN_04	The methodology has to be based on a modelling strategy that allows the categorization of the buildings from an energy and cultural point of view	Mandatory
DM_REQ_GEN_05	The methodology has to filter the solutions according to their applicability, impact in the HS of the building and compatibility with the fabric	Mandatory
DM_REQ_GEN_06	The methodology has to take into account the preferences and priorities of the decision maker.	Mandatory

Figure 27: Requirements for the DM methodology

2.7 EFFESUS decision making methodology

The EFFESUS methodology is intended to be implemented in a software tool in order facilitate all the calculations. This Decision Support System (EFFESUS DSS) will help the decision maker through the different steps that will be explained in the following sections. As explained in the previous section, the methodology is structured in different LoDM with different input requirements and accordingly different levels of accuracy in the outputs. The following figure summarized this structure:

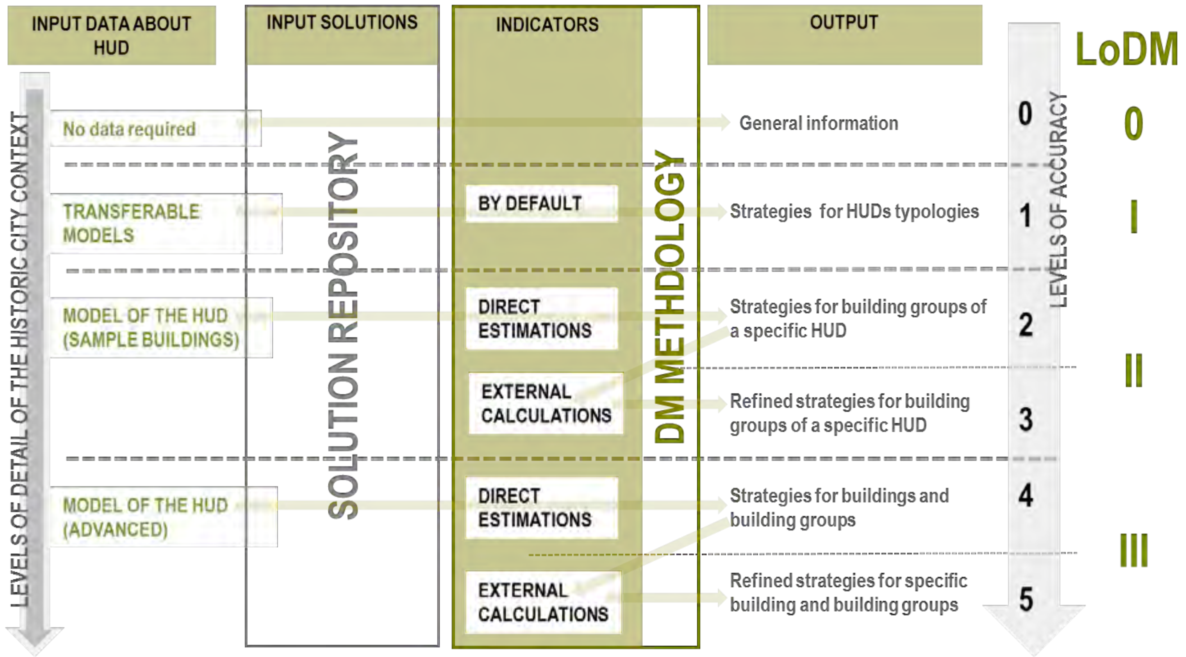

Figure 28: Inputs and outputs for the different LoDM

2.7.1 Scope

The LoDM II at the Level of Accuracy 2 is where one of the main hypotheses of this research is tested: the hypothesis that with easily available (and easily processed and structured) data meaningful results can be obtained at HUD. Therefore this level can be considered as the core of this methodology. It has been considered interesting to focus the research and the implementation in this level, moreover, since for the implementation of the other levels an automatization through a DSS would be necessary. Anyway, the other LoDMs and accuracy levels will be described with less detail in Section 2.8.

At this level the methodology will provide results using sample buildings as explained in Section 2.5.3. That will allow extrapolating the results obtained to the rest of the buildings of their category and obtain the impact of the selected strategies. The following diagram shows the information and methodological flow at this level and the next chapters will explain it in detail:

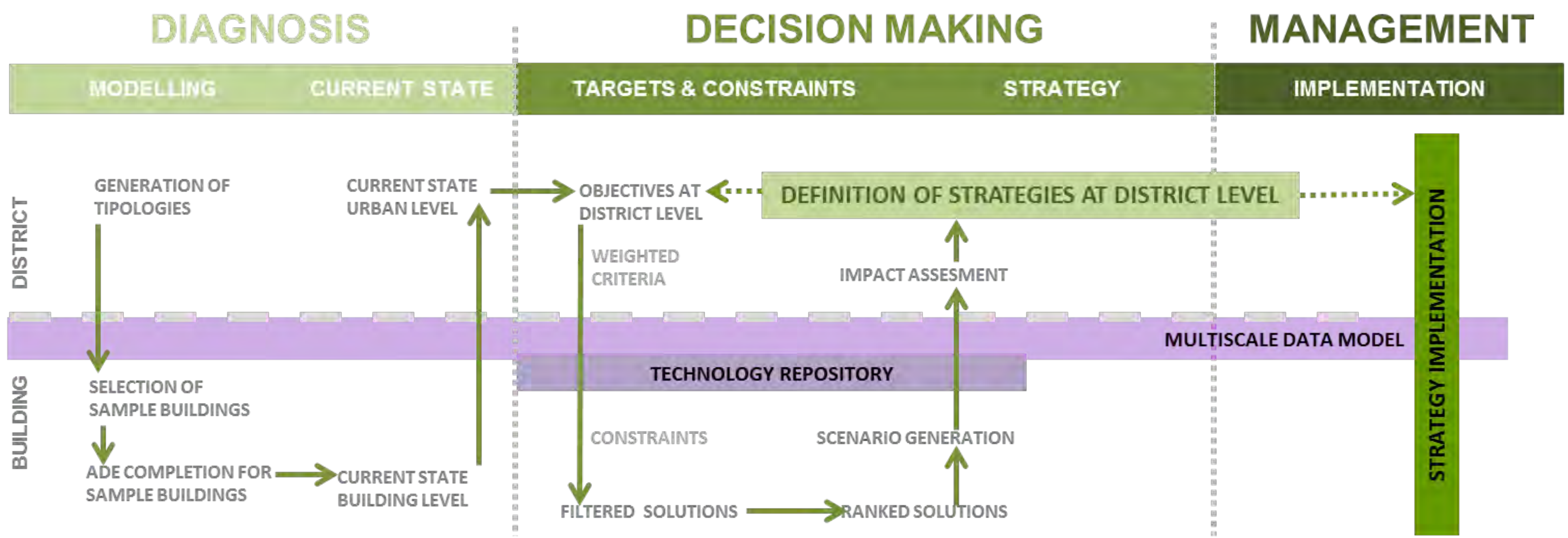

Figure 29: Methodology at LoDM II and Level of Accuracy 2

2.7.2 Modelling

Input	Low level semantic information regarding all the buildings from the HUD
Output	The buildings of the HUD categorized in typologies. Sample buildings from each category

Parameters for the selection of typologies

As it has been seen in Section 2.5, at bigger scales the typologies are created, usually in a matrix form using two main parameters, and then the individual building is assigned to one of the categories. This method is very useful at national or regional scale when large building stocks have to be taken into account and where generic typologies has to be used in order to cover as much as possible. But one of the disadvantages of this method is that it does not take into account the historical singularities at city or district level and these singularities are extremely important in the cases of HUDs. In order to solve this, it is necessary to create specific building typologies for each HUD as it has been seen in (Dall'O' et al. 2012).

The objective is to create a limited number of unique samples that reflect almost the entire stock of the HUD within the constraints of the data available. It is important to take into account some guidelines for the clustering process:

- → The variations between groups must reflect the energetic features as well as the historic ones. Basically it has to group the buildings regarding their energy characteristics and HS peculiarities.
- → The clustering criteria have to be coherent with the criteria and constraints that later will be used for the DM.
- → The required data has to be automatic or semi-automatically obtained. There are two kinds of data that can be obtained very easily: the geometric data obtained directly from the model and the semantic data obtained from public official data as cadastre.

Within the EFFESUS it was identified some of the key parameters: climate zone, type of building, use, size, year of construction, envelope and heating/cooling systems (Brostrom et al. 2013) and a method for categorization of European Historic Districts was developed[37].

In order to cluster the buildings of a HUD two different typologies has to be combined: an energy typology (representing the energetic characteristics) and a historic typology (representing the historic features). The previous proposals have been focused in the energy side of the buildings, but the merge of the two

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[37] EFFESUS (2013). Deliverable D1.4 – Database of the structured categorisation method for historic European building stock. EFFESUS Project (FP7/2012-2016 grant agreement n° 314678), 2013

typologies is the one that allows the adequate clustering in order to model the HUD for energy retrofitting purposes. Therefore the selected key parameters are the following:

- → Principal use: mainly if it is residential or not, since their final energy consumption changes significantly (different use patterns and operating systems).
- → Number or facades: as it shows the "exposed area" of the building is very important for the EP of the building.
- → Year of construction: buildings built in the same period have similar construction techniques. It can be used also, along with the level of protection, to assume homogenous HS of the buildings.
- → Level of protection: a direct indicator of the HS and of the measures that can be applied.
- → Volume: the size of the building is another indicator of the EP of the buildings.

Data category	Parameter	Inferred information		Typology
Geometric	Volume	Heated volume		Energy typology
	Nº facades	Exposed area		
Semantic	Use	Operating parameters		
	Year of construction	Materials	Thermal characteristics	Historic typology
			Fabric compatibility	
	Level of protection	Historic significance		

Table 10: Key parameters to build the typologies

The parameters have to be chosen carefully in order to get a right balance between representativity, easiness to acquire the data, number of typologies and meaningfulness of the inferred information. The whole process for modelling the HUDs through a strategy of sample buildings is the following:

1. Statistical overview of the HUD.
2. Discarding of the buildings that are not included in the scope of the action for different reason (mainly year of construction and use).
3. Selection of the parameters that will be used for the generation of typologies: depending on the statistical distribution, a different number of parameters could be selected for the generation. The goal is to get the maximum representativeness with the minimum number of typologies and a good quality of information inferred. Usually four parameters are enough for categorization purposes, so one of the five parameters aforementioned can be let out. In the case of a HUD with a high cultural value the parameter regarding the level of protection is usually preferred to the volume. The parameter regarding the level of protection has usually a

direct link with the opportunities to improve the HUD (it's a clear indicator of the measures that could be implemented) and with the HS of the building and usually generates significant groups of buildings.

4. Selection of the threshold for the minimum representation: that means that all the typologies with a lower representativeness that this threshold will be discarded.
5. Generation of the typologies.
6. Selection of the representative typologies.
7. Selection of the sample buildings.

Statistical overview of the historic urban district

The configuration of the typologies within a HUD is strongly related with its history and location. It is not possible to generalise at European level due to diverse climate conditions, construction material, historical circumstances or construction techniques. Therefore the objective of this methodology is to offer a tool to the expert to support the identification of those groups within its own HUD. With the use of the categorization tool the visualization properties of the models can be used to facilitate the process.

The buildings will be clustered regarding basically their energy features (energy typology) and their HS (historic typology) as explained in the previous section. Five different parameters, as the ones described before, can produce a huge number of different typologies making the analysis unmanageable (five parameters with three range groups for example would suppose 241 different typologies). Consequently, it is necessary to select the proper threshold that will divide the different ranges for each parameter, but also to discard the less representative range groups.

Frequency histograms for the representation of the distribution of the different parameters in building stock analysis have been previously used in the literature as in (Famuyibo et al. 2012) in order to identify concentrations of particular values. Frequency histograms for each parameter will be automatically generated by the categorization tool to provide a first overview of the statistical distribution of the characteristics of the HUD.

Once the user has a clear vision of the distribution of each parameter, the different range and the threshold that limited each group will be decided. The method intends to be flexible regarding the used parameters; so parameters can be discarded if they do not suppose determinant differences. The user will be able to interact with the categorization tool editing parameters and thresholds for clustering.

Generation of the typologies and selection of the representative typologies

The user can start from a first parameter (tentatively the one with the fewest number of variables, e.g. use), and then proceeds to subdivide the categories with respect to other parameters. By adjusting the intervals and ranges for each parameter the building typologies will be constructed.

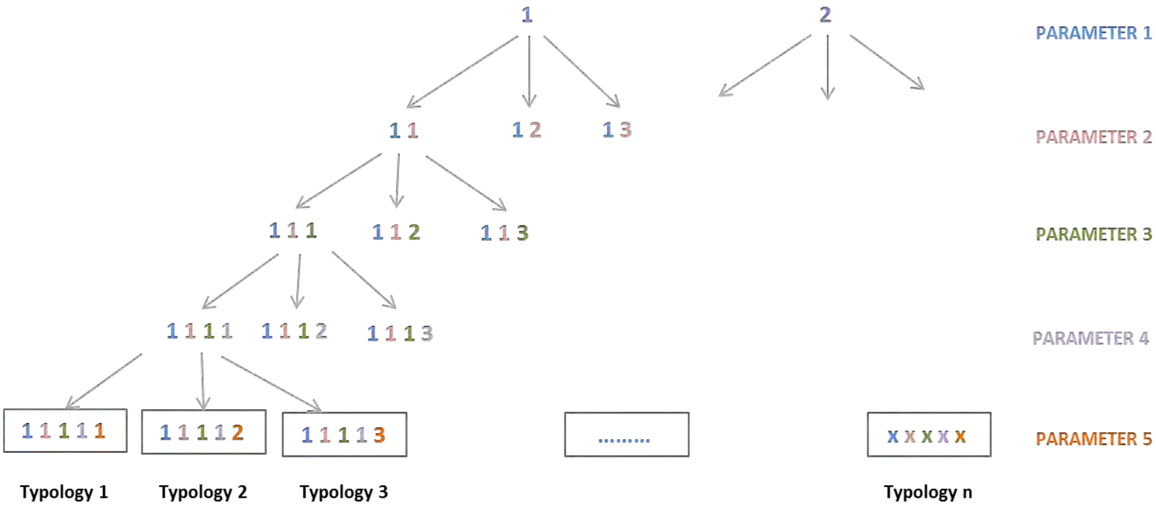

Figure 30: Generation of typologies

When all the possible typologies have been identified the most representative ones have to be selected. As stated before, this is done by the establishment of a threshold of minimum representativeness. This minimum has to be carefully selected in order to achieve the optimum balance between the number of typologies and the representativity that is obtained with them. The acceptable number of typologies and percentage of building stock represented will be different depending on the homogeneity of the building stock, the size of the HUD, the resources involved or the expert judgement of the user. But usually a minimum threshold between 2% and 5% provides good results.

Selecting sample buildings

Once the building typologies have been identified and their statistical representation assessed, the next step involves selecting a building for each typology. This is a crucial decision as the results obtained with this building are going to be extrapolated to the entire category. It is important also to select a building where information regarding their characteristics is available.

One of the main determinant factors when it comes to select the strategies is going to be the applicability of them. That is going to be determined for the constraints that in this level are the HS of the building and its elements. When the level of protection is included as parameter in the categorization, the general HS of the sample building is the same of all the buildings within the typology. In some cases, the level of protection implies also the level of protection of some of the elements (walls, windows or roofs), but a more complicated issue is faced when the correlation between the level of the protection of the building in general and their elements is not given.

In this case the user has to keep in mind that the final impact is going to be influenced by the HS of the elements of the sample building in a mixed way:

- → The selection of a sample building with the HS of their elements in the high end of the typology is going to suppose a higher application (the selected strategies will be applicable to similar buildings but also to buildings with less protected building elements) but also a lower energy saving (the suitable strategies will be less effective due to heritage conservation).
- → The selection of a building with its elements in the low end of the HS scale will provide higher energy savings but a lower applicability.

Therefore the decision that is made in this step (the level of protection of the elements of the sample building) is going to have a consequence in the impact adjustment factors that will be applied later (see Section 2.7.4) but also in the strategies that could be applied and therefore in the energy savings.

Although to select the highly respectful strategies (i.e. a sample building with high HS in its elements) seems at first glance like the soundest strategy as they are more applicable, the decision maker should keep in mind the *lost opportunity* that supposes a minor renovation. Sometimes it can be preferred a strategy where mayor renovations are carried out in the less restrictive buildings and the more constrained ones wait for the evolution of the state of the art in technologies with less impact in the heritage.

The following table aims to support the election of the sample building in the cases that the significance of the elements cannot be inferred by the general level of protection of the building. It shows the impact adjustment factors that should be applied in the cases that a sample building is selected with elements with a lower HS than the building in general:

BUILDING HS	3					2					1					0				
ELEMENTS HS	4	3	2	1	0	4	3	2	1	0	4	3	2	1	0	4	3	2	1	0
Externall walls			0,80	0,80	0,30				1,00	0,75					0,90					
Roof			0,90	0,90	0,50				1,00	0,75					0,90					
Windows			0,90	0,90	0,15				1,00	0,20					0,40					
Doors			1,00	1,00	1,00				1,00	1,00					1,00					
Internal walls			1,00	1,00	1,00				1,00	1,00					1,00					
Installations			1,00	1,00	1,00				1,00	1,00					1,00					

Table 11: Impact adjustment factors according to the sample selection

These factors are calculated based on the case of Santiago of Compostela; therefore the decision maker could change them for a specific HUD. In this case the question to be answered is *"What is the percentage of buildings in this typology that have the same or lower HS on their elements than in the selected sample building?"*

As it have seen in Section 2.5.3, the sample buildings can be selected also analysing the building sample to find out a building showing characteristics similar to the mean geometrical and construction features of the statistical sample or by expert judgement.

Once the sample buildings have been selected, the methodology described in the Section 2.6 will be applied to them in order to assess the saving potential of the different proposed strategies

Completion of the information

Once the sample buildings have been selected, the data model will be completed with detailed information for these buildings. The geometric information contained in the model is already sufficient but the semantic information has to be completed regarding the two main topics: cultural value and energy characteristics.

Regarding HS, the necessary information at this level is the necessary to make the assessment about the HS at district, building and component level. This information could be obtained using the public data bases that documents the historic values of the HUDs or by expert judgment if this data bases are not available, are not considered of enough quality or do not exist.

Regarding the energy characteristics, different methods are usually used to get this semantic information: public data bases, expert judgment, European databases (e.g. the one created by the TABULA project[38] or others[39]) or even Google street map as in (Carpenter et al. 2014).

The Chapter 3 will describe in the detail the information requirements regarding the two fields (see Section 3.4.2).

Work flow of the modelling

The following figure shows the work flow of the modelling phase that summarized the different phases of the methodology described until now:

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[38] *Ibid 36*

[39] http://www.buildingsdata.eu/data-search/results

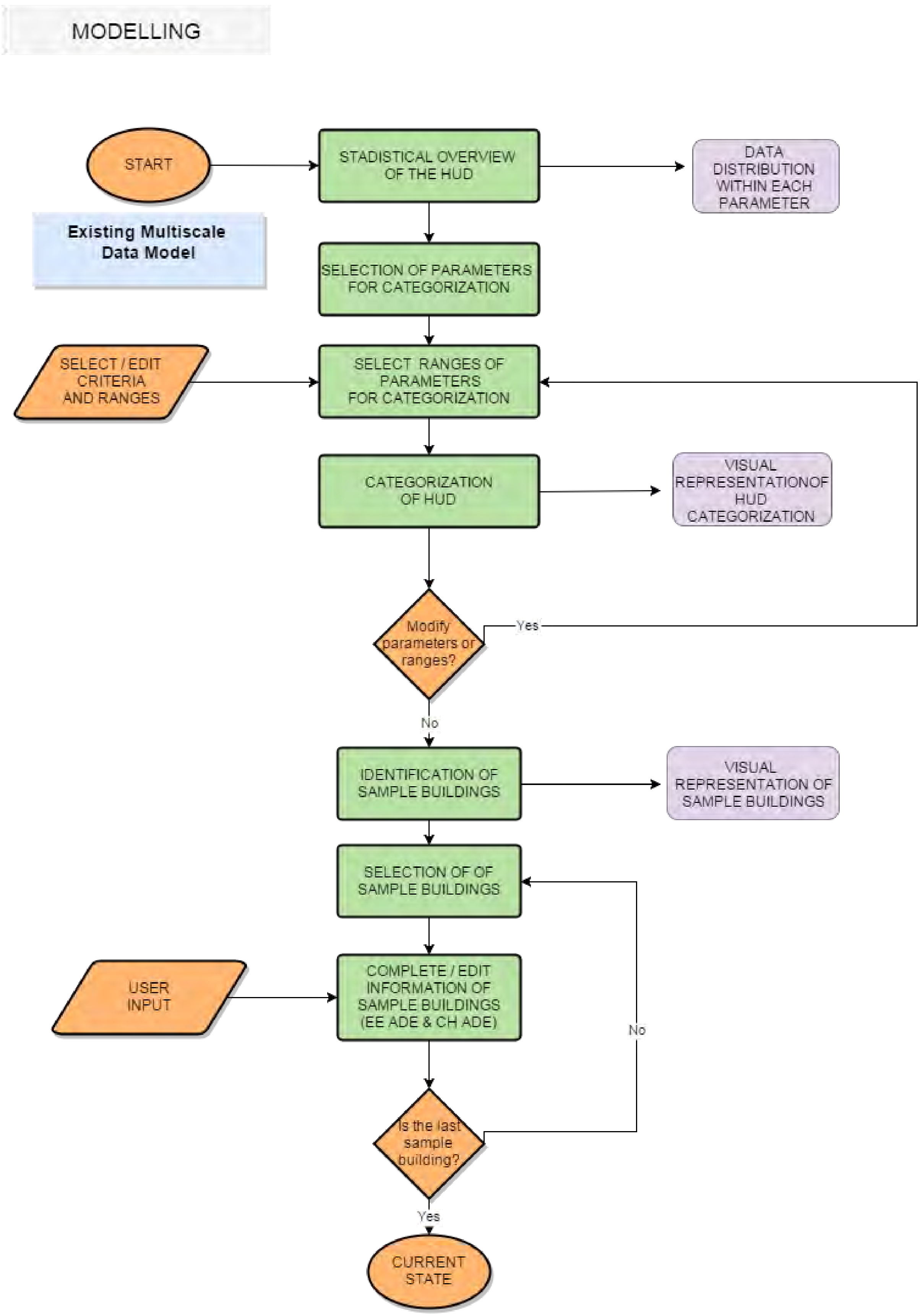

Figure 31: Work flow regarding the modelling phase at LoDM II

2.7.3 Current state identification

Input	Information of the sample building regarding HS and EP
Output	The baseline regarding HS and EP

At this point the current state will be identified regarding the EP and the HS of the sample building, this identification will made possible to set the priorities and establish the base line for posterior estimations.

Energy Performance

The identification of potential measures for improving energy efficiency in HUDs by reducing energy demand requires a solid base of information on baseline energy consumption Building physics based models have a high potential for supporting policy making and strategic development due to their flexibility and level of detail. But these types of models require a large amount of data and high computational capacity in order to obtain accurate results from the building energy calculation method (Ramirez Camargo 2012). A 3D city model that aims to simulate the energy demand of existing building stocks faces the challenge of establishing a energy demand calculation method adapted for a city scale purpose, offering a good compromise between low computation time and high result accuracy, while dealing with limited input requirement (Eicker et al. 2014). When the DM is focused on early stages a balance between the data necessary and the accuracy of the results is even more necessary. The requirements for this calculation method are:

- → The calculation procedure has to provide enough accuracy and flexibility to model the building stock of any district without relying heavily on a large amount of input data.
- → It must be capable of predicting energy requirements for individual end-uses or individual buildings, and therefore be appropriate for detecting specific areas of potential improvement.
- → It should offer high flexibility for modelling alternative scenarios related to changes in climate and occupancy behavior.
- → It has to be robust and flexible enough to be applicable to different regions under different climatic conditions and be able to integrate new emerging data sets.

The model considered is the quasi-steady state monthly method explained in the EN ISO 13790:2008, EP of buildings - Calculation of energy use for space heating and cooling (ISO 2008). It is thought to predict the energy needs for heating and cooling of one zone buildings, and n-zones.

In the EN ISO 13790:2008, a significant number of possible situations concerning the input data are explicitly considered in the calculations. The method, being the result of an international consensus of well-known institutions, can be considered legally secure, and can be accepted from the wider public. But it is the high level of robustness and flexibility of this calculation method that have led to the selection of the EN ISO 13790:2008 as the core calculation method for the first phase. Moreover, methods for energy diagnosis based on this standard have been already tested over several districts in German and Netherland (Nouvel et al. 2013) (Eicker et al. 2012). And it has been used also with a multiscale approach as in (Dalla Costa et al. 2011). For further phases of the DM process, with a higher accuracy level, a more detailed method (i.e. dynamic method) may provide higher flexibility and perhaps a more direct link with building simulation tools used for design purposes.

Using this procedure and the information included in the model the current state regarding the indicators of energy saving will be estimated as following:

Category	Subcategory	Specific Indicator	Calculation method
Energy Saving	Thermal energy use	Total use/year of the district	EN ISO 13790:2008 + TOTAL HEATED AREA OF THE TYPOLOGY
	Thermal energy use	Thermal energy use per m^2 building area	EN ISO 13790:2008
	Electrical energy use	Total use/year of the district	ESTIMATION BASED ON THE TYPE OF BUILDING AND THE CLIMATIC ZONE +TOTAL AREA OF THE TYPOLOGY
	Electrical energy use	Electricity use per m^2 building area	ESTIMATION BASED ON THE TYPE OF BUILDING AND THE CLIMATIC ZONE
	CO_2 emissions	Total for a building	CALCULATION BASED ON PRIMARY ENERGY

Table 12: Energy Savings Indicators

Heritage Significance

Regarding the constraints, if the information regarding HS is filled with the minimum information defined in Section 3.4.2 there should be a complete current state definition. The element considered will be the following:

Category	Scale	Building or urban element	Impact area	Value
HS And Conservation Principles	**Urban**	Settlement pattern	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Roof-scape	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Water elements	Visual	0-4
			Physical	0-4

Category	Scale	Building or urban element	Impact area	Value
			Spatial	0-4
		Street-scape	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Public spaces	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Curtilage	Visual	0-4
			Physical	0-4
			Spatial	0-4
	Building exterior	Walls	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Roofs	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Roof Features	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Windows	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Shading devices	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Doors	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Balconies	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Porches	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Shopfront	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Building general	Visual	0-4
			Physical	0-4
			Spatial	0-4
	Building interior	Common use space	Visual	0-4
			Physical	0-4

Category	Scale	Building or urban element	Impact area	Value
			Spatial	0-4
		Common Interior finishes of the external envelope	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Common Internal Walls	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Common Ceilings	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Common Internal Doors	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Private Space	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Private Interior finished of the external envelope	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Private Internal Walls	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Private Ceilings	Visual	0-4
			Physical	0-4
			Spatial	0-4
		Private Internal Doors	Visual	0-4
			Physical	0-4
			Spatial	0-4

Table 13: HS and Conservation Principles

Summary of current state identification

In order to facilitate the setting of priorities and targets it is necessary a descriptive summary regarding the EP and HS.

For the assessment of the current state regarding the EP it has been considered that the most useful and descriptive scale is the one provided by the Energy Performance Certification based on "Energy Performance of Buildings Directive 2002/91/EC"[40]. Although this scale has to be used carefully with preindustrial and listed buildings, it gives an idea of the EP of the building compared with more modern standards.

[40] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0071:EN:PDF

The results regarding HS will be summarized by scale and element and will be used the most restrictive of the three HS assessment values (i.e. visual, spatial and physical). The table with the results will be the following:

Scale	**HS**
District	0-4
Building	0-4
External wall	0-4
Roofs	0-4
Windows	0-4
Doors	0-4
Internal walls	0-4
Installations	0-4

Table 14: Current State regarding HS

The following diagram shows the work flow of this step:

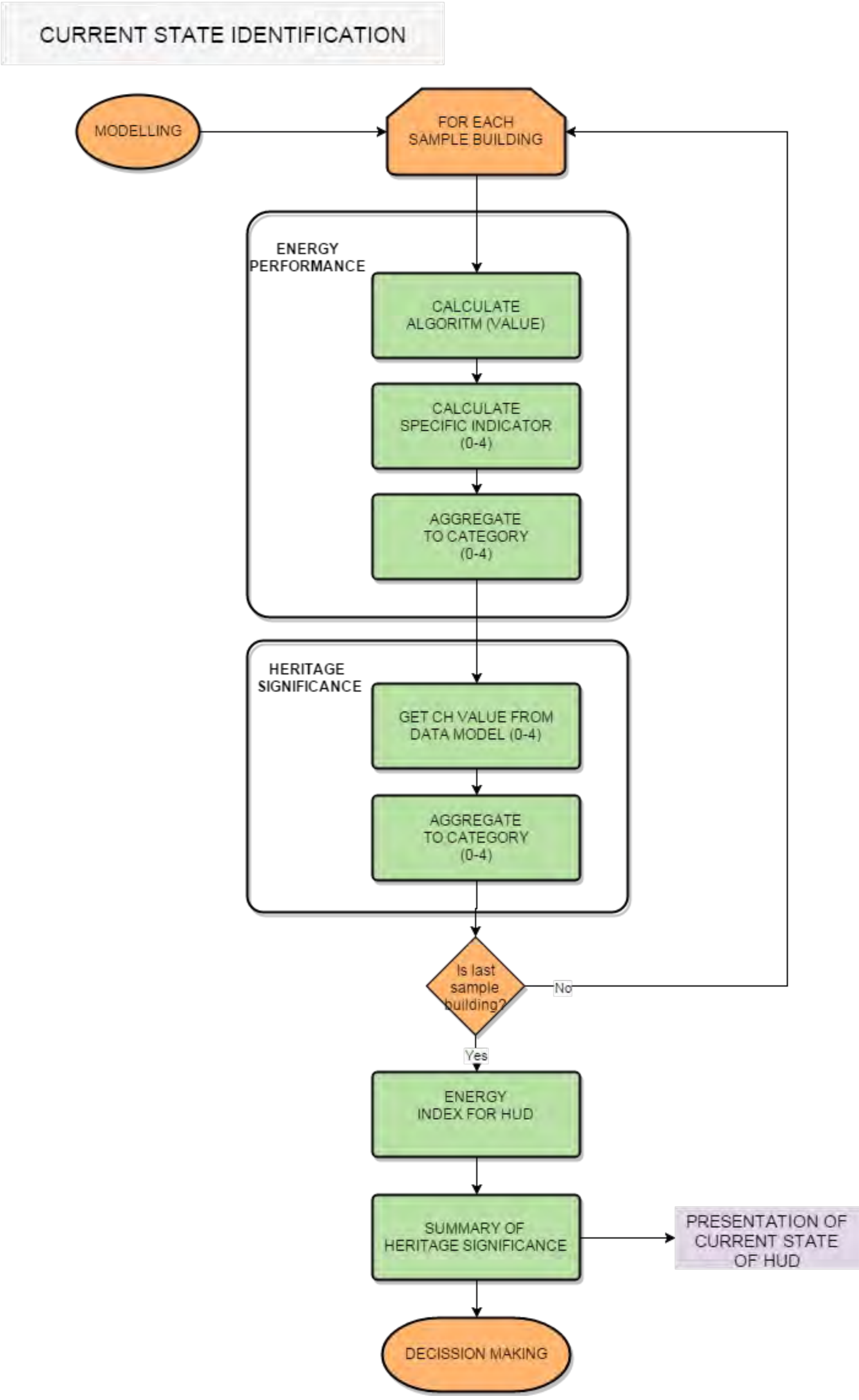

Figure 32: Work flow for current state identification (LoDM II and Level of Accuracy 2)

2.7.4 Decision making

Filtered list of solutions according to the constraints

Input	Information regarding the constraints structured in the multiscale data model Information regarding the impacts of the solutions that contain the repository
Output	A filtered list of the solutions of the repository where the non-acceptable solutions will be eliminated and the rest will be classified for their suitability degree

The constraints will provide a filtered list of technologies for each typology. At this level the constraints regarding HS will be used. The constraints regarding *fabric compatibility* will be used at Level of Accuracy 3. Every retrofit measure applied to the HUD has the potential to damage its HS. Its *degree of suitability* depends on the severity of their impacts together with the value of HS that is assigned to the affected building or urban component. Establishing the suitability of retrofit measures is therefore a balancing act, weighing impacts against HS. Within EFFESUS project a methodology was developed to carry out this heritage impact assessments (Eriksson et al. 2014). This methodology consisted of three parts: a system to assess the HS of the buildings and their elements in sufficient detail (information contained in the multiscale data model, see Chapter 3); definitions of the impact of retrofit measures on HS (data set contained of the repository); and the logic that balanced the two of them.

The methodology that will be used is an adaptation of the one described in (Eriksson et al. 2014). As explained before (see Section 2.4.2), the HS assessment is carried out for three *types* of HS (visual, physical and spatial) and the assessment is conducted using a five-step scale to describe values of HS.

The compatible structuration of both data sets (with the same scale and same referred element) allows the systematic comparison. The impacts of each retrofit measures in the repository can be compared to the HS of a particular assessment category. The logic regarding this comparison is the following:

		Impact definition				
		0= No impact	1=No significant impact on heritage significance	2=Minor impact on heritage significance	3=Major impact on heritage significance	4= Outstanding impact on heritage significance
Heritage significance	0= Neutral or negative significance	0	0	0	0	0
	1= Minor significance	0	1	2	3	4
	2= Major significance	0	2	4	6	8
	3= Outstanding significance	0	3	6	9	12
	4= Exceptionally outstanding significance	0	4	8	12	16

Table 15: HS impact assessment

The results of the assessment vary from 0 to 16. Therefore the solutions will be classified in 4 categories of applicability as follows:

Class	Results	Applicability
0	0-1	Acceptable
1	2-3	Likely to be acceptable
2	4-6	Potentially acceptable
3	7-12	Not acceptable

Table 16: Results of HS impact assessment

The first two classes will be considered for the design of the strategies and the fourth one will be automatically discarded. The class 2 solutions will be considered or not according to the expert judgment. This assessment will be done for each type of impact (visual, physical and spatial). The most restrictive result will be selected and the solutions will be shown to the user ranked and grouped in the four classes.

Target definition and definition of weighting criteria

Input	The preferences of the user regarding the different criteria by decision maker's pairwise comparisons of the criteria
Output	The weighting of each criterion

With the current state defined, the decision maker has to start deciding about the targets. At this level and accuracy the target definition can be quantitatively done just regarding the energy savings (ES):

→ Reduction of thermal energy use (per area or for the total typology)
→ Reduction of electrical energy use (per area or for the total typology)
→ Reduction of CO_2 emissions

But some qualitative target identification can be done regarding the percentage of achievement of the other indicators:

→ Thermal Comfort (TC)
→ Indoor air quality (IAQ)
→ Cost
→ Low impact solutions (LIS)

After the decision maker has to translate those targets to preferences regarding the different criteria. Regarding the subcriteria of improvement of the habitability and indoor environmental, at this stage, just thermal comfort and indoor air quality will be considered (the criteria regarding acoustic comfort and visual comfort will be considered at Level of Accuracy 3). Therefore, five different criteria will be considered (TC, IAQ, ES, Cost and LIS)

In order to translate user's preferences into weighted criteria, the Analytic Hierarchy Process (AHP) method is used (Saaty 1978). The AHP method transforms the pairwise comparisons of criteria done by the users into the different weights of those criteria. That provides the synthesis of the decision maker judgments and allows obtaining priority rankings of the alternatives with respect to each criterion and the overall priority ranking for the problem. The weighting by pairwise comparison offers more consistent results than simply trying to assign relative weights to a list of criteria. The decision maker will be asked to compare each pair of criteria according to this scale:

- → Extremely preferred = 9
- → Very strongly preferred = 7
- → Strongly preferred = 5
- → Moderately preferred = 3
- → Equally preferred =1

2, 4, 6 and 8 will be used to express intermediate values. With the information generated in those pairwise comparisons the *comparison matrix* is built. With the AHP method a weight for each evaluation criterion will be generated according to the decision maker's pairwise comparisons of the criteria and the comparison matrix that have previously been developed. The higher the weight, the more important the corresponding criterion is for the decision maker.

Ranked list of solutions

Input	The weighting of each criterion. The values regarding each solution and each criterion in the repository
Output	A ranked list of the suitable solutions

In this step the specific goal that the methodology aims to solve is to find the best single retrofit solution regarding the criteria that has been defined previously. In this case the decision hierarchy is the following:

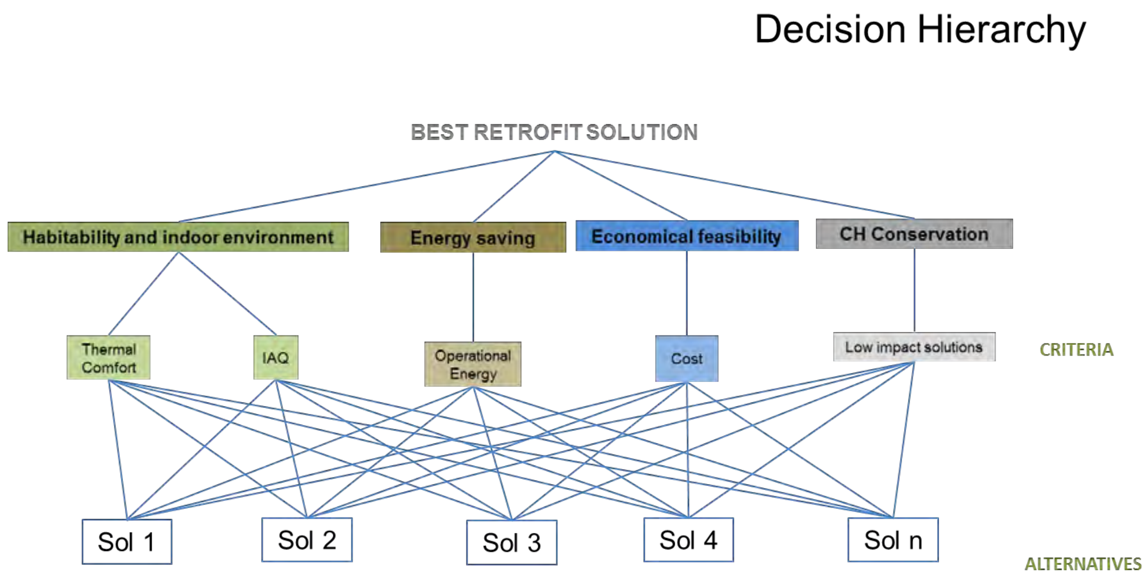

Figure 33: Decision hierarchy

In the repository each solution is characterized regarding the seven criteria listed below, using a 0-4 scale (the acoustic comfort and visual comfort indicators will be used only in Level III of DM)

Category	Subcriteria	Value
Habitability and indoor environment quality improvement	Thermal comfort	0-4
	Acoustic comfort	0-4
	Visual comfort	0-4
	Indoor air quality	0-4
Energy Saving		0-4
Cost		0-4
Impact on HS		0-4

Table 17: Characterization of values in the repository

With this information and the weightings developed in the previous step, a first ranked list of solution is obtained from the filtered list for each sample building. At this stage, the decision maker can decide to discard specific solutions.

Potential Retrofit Scenario Generation

Input	Ranked list of solutions
Output	Packaged solutions (strategies)

In this step the retrofit scenarios or strategies will be developed, where the different complementary solutions are selected. This selection could be done manually by the user or using optimization techniques to find the pack of solutions that will achieve the targets. In order to implement the later the development of the DSS would be necessary therefore this research is focused in the manual option.

As explained in the description of the repository of solutions (see Section 2.2.2) the solutions are classified according to the different strategies to achieve the energy efficiency. There are four main categories that answer to different sustainable strategies:

- → Solutions that intent to improve the management
- → Passive Solutions that aim the reduction of the demand
- → Active Solutions that pursue the improvement of the efficiency of equipment
- → RES

Within these four main strategies can be break down in sub-strategies that are compatible among them. For example within the strategy that aims to reduce the energy demand different sub-strategies as the improvement of the airtightness, the insulation of the walls, the improvement of the windows or insulation of the roof can be included. In order to achieve a comprehensive strategy the user has to select a solution of each sub-strategy category. In theory the best selection will be to choose the best ranked solution of each category, but the expert judgment of the user could advise otherwise.

Impact adjustment

Input	HS of the elements of the sample building
Output	Impact adjustment coefficient

As it was seen in the section with the conclusions about modelling strategies (Section 2.5.5), the main disadvantage of the sample buildings strategy is the uncertainty regarding the extrapolations. This issue has been addressed already with the selection of the sample building (see Section 2.7.2), but in this phase the second step has to be made in order to translate the selection of the sample building to an impact adjustment factor that will correct the considered impact area of each typology.

The base impact area of a typology considered would be the heated area (m^2) of all the buildings included in the typology. This base impact has to be adjusted according to the following criteria:

- → It has to be excluded the percentage of the area that would not be heated, as common areas and other non-heated spaces.
- → It has to be limited the impact to the measures that are not applicable in other buildings even though they are applicable in the sample building. This number depends of the homogeneity of the HUD, but also of the HS of the elements of the sample buildings. The higher the HS value the easier it will be that a great amount of buildings could apply the same strategies.

The calculation of *Impact Adjustment Factors* will vary from case to case, but some base metrics could be provided to support the user in the estimation:

→ If better data are not available regarding the habitable surface a coefficient between 0.7 and 0.8 will be used.

→ As it was explained before, the following coefficient could be used to take into account the limitation of the applicability of the measures when the link between the HS of the whole building and the different elements is not direct (e.g. in a building with a general HS of 1, if a sample building is selected whose windows have a HS of 0, a coefficient of 0,40 will be applied to the total impact area).

BUILDING HS	3					2					1					0				
ELEMENTS HS	4	3	2	1	0	4	3	2	1	0	4	3	2	1	0	4	3	2	1	0
Externall walls			0,80	0,80	0,30				1,00	0,75					0,90					
Roof			0,90	0,90	0,50				1,00	0,75					0,90					
Windows			0,90	0,90	0,15				1,00	0,20					0,40					
Doors			1,00	1,00	1,00				1,00	1,00					1,00					
Internal walls			1,00	1,00	1,00				1,00	1,00					1,00					
Installations			1,00	1,00	1,00				1,00	1,00					1,00					

Table 18: Impact adjustment factors according to the sample selection

→ It can be also excluded another 1% of the percentage of buildings that will represent the recently renovated buildings and that consequently it is not probable that they will undertake another similar process in a short-medium future (Economidou et al. 2011).

Assessment of the Scenarios

Input	Packaged solutions (strategies)
Output	Ranked list of strategies

The different strategies will be assessed against the energy indicators through analogously to the current state identification, using the method based on EN 13790:2008 and the information in the repository. The same indicators as in the current state identification will be obtained:

Category	Subcategory	Specific Indicator	Calculation method
Energy saving	Thermal energy use	Total use/year of the district	EN ISO 13790:2008 + CONSIDERED AREA OF THE TYPOLOGY
	Thermal energy use	Thermal energy use per m^2 building area	EN ISO 13790:2008
	Electrical energy use	Total use/year of the district	ESTIMATION BASED ON THE TYPE OF BUILDING AND THE CLIMATIC ZONE + CONSIDERED AREA OF THE TYPOLOGY

Category	Subcategory	Specific Indicator	Calculation method
	Electrical energy use	Electricity use per m^2 building area	ESTIMATION BASED ON THE TYPE OF BUILDING AND THE CLIMATIC ZONE
	CO_2 emissions	Total for a building	CALCULATION BASED ON PRIMARY ENERGY

Table 19: Energy Savings Indicators

With this information the indicators for the *cost of energy saved* can be calculated also, although some external data base will be necessary.

The qualitative achievement of each indicator is calculate also given the percentage of achievement regarding the maximum achievement possible (the maximum in the scale * number of measures in the strategy). Finally the results are compared with the previously defined targets.

Urban level strategy selection

The last step is to calculate the impact of the packaged solutions for each group and after the impact for the whole district. Using the representativeness of each sample building the contribution of each strategy to the general goals of the district is shown.

Taking into account the rehabilitation rate previsions, it can be calculated the time that is necessary to reach the defined targets. If better data is not available, it could be used a rehabilitation rate of 1% as the current prevailing renovation rate across Europe (Economidou et al. 2011). If the time horizon is too long, the decision maker has to decide either to speed up the rehabilitation rates or to choose other strategies. The percentage of achievement of the indicator ES give a good idea about the potential energy saving still remaining. The following diagram shows the work flow for the DM phase at this step:

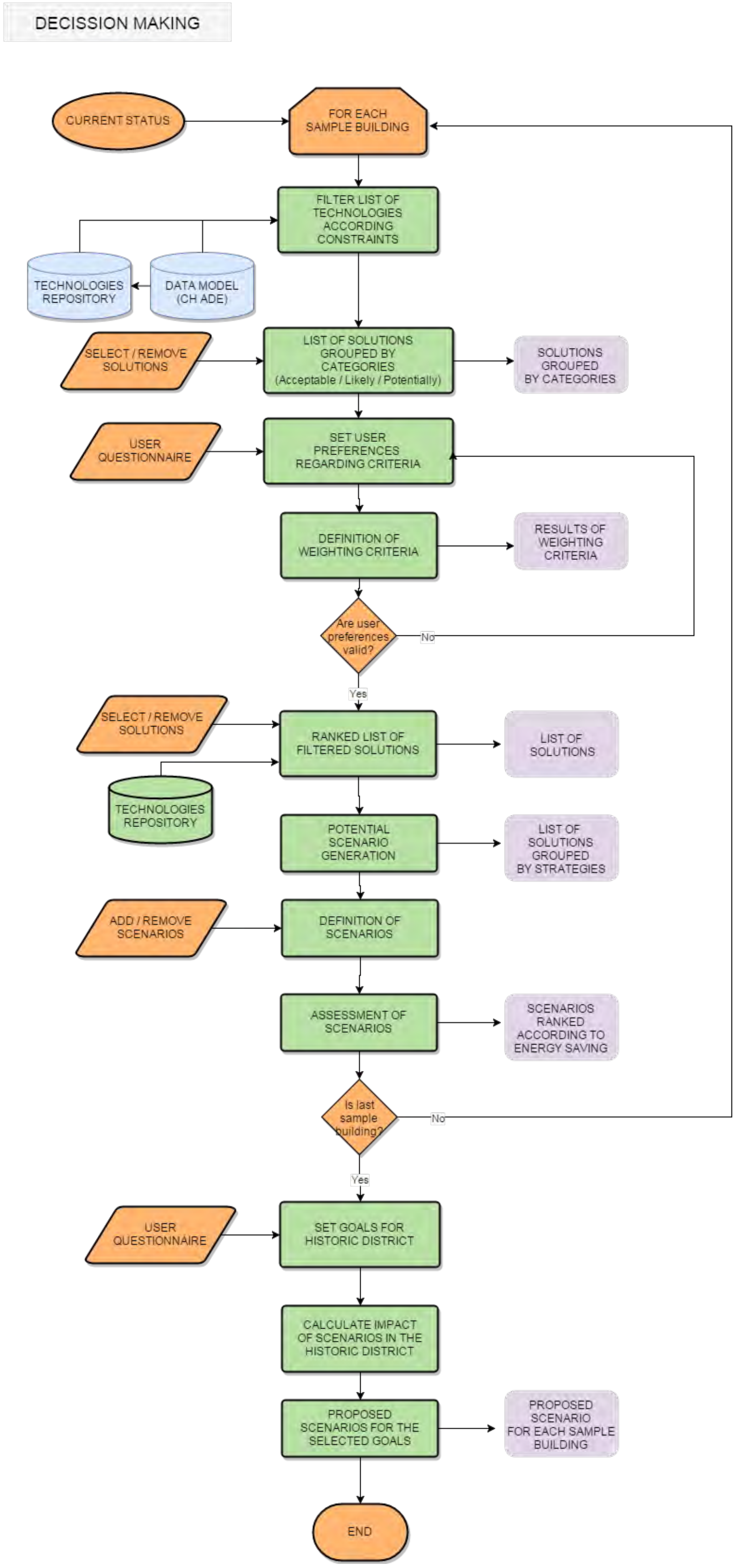

Figure 34: Work flow at DM phase at LoDM II and Level of Accuracy 2

2.8 Decision making at higher levels of accuracy and decision making through a decision support system

The whole methodology is intended to be implemented in a DSS but in a lower LoDM and accuracy it could be used without that automatization. However, as the LoDMs and accuracy levels are getting more complex that implementation would be mandatory. The following figure shows the complete methodology in LoDM II and III.

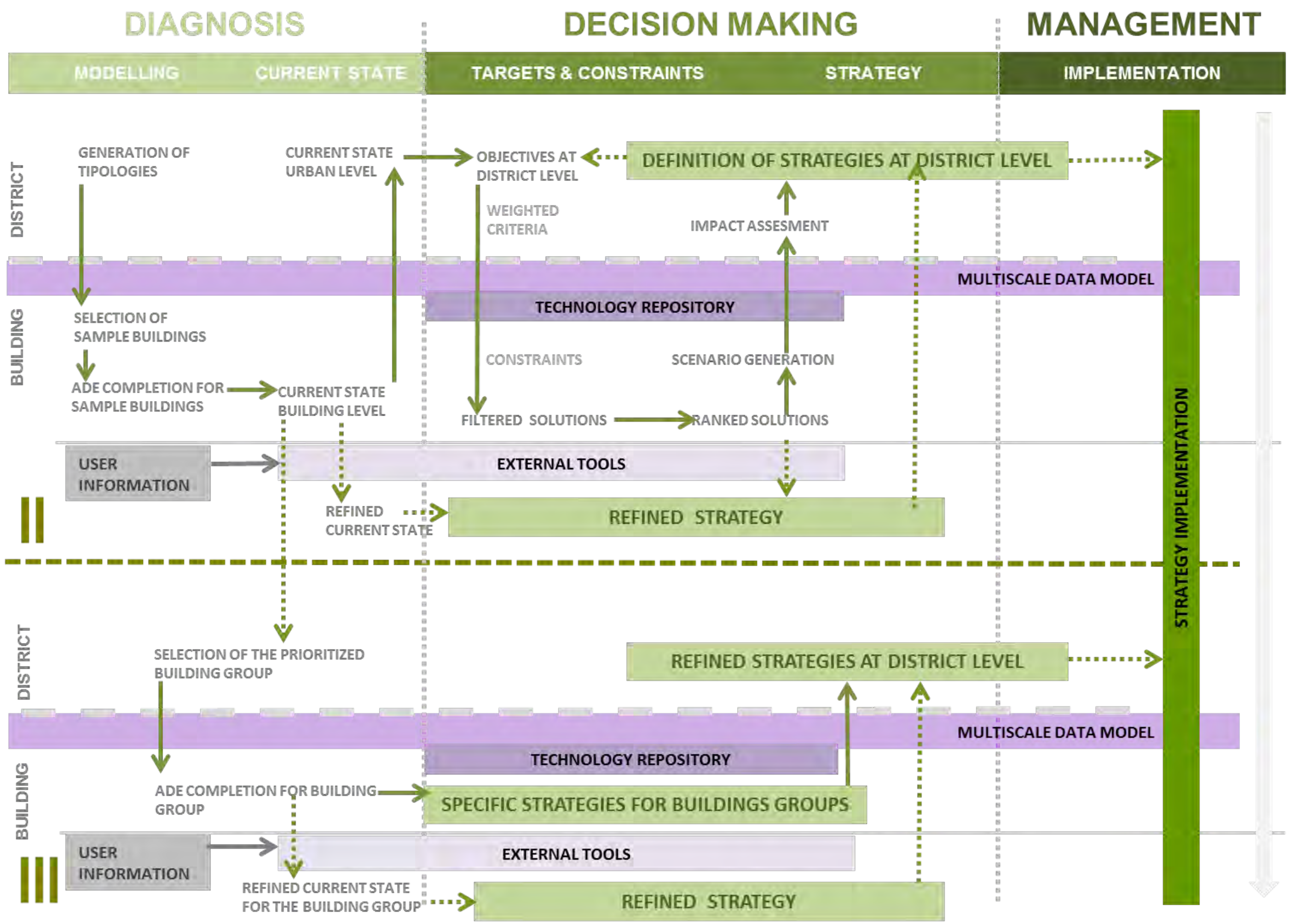

Figure 35: Methodology at LoDM II and III

2.8.1 Decision making at higher levels of accuracy (LoDM II - Level of Accuracy 3)

A higher level of accuracy in the same LoDM could be obtained using more sophisticated tools for the calculation of the more complex indicators. The following sections will explain the differences with the Level of Accuracy 2.

Current state identification

In this level, under the supposition of the use of other tools apart from the EFFESUS DSS, almost all identified indicators (see Section 2.4.3) can be used as the required information will be asked to the user. As the indicators have to be used to estimate the improvement of the solutions, the indicators that could be obtained by simulation will be considered key for the DM. The indicators that are estimated by sensors will be informative, as a baseline for the estimations of improvements is not easy to obtain. The following table shows a categorization of identified indicators (highlighted the preferred ones):

Category	Subcategory	Specific Indicator	Calculation method	Type
Habitability	**Thermal comfort**	**Temperature**	**Simulation**	**DM**
		Relative humidity	**Simulation**	**DM**
		PMV	**Simulation**	**DM**
		PPD	**Simulation**	**DM**
	Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	Simulation	Informative
	Visual comfort	Mean maintained illuminance	Sensors	Informative
		Illuminance uniformity	Sensors	Informative
		Colour rendering index (CRI) for lighting	Sensors	Informative
		Daylight factor	Simulation	Informative
	IAQ	Pollutants	Sensors	Informative
		Microbial pollution	Sensors	Informative
		Ventilation rate	**Simulation**	**DM**
Energy saving	**Thermal energy use**	**Total use/year**	**More accurate simulations**	**DM**
		Thermal energy use per	**More accurate simulations**	**DM**

Category	Subcategory	Specific Indicator	Calculation method	Type
		m^2 building area		
	Electrical energy use	Total use/year	Simulation	DM
		Electricity use per m^2 building area	Simulation	DM
	CO_2 emissions	Total for a building or a district	DSS calculation	DM
	Peak power demand	Total for a building or a district	Simulations	DM
	% RES	Fraction of energy supply from RES	Simulation	DM

Table 20: Indicators at LoDM III

Regarding the *Economic Indicators*, due to the difficulty to estimate the influence of the solutions in the macroeconomic scale they have not considered for current state identification.

The result obtained in each specific indicator will be translated in a 0-4 scale according to the threshold identified. This will give the user an easy picture of the current state of his/her HUD in order to establish the goals. Anyway in order of calculate the improvement of each scenario the real data will be used. In the Annex II it could be seen all the indicators at this level.

The following diagram shows the work flow of this step:

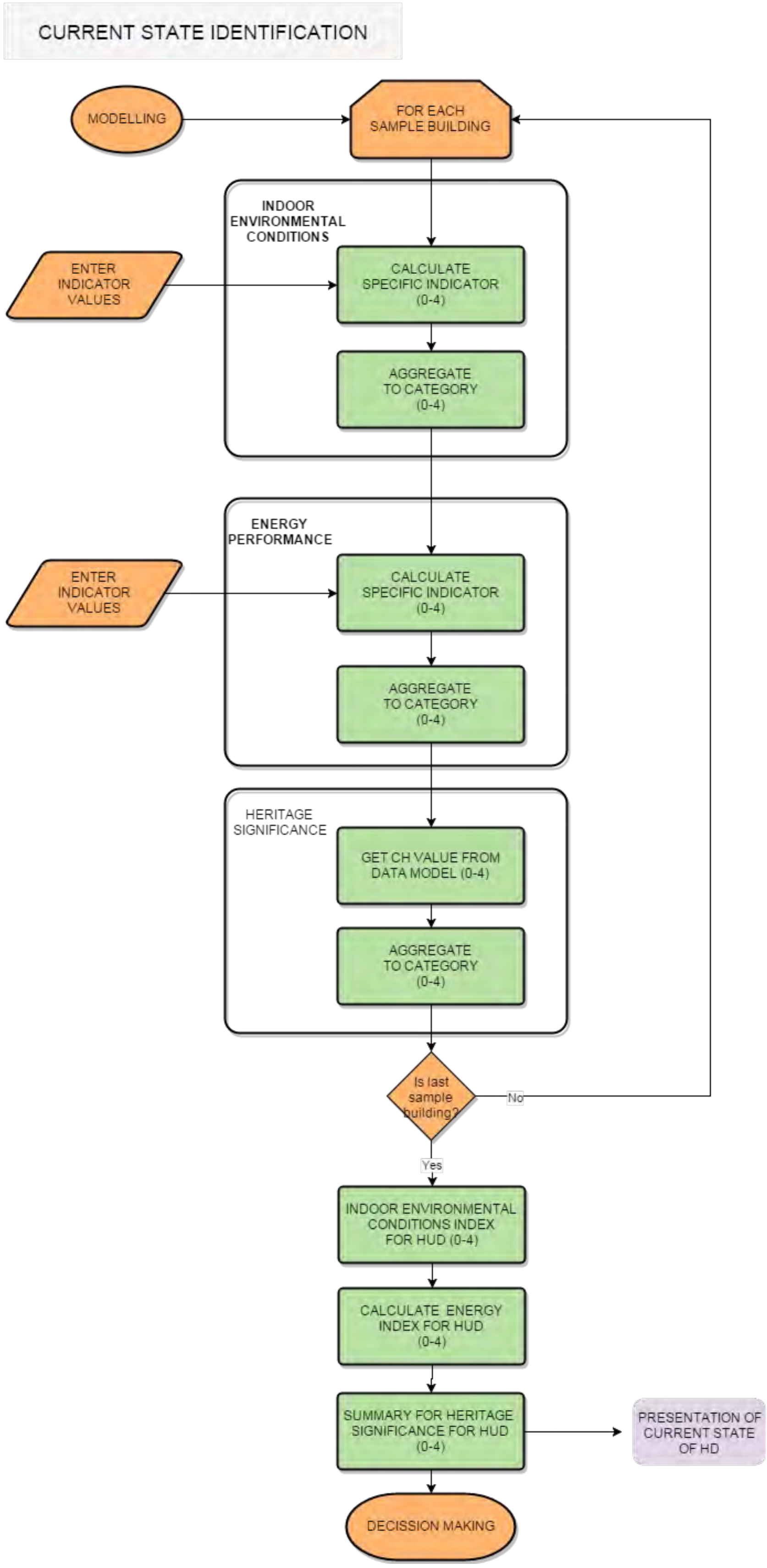

Figure 36: Work flow at current state phase at LoDM II and level of Accuracy 3

Ranked list of solutions

With the new information about specific indicators calculated by external tools, the information about HUD from the multiscale data model and the weighting system is obtained a new more precise ranking of strategies. Even though, as in the current state the indicators calculated by simulation may be preferred. The following table shows a categorization of identified indicators (highlighted the preferred ones):

Category	Subcategory	Specific Indicator	Calculation method	Type
Habitability	**Thermal comfort**	**Temperature**	**Simulation**	**DM**
		Relative humidity	**Simulation**	**DM**
		PMV	**Simulation**	**DM**
		PPD	**Simulation**	**DM**
	Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	Simulation	Informative
	Visual comfort	Mean maintained illuminance	Sensors	Informative
		Illuminance uniformity	Sensors	Informative
		Color rendering index (CRI) for lighting	Sensors	Informative
		Daylight factor	Simulation	Informative
	IAQ	Pollutants	Sensors	Informative
		Microbial pollution	Sensors	Informative
		Ventilation rate	**Simulation**	**DM**
Energy saving	**Thermal energy use**	**Total use/year**	**More accurate simulations**	**DM**
		Thermal energy use per m^2 building area	**More accurate simulations**	**DM**
	Electrical energy use	**Total use/year**	**Simulation**	**DM**
		Electricity use per m^2 building area	**Simulation**	**DM**
	CO_2 emissions	**Total for a building or a district**	**DSS calculation**	**DM**
	Peak power demand	**Total for a building or a district**	**Simulations**	**DM**
	% RES	**Fraction of energy supply from RES**	**Data available or easily measurable**	**DM**

Category	Subcategory	Specific Indicator	Calculation method	Type
	Comprehensive (life cycle) energy saving	Total Primary Energy saving (over 100 years)	Data base	Informative
		Total Primary Energy saving (over 100 years) per year	Data base	Informative
		Total Carbon saving (over 100 years)	Data base	Informative
		Total Carbon saving (over 100 years) per year	Data base	Informative
Economic Return	**Cost of Retrofit Measures**	**Cost in euros**	**Database**	**DM**
	Value of energy saved	**Value in euros**	**DSS calculated**	**DM**
	LCA (Life Cycle Analysis)	Combined Environmental Impact Indicator	Complex assessment procedure	Informative
	NPV (Net Present Value)	Value over time	External calculation	Informative
	ROI	**Efficiency of investment**	**External Calculation**	**DM**
	Overall Payback Period	**Payback time taking account of all benefits**	**DSS calculation**	**DM**
	Energy Payback Period	**Payback time only taking account of cost of energy**	**DSS calculation**	**DM**

Table 21: Indicators at DM phase at Level of Accuracy 3

The ranking regarding the cultural value will be the same as in Level of Accuracy 2 as it does not depend of external calculations.

Assessment of the Scenarios

Simulation tools will be used along with the multiscale data model in order to calculate a more accurate impact of the generated alternatives.

Work Flow

The following diagram shows the work flow for DM phase at this level of accuracy:

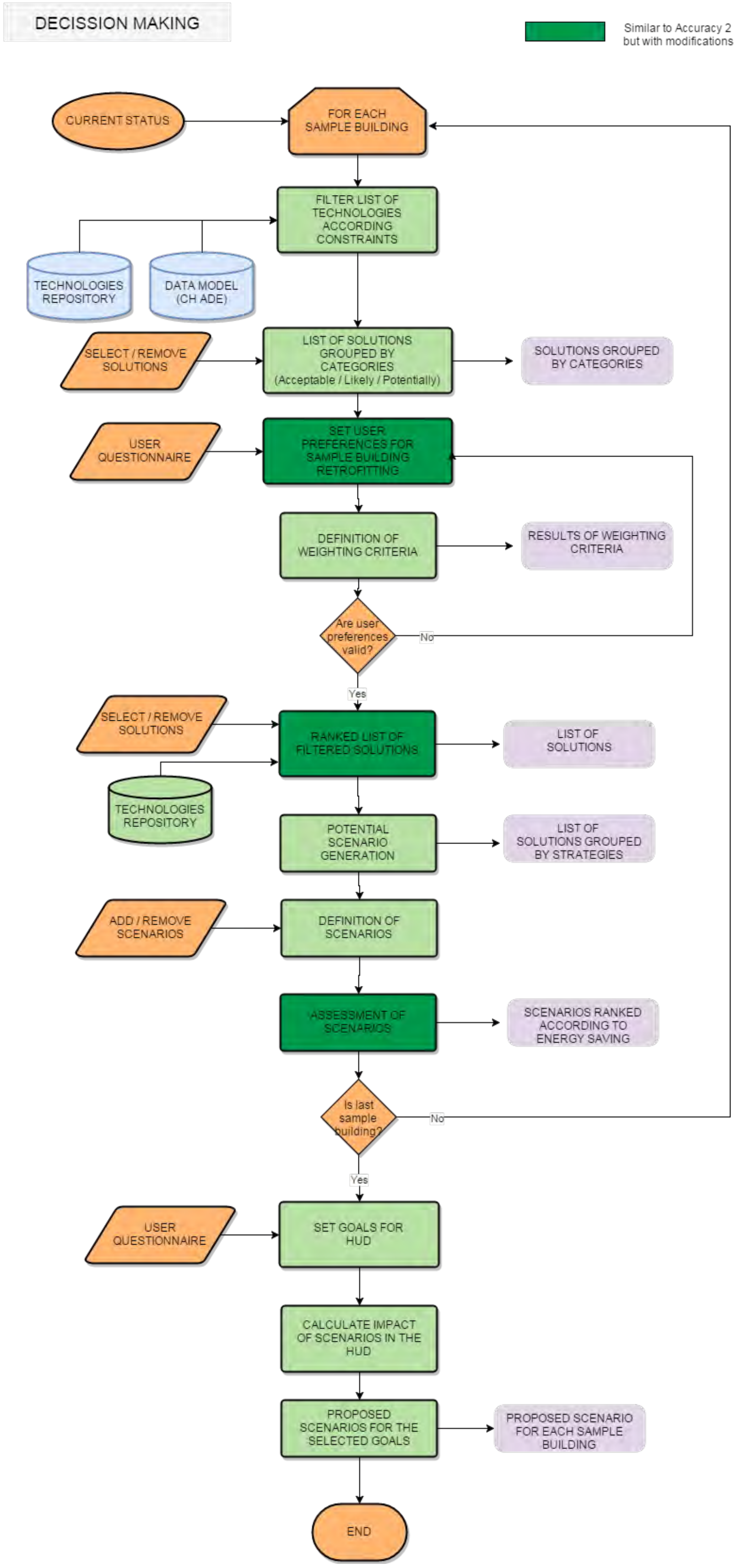

Figure 37: Work Flow for LoDM II at Level of Accuracy 3

2.8.2 Decision making at higher levels (LoDM III – Level of Accuracy 4)

The LoDM III will work with more detailed information. Its target will be the groups of buildings that have been considered as a priority in the previous steps. The prioritization could be done using the method of *identification of priority areas* explained in Section 2.5.2.

But the process that has been run in the LoDM II for each group provides also the information that will allow the decision maker to prioritise the different groups of buildings and to decide the group that will be analysed in the level III following information for each group:

→ current state of the buildings of this group
→ weighted representativeness of the group
→ most suitable retrofitting strategies for this group
→ impact of this group in the global objectives for the whole HUD

Modelling

The following diagram shows the work flow for modelling phase at this level of accuracy:

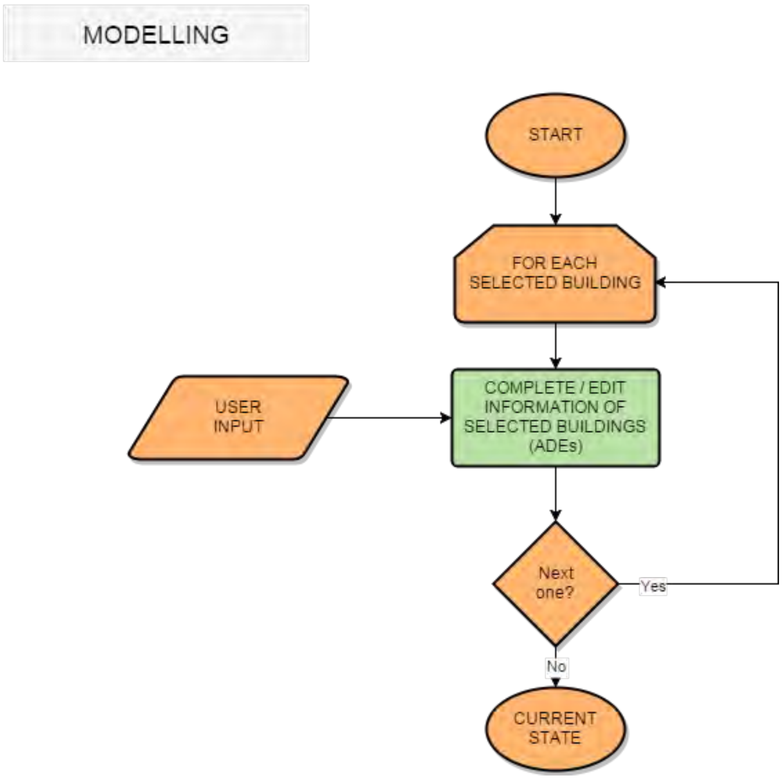

Figure 38: Work Flow for modelling at LoDM III and Level of Accuracy 4

Current state identification

One of the main differences is that, in this step the vulnerability regarding the *technical compatibility risks* will be included apart from constraints used in LoDM II. The assessment is very similar to the one carried out for the HS in LoDM II (see 0). The following table shows the criteria used for this assessment regarding the building and its elements:

	Indicator	Sub-indicator in data model	Value
Chemical	Efflorescence and salt reaction	Presence of water-soluble salts in concerned fabric	0-4
		Presence of water-soluble salts in concerned environments	
	Corrosion	Presence of metals in concerned fabric Presence of corroding and/or corrosive substances at fabric surface	0-4
Physical	Moisture performance: moisture content and moisture movement	Capability of liquid transport of concerned fabric	0-4
		Capability of vapour permeability -of concerned fabric	0-4
	Moisture performance: surface and interstitial condensation	Ability of concerned fabric to resist bio-deterioration (incl. rot, mould)	0-4
	Mechanical performance: structural movement	Spare load capacity of concerned fabric	0-4
	Mechanical performance: material contraction and expansion	Flexibility of the fabric	0-4
	Mechanical performance: reversibility	Resistance to mechanical damage of concerned fabric	0-4

Table 22: Technical compatibility risks

Using the DSS the current state for all the buildings can be calculated with enough information of the selected group, and present them through the multiscale data model.

The following diagram shows the work flow for current state identification phase at this level of accuracy:

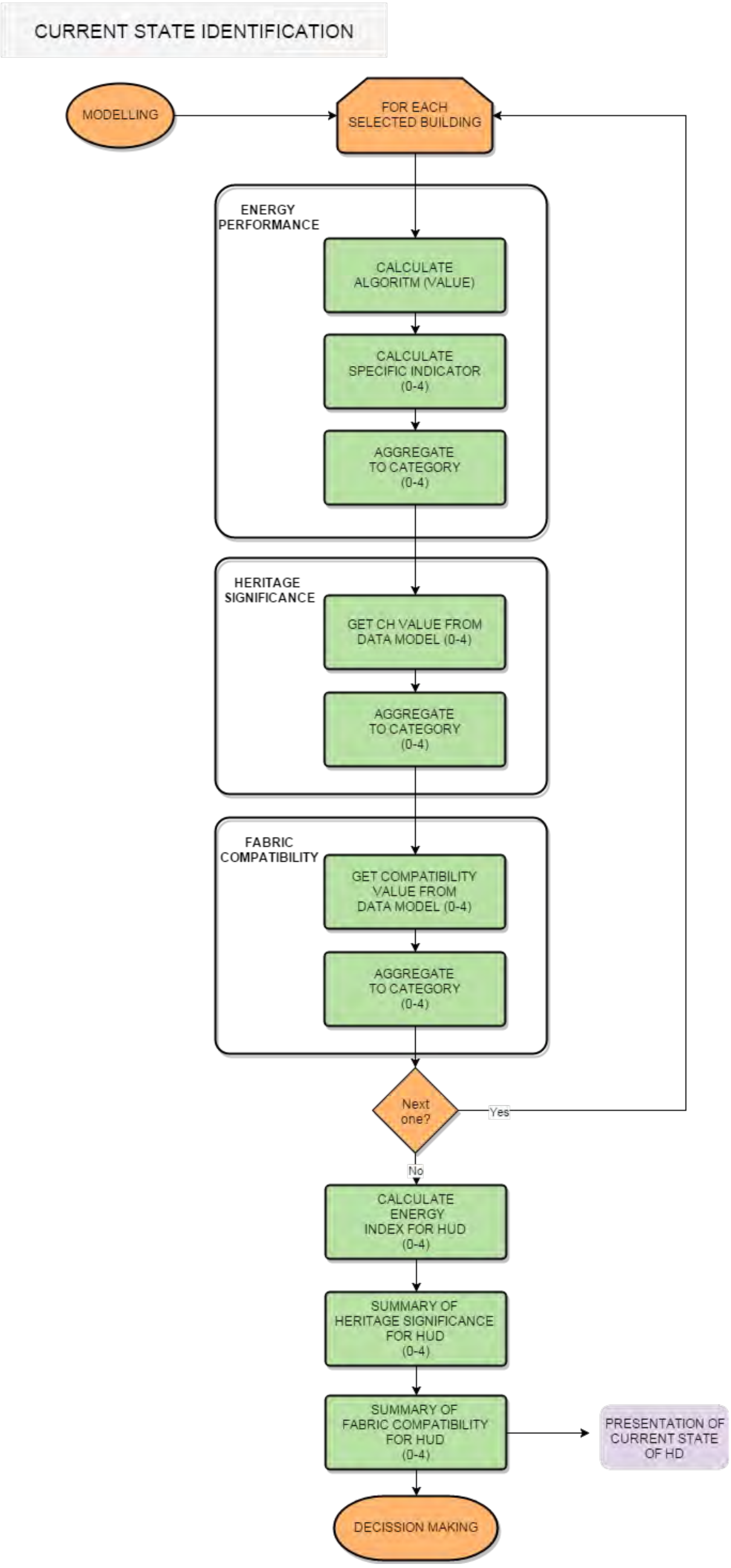

Figure 39: Work Flow for Current State phase at LoDM III and Level of Accuracy 4

Filtered list of solutions according to the constraints

At this level the constraints regarding the *technical building and fabric compatibility* will be added to the ones regarding HS. They will be assessed in an analogue way. The assessment regarding the fabric compatibility is challenging and not always easy, therefore the decision maker has to evaluate the results carefully. The assessment will match information about the HUD stored in the multiscale data-model about the *vulnerability degree* of the fabric and information regarding the technology regarding its risk of impact. In the previous section it has been shown the way to assess the *fabric vulnerability*. In the following table, to this assessment the scale for the impact of the retrofitting solutions is added:

	HUD CHARACTERISTIC			**TECHNOLOGY CHARACTERISTICS**		
	Indicator	**Sub-indicator in data model**		**Sub-indicator in the repository**		**Element of impact**
Chemical	Efflorescence and salt reaction	Presence of water-soluble salts in concerned fabric	0-4	Reactivity of measure when in contact with salts	0-4	Boundary surface
		Presence of water-soluble salts in concerned environments				
	Corrosion	Presence of metals in concerned fabric Presence of corroding and/or corrosive substances at fabric surface	0-4	Content of corrosive materials in the measure reactivity of corroding and/or corrosive substances at measure surface	~~0-4~~	Boundary surface
Physical	Moisture performance: Moisture content and moisture movement	Capability of liquid transport of concerned fabric	0-4	Capability of liquid transport of concerned measure	0-4	Boundary surface
		Capability of vapour permeability -of concerned fabric	0-4	Capability of vapour permeability of concerned measure		Boundary surface
	Moisture performance: Surface and interstitial condensation	Ability of concerned fabric to resist bio-deterioration (incl. rot, mould)	0-4	Impact on hygrothermal performance	0-4	Boundary surface

Indicator	HUD CHARACTERISTIC Sub-indicator in data model		TECHNOLOGY CHARACTERISTICS Sub-indicator in the repository		Element of impact
Mechanical performance: Structural movement	Spare load capacity of concerned fabric	0-4	Weight of the measure	0-4	Boundary surface
Mechanical performance: Material contraction and expansion	Flexibility of the fabric	0-4	Flexibility of the measure	0-4	Boundary surface
Mechanical performance: Reversibility	Resistance to mechanical damage of concerned fabric	0-4	Damage caused by removal of measure	0-4	Boundary surface

Figure 40: Technical Building Fabric compatibility

As in the HS, the impacts of each retrofit measures in the repository can be compared to the vulnerability of the fabric. The logic regarding this comparison is the following:

		Degree of impact /risk on the retrofit measure				
		0= No impact	1=Will not negatively affect the fabric performance in the concerned impact area short- and/or long-term	2=Unlikely to negatively affect the fabric performance in the concerned impact area short- and/or ong-term	3=Might negatively affect the fabric performance in the concerned area short- and/or long-term	4= Will detrimentally affect the fabric performance in the concerned impact area short- and/or long-term
Building and urban fabric compatibility	0= No impact	acceptable	acceptable	acceptable	acceptable	acceptable
	1=Unlikely to occur now and in the future	acceptable	likely to be acceptable	likely to be acceptable	likely to be acceptable	likely to be acceptable
	2=Might occur at some point in the future	acceptable	might be acceptable	might be acceptable	might be acceptable	likely not to be acceptable
	3=Occurs occasionally	acceptable	likely not to be acceptable	likely not to be acceptable	likely not to be acceptable	likely not to be acceptable
	4=Occurs regularly and repeatedly	acceptable	likely not to be acceptable	likely not to be acceptable	likely not to be acceptable	likely not to be acceptable

Table 23: Technical Building Fabric compatibility assessment results

As in the previous steps, the constraints assessment will be done by the DSS for all the buildings complying with the minimum information requirements defined and it will provide the solutions with a higher degree of suitability regarding the two kinds of constraints.

Ranked list of solutions

The DSS provides a ranked list of solution for each building of the group, and find the patterns with the strategies that will fit better the preferences of the user. Synergies between strategies can be identified.

Potential Scenario Generation and Assessment of Scenarios

The scenarios will be generated in the same way as in LoDM II and the selection of the best strategy will be done through the assessment of the impact of the strategy applied to all the buildings of the group. The following diagram shows the work flow for modelling phase at this level of accuracy:

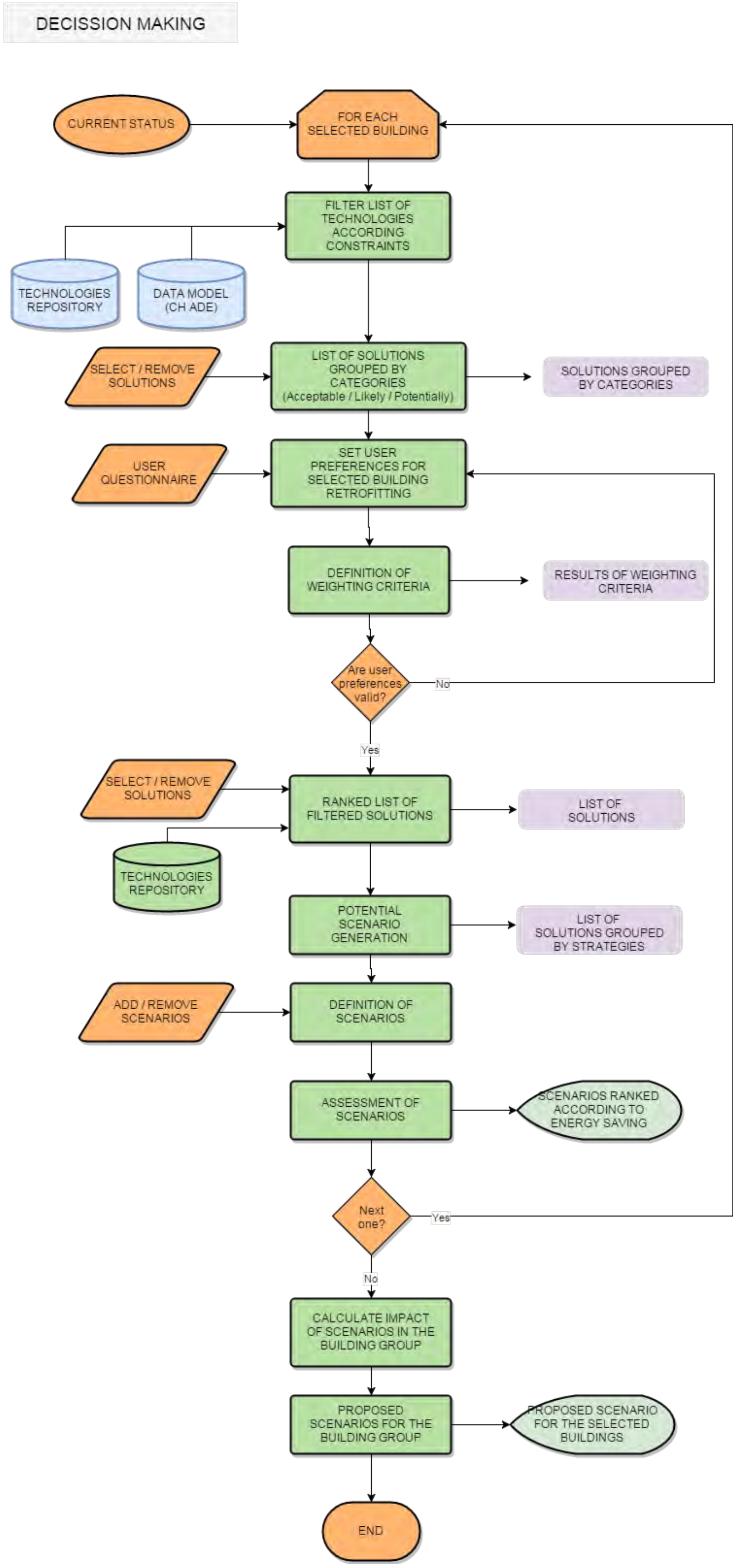

Figure 41: Work Flow for DM phase at LoDM III and Level of Accuracy 4

2.8.3 Decision making at LoDM III and Level of Accuracy 5

The Level of Accuracy 5 is analogue to the Level of Accuracy 3 (Section 2.8). The main differences between these two levels are that in LoDM III the results are focused in groups of buildings and that the *technical building and fabric compatibility* constraints are taking into account.

2.9 Management phase

This phase includes the implementation of the strategies according to the previous phase and their monitoring and maintenance. The intervention at building level will need a detailed rehabilitation project that is beyond the scope of this research; however its definition could be supported by the methodology described, as the constraints, criteria and ranking methods could be used at a single building level. Moreover the rehabilitation project should be coherent with the strategy and the objectives that have been defined in the previous phase at building level. The multiscale data model will store the information in order to monitor the defined targets.

The whole methodology has to be able to articulate the structuration of all the new information and feedback generated during the whole process. All the phases of the intervention at building level (the diagnosis, the design of the intervention and its implementation) will generate new information about specific buildings that will complete the multiscale data model of the historic district and enable more accurate DM. The indicators at urban level will allow monitoring the real improvement of the strategies and consequently the whole process will be refined. In the following table it is shown the indicators during all the phases at Level of Accuracy 2 and 4. At Annex II it can be found the indicators at higher levels of accuracy.

LEVELS OF DM						CRITERIA	CURRENT STATE			DECISION MAKING			MONITORING		
							DSS			DSS			MODEL		
Level		Accuracy		Scale		Category	Subcategory	Specific Indicator	Calculation	Subcategory	Specific Indicator	Calculation	Subcategory	Specific Indicator	Calculation
				building		Habitability				Thermal comfort		REPOSITORY	Thermal comfort		Sensors
				building						Acoustic comfort		REPOSITORY	Acoustic comfort		Sensors
				building						Visual comfort		REPOSITORY	Visual comfort		Sensors
				building						IAQ		REPOSITORY	IAQ		Sensors
				building	district	Energy saving				Energy Saving		REPOSITORY	Energy Saving		Billings
				building	district		Thermal energy use	Total use/year	EE ADE + EN ISO 13790:2008	Thermal energy use	Total use/year	EE ADE + EN ISO 13790:2008+ REPOSITORY	Thermal energy use	Thermal energy use per m^2 building area	Billings
				building	district		Thermal energy use	Thermal energy use per m^2 building area	EE ADE + EN ISO 13790:2008	Thermal energy use	Thermal energy use per m^2 building area	EE ADE + EN ISO 13790:2008+ REPOSITORY	Thermal energy use	Total use/year	Billings
II	III	2	4	building	district		Electrical energy use	Total use/year	DSS ESTIMATION	Electrical energy use	Total use/year	REPOSITORY	Electrical energy use	Total use/year	Billings
				building	district		Electrical energy use	Electricity use per m^2 building area	DSS CALCULATION	Electrical energy use	Electricity use per m^2 building area	DSS CALCULATION	Electrical energy use	Electricity use per m^2 building area	Billings
				building	district		CO_2 emissions	Total for a building or a district	DSS CALCULATION	CO_2 emissions	Total for a building or a district	DSS CALCULATION	CO_2 emissions	Total for a building or a district	DSS CALCULATION
				building	district	Economic feasibility				Cost of Retrofit Measures	Cost in euros	REPOSITORY	Cost of Retrofit Measures	Cost in euros	Not applied
				building	district					Value of energy saved	Value in euros	DSS ESTIMATION	Value of energy saved	Value in euros	Billings
				building	district					Energy Payback Period	Payback time only taking account of cost of energy	DSS ESTIMATION	Energy Payback Period	Payback time only taking account of cost of energy	DSS ESTIMATION

Table 24: Indicators in the current state, DM and monitoring phases at Level of Accuracy 2 and 4

3 MULTISCALE INFORMATION MANAGEMENT

It is not the amount of knowledge that makes a brain. It is not even the distribution of knowledge. It is the interconnectedness.

James Gleick

The Information: A History, a Theory, a Flood

The previous chapters have described a framework and a DM methodology for improving the EP and indoor comfort of buildings of a HUD while protecting their cultural values. These framework and methodology are deeply rooted in a concept of strategic information management that operates within a multiscale approach.

HUDs are complex urban ecosystems that generate large volume of heterogeneous data. These data work on different scales and are of different nature, are created by different tools and stakeholders and are produced and stored in different formats and for different uses. The evolution towards the SmartCity concept is going to make this information in the near future to grow exponentially making the strategic information management unavoidable (Egusquiza et al. 2013).

The methodical creation, structuration, harmonization, updating and exploitation of the urban data are crucial for an informed DM regarding the sustainability of the HUDs. This strategy has to be interscalar and cross-thematic, linking the information at different scales (city, district, building and component) and from different domains (housing, cultural heritage, energy, social economics...). In order to fully exploit the potential of this information an interoperable and multiscale data model is required. This complete and single data model is nuclear for the implementation of the information management strategy and will organise the domain knowledge supporting the DM process explained in the previous chapter.

Besides the multiscale data model, a database that will organise the data of EEIM and RES is also necessary if we want to match the information regarding the HUD with the information about different possible retrofitting measures in a structured and automatic way.

3.1 Requirement for the multiscale data model

First step for the definition of the data model, which represents the HUD, is to identify the main requirements that the data model should address. Those requirements for the data model can be divided into four main categories: general requirements, geometric requirements, domain specific requirements and application specific requirements.

In the following sections requirements are presented divided into these four categories. Each of the requirements has a unique identifier and includes also whether the requirement is mandatory for the data model or is optional.

3.1.1 General requirements

REQ. ID	REQUIREMENT	
M_REQ_GEN_01	Data model must be a unique data model that allows representing all the necessary information for DM of an entire HUD	Mandatory
M_REQ_GEN_02	Data model must support information at different scales (from the building element to the city, reaching at least to the level of HUD)	Mandatory
M_REQ_GEN_03	Data model must include 3D geometric information as well as semantic information (attributes / properties)	Mandatory
M_REQ_GEN_04	Data model must be based on standards in order to facilitate interoperability with existing tools for modelling, simulation and analysis	Mandatory
M_REQ_GEN_05	Data model must include at least information at building scale, both geometric and semantic	Mandatory
M_REQ_GEN_06	Data model must represent other urban elements, in addition to buildings (roads, green areas, etc.)	Optional
M_REQ_GEN_07	All the elements included in the data model must be correctly georeferenced on a universal coordinate system in longitude, latitude and elevation	Mandatory
M_REQ_GEN_08	Data model should be easily extensible in both spatial extension of the model (adding a new neighbourhood or area) and in the information domain (adding information for a new domain)	Mandatory
M_REQ_GEN_09	Data model must enable the grouping of buildings in areas or districts	Mandatory
M_REQ_GEN_10	The process of completing the model with real and accurate data should be low cost	Optional
M_REQ_GEN_11	Geometric and semantic information of the data model must be represented in different layers, in order to reduce the coupling and to promote the reuse	Optional

Table 25: General Requirements for EFFESUS data model

3.1.2 Geometric requirements

REQ. ID	REQUIREMENT	
M_REQ_GEO_01	Data model must allow representation of geometric models with different LoDs (from footprints to high resolution and photorealistic 3D models)	Mandatory
M_REQ_GEO_02	The language or file format for the representation of geometric information should allow modelling and storing geographic information	Mandatory
M_REQ_GEO_03	Data model must store information representative of the geometry of the buildings	Mandatory
M_REQ_GEO_04	Data model must store information of the geometry of other urban elements such as roads, green areas, urban furniture, etc.	Optional
M_REQ_GEO_05	Data model must be able to store information of the geometry of the main structural elements of buildings (doors, windows, walls and roofs)	Mandatory
M_REQ_GEO_06	Data model must contain information about the textures of buildings and building elements	Optional
M_REQ_GEO_07	Geometry of the buildings must be properly referenced in elevation according to the digital elevation model (DEM) of the area	Mandatory
M_REQ_GEO_08	Geometry of the buildings must be properly referenced with respect to the orthophotography of the area	Optional

Table 26: Geometric Requirements for EFFESUS data model

3.1.3 Domain specific requirements

REQ. ID	REQUIREMENT	
M_REQ_DOM_01	Elements of the data model should include information from different domains: energy, cultural heritage, climate, etc. into a unique data model	Mandatory
M_REQ_DOM_02	Semantic information about the elements in the model must be georeferenced	Mandatory
M_REQ_DOM_03	Semantic information should be based on existing ontologies, standards, normative, directives or guidelines recognized by the international community expert in each domain	Mandatory
M_REQ_DOM_04	Semantic information must be linked to the corresponding geometric element	Mandatory
M_REQ_DOM_05	Data model must collect the energy characteristics relevant for building energy analysis, considering all those that have special relevance in traditional building	Mandatory
M_REQ_DOM_06	Data model must support the representation of the information of other energy specific data models and energy simulation software tools (gbXML, idf (e +), etc.)	Optional
M_REQ_DOM_07	Data model must include information representing the HS of the HUD (from the district to component level)	Mandatory

REQ. ID	REQUIREMENT	
M_REQ_DOM_08	Data model must allow representation of some non-standardized construction elements used in ancient buildings (arches, vaults, pillars, etc.)	Optional
M_REQ_DOM_09	Data model should also represent temporal information to track changes, updates or interventions along the time	Mandatory

Table 27: Domain Specific Requirements for EFFESUS data model

3.1.4 Application specific requirements

REQ. ID	REQUIREMENT	
M_REQ_APP_01	Data model should facilitate the exchange of information between different stakeholders and institutions involved in the DM	Mandatory
M_REQ_APP_02	Data model should foster the public access to information facilitating the accessibility and understanding of this information to policy makers, technicians and citizens	Mandatory
M_REQ_APP_03	The information included in the data model must be accessible (use and update) through standard web services	Mandatory
M_REQ_APP_04	Access to information in the data model should be done with appropriate time of response, according to application performance requirements	Mandatory
M_REQ_APP_05	Storage and management of the data model must be carried out through a geospatial database	Mandatory
M_REQ_APP_06	Data model must allow different stakeholders to share always updated information	Mandatory
M_REQ_APP_07	The information contained in the data model should allow the development of domain analysis and simulations both at building and urban district scale	Mandatory
M_REQ_APP_08	Data model must support different modelling strategies as the identification of sample buildings or the development of vulnerability and opportunity maps	Mandatory
M_REQ_APP_09	Data model should enable the generation of tools and solutions in the cloud (cloud computing) for the analysis, management and DM	Mandatory
M_REQ_APP_10	Data model should interconnect the information at different scales and levels of detail in order to allow visualization and analysis of data at different resolution and scale, depending on the requirements of each stakeholder.	Mandatory
M_REQ_APP_11	Data model must facilitate the sustainable management of the historic centres using existing information of city models	Optional

Table 28: Application Specific Requirements for EFFESUS data model

3.2 Data models for the representation, structuration and exploitation of urban information

The previous section can be summarised saying that in order to achieve a suitable multiscale information management a 3D georeferenced, extensible, multiscalar, and interoperable model is required. A low cost generated single model, based on real data, can structure all the geometric and crossthematic semantic information necessary to back the whole methodological framework described in Chapter 1 and to support the DM process described in the Chapter 2.

3.2.1 State of the Art

A 3D city model is defined as a georeferenced digital representation of objects, structures and phenomena that correspond to a real city (Ross et al. 2009). There are several options to generate urban models quite easily when high realism and semantic information are not necessary. Methods as the procedural city generation (Gain et al. 2014), generate a lot of buildings through the repetition of the structures. Although it is possible to specify parameters such as population density or age of buildings, the generated virtual cities are pure geometry and they lack of semantic information. Another alternative without semantic information is the generation of virtual 3D cities by Google (Google Earth)[41], which generates a geometric 3D model of an entire city from user contribution (and commitment of local governments). But these models represent the city as a whole and there is no integration between urban scale and building, or other city elements. The fully automatically generation of the entire city from LiDAR data provides a realistic model very rapidly. But the lack of identification of urban elements (buildings, trees, urban furniture, etc.) makes it not very useful for other than realistic visualization.

The lack of semantic information of the previous mentioned models is a serious limitation for the DM processes like the one proposed in this research. But modelling a realistic 3D city model combining geometric information and semantic information in a cost-effective and reliable way is still a great challenge. Only starting from free (or low cost) data makes feasible the development of cost-effective realistic 3D models of a HUD. In this direction, the data sources that provide more information to generate a 3D model at urban scale are the cadastre and the remote imagery. Although these data sources make possible to generate 3D urban models, the LoDs and the semantic information are still not complete. The model can be complemented by geographic and semantic information provided by initiatives such as OpenStreetMap[42]. The drawback is that they are data generated by non-professional users and only are available for specific areas or regions.

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[41] Google Earth Cities in 3D, http://www.google.com/intl/es/help/maps/citiesin3d/

[42] OpenStreetMap. http://www.openstreetmap.org/

When semi-automatic high resolution 3D reconstruction of buildings is required, the most useful data are images and laser scanner. For geometry, aerial orthophotography and terrestrial photogrammetry are very effective. Terrestrial photogrammetry has great potential for simple geometries and isolated objects but is complicated for urban environments demanding a lot of field work. The laser scanner provides a high resolution 3D model but the amount of data makes the post-process very time demanding.

When it comes to select the proper format, two severe limitations in current 3D models are the lack of interoperability between data formats at syntax level, due to the fact that most of the existing data formats lack of semantic information, and the absence of integration between urban scale and building scale. Traditionally urban and building scale has been two separated scales. The regional and urban scales have been dominated by the use of GIS tools (ArcGIS[43], gvSIG[44], CityEngine[45], etc.). At building level, the most used tools come from the Architecture, Engineering and Construction (AEC) sector (Revit[46], Allplan[47], ArchiCAD[48], SketchUp[49], etc.). The traditional tools based on Computer-Aided Design (CAD) have evolved to the Building Information Model (BIM) paradigm, under the Industry Foundation Classes (IFC) format. IFC is focused on building and provide detailed building information (both geometric and semantic). It is a good approach for the generation of semantic-aware high detailed 3D models of buildings, but it is not time / cost-effective for the generation of an entire HUD.

Nowadays, one of the main requirements to develop data models is the conformity to standards or to formats commonly adopted to facilitate interoperability. Many of the existing software tools for 3D modelling use proprietary formats to represent the geometry of the models and that makes difficult the interoperability and the information sharing. In GIS environments, despite of the existence of data formats like SHP that are widely used and could be considered as de facto standard, each software tool has its own formats which hinders interoperability (Towne 2009). Regarding the 3D representations, at urban scale, GML[50] and KML[51] are the most used data formats for 3D representation. Although both are aimed to store geometry they are not intended to store semantic information. At building scale, a big step was done when CAD tools evolved to the BIM concept, adding semantic information to the building models and making them interoperable through the implementation of the open standard for BIM through IFC.

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[43] ArcGIS http://www.arcgis.com/
[44] gvSIG http://www.gvsig.com/
[45] CityEngine http://www.esri.com/software/cityengine
[46] Revit, http://www.autodesk.com/products/revit-family/overview
[47] Allplan, http://www.allplan.com
[48] ArchiCAD, http://www.graphisoft.com/archicad/
[49] SketchUp, http://www.sketchup.com/
[50] Geography Markup Language. Open Standard defined by OGC
[51] Keyhole Markup Language. Open Standard defined by OGC and used by Google.

A multiscale data model format that falls between the GIS and BIM scales is CityGML. CityGML[52] is an open data model based on Extensible Markup Language (XML) format for storage and exchange of virtual models of 3D city defined by the Open Geospatial Consortium (OGC). The aim of the development of CityGML was to reach a common definition and understanding of the basic entities, attributes, and relations within a 3D city model (Kolbe 2009). It allows the reuse of the same data in different fields of application (Gröger & Plümer 2012). It has been designed to store semantic and 3D multiscale geometric information, considering urban and building scales. CityGML can be linked with IFC at a specific LoD in order to develop a holistic data model covering the different levels of detail.

The following table made by (Vandysheva et al. 2012) summarised the comparison between different 3D data exchange standards:

	DXF	SHP	VRML	X3D	KML	Collada	IFC	CityGML	3D PDF
Geometry	++	+	++	++	+	++	++	+	++
Topology	-	-	0	0	-	+	+	+	-
Texture	-	0	++	++	0	++	-	+	+
LOD	-	-	+	+	-	-	-	+	-
Objects	0	+	+	+	-	-	+	+	+
Semantic	+	+	0	0	0	0	++	++	+
Attributes	-	+	0	0	0	-	+	+	+
XML based	-	-	-	+	-	-	+	+	-
Web	-	-	+	++	++	+	-	+	0
Georef.	+	+	-	+	+	-	-	+	+
Acceptance	++	++	++	0	++	+	0	+	++

- not supported; 0 basic; + supported; ++ extended

Table 29: Comparison between different 3D exchange standards (Vandysheva et al. 2012)

As it can be seen in this table CityGML is the most complete standard and moreover fulfils all the requirements defined in the previous section, being the only standard that supports different LoDs and one of the most complete ones regarding the inclusion of semantic information as well as geometric information. The widespread use of CityGML across Europe is another of its advantages. Most of the German cities have a CityGML model at least at its lowest LoD (Nouvel et al. 2013) and others as Berlin [53] has one of the most advanced CityGML models.

[52] OGC City Geography Markup Language (CityGML) Encoding Standard 12-019 - http://www.opengeospatial.org/standards/citygml

[53] http://www.virtualcitysystems.de/en/references.html#3d-city-models

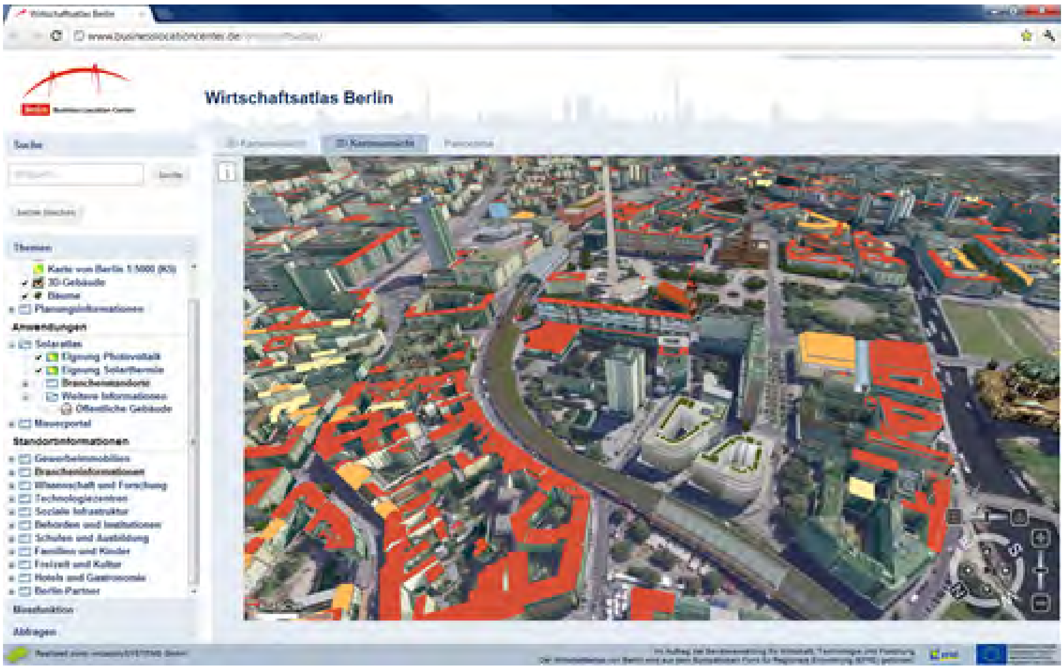

Figure 42 Example of 3D City Model based on CityGML (3D City Berlin. 2013)

Another example of its acceptance is the Dutch 3D standard IMGeo[54] that is based on CityGML ADE or the case that the INSPIRE directive[55] connects to CityGML in the specification for buildings. Since 2007, the INSPIRE directive aims to establish the general rules and the legal framework for spatial information in the EU. This directive requires data harmonization and interoperability of the system in order to have more quantitative and reliable spatial data available to all (administrations, companies and citizens). One objective of this directive is to use and optimize the operation of currently existing spatial data. This requires that the data are properly documented and information is made accessible through services thus achieving greater interoperability and data accessibility.

One of the main features of the CityGML is being a spatio-semantic model, that is, the geometric information in CityGML is extended with semantic information. This kind of semantically enriched model has a huge potential addressing numerous diverse spatial analyses as noise mapping (Herman & Reznik 2013), urban wind flow study, district networks analysis and, specially, photovoltaic potential study (Strzalka et al. 2012) (Eicker et al. 2014) (Alam et al. 2013). There are also several application for disaster management based on CityGML (Kemec et al. 2012) (Ren et al. 2012).

Along the same lines, the structuration of the semantic information based on the city elements makes CityGML a compelling way for documentation needs as in immovable property taxation (Cagdas 2013) or built heritage (Inaki Prieto et al. 2012) (Tekdal-Emniyeti et al. 2011).

[54] Modeling an application domain extension of Citygml in UML, 2012.

[55] INSPIRE, “Infrastructure for Spatial Information in the European Community”, http://inspire.jrc.ec.europa.eu/

In energy modelling, heating demand of buildings, and therefore of districts, is strongly dependant of the geometry of those buildings and their construction characteristics (semantic information). Consequently, the combination of spatial analysis with thematic data structuration offer an excellent way to calculate the heating demand at urban level (Strzalka et al. 2011) (Kaden & Kolbe 2013), to estimate the energetic rehabilitation state of the buildings in a city (Carrión et al. 2010) or the integration of energy-related key indicators of buildings and neighbourhoods within 3D building models (Krüger & Kolbe 2012).

The prediction of the heating energy demand of urban districts, can be used as basis for the simulation of energy refurbishment scenarios as in (Eicker et al. 2014) and therefore for the DM regarding energy interventions. But up to now the spatial potential of a model based on CityGML has not been use to add the cultural and historic constraints to this DM process.

In summary, a semi-automatic generation of 3D models with multiple resolutions from different data sources, free or low-cost acquisition (cadastre, aerial imagery, LiDAR, DTM, etc.), and based on the adaptation / extension of the CityGML data model to historic structures could be the optimal strategy in order to support the DM process (see Chapter 2) and the methodological framework (see Chapter1). The following sections will describe the characteristics of this model for its use as support of the energy retrofitting of HUD.

3.2.2 CityGML data model

CityGML data models have several features that make it the most suitable alternative for use as a basis for the representation of the EFFESUS data model. Main features provided by CityGML are:

Modularity: CityGML data model is broken down into a core module and thematic extension modules. The main module covers the basic concepts and components of the CityGML data model and, therefore, must be executed by any system. The CityGML data model includes the geometry and thematic information of the different city elements such as digital terrain model, buildings, vegetation, water bodies, transportation facilities and urban furniture. Other objects, which are not explicitly modelled, can be represented using the concept of generic objects and attributes. Based on the core module, each extension covers a specific topic within the virtual 3D city model. Extensions can be made in the CityGML data model using the ADEs. Hitherto several ADEs has been developed: Noise ADE for a noise mapping, the HydroADE for hydrographical applications (Schulte & Coors 2008), the Standard Opening ADE or the URN ADE for indoor navigation and mobile robotics tasks (Gröger & Plümer 2012)

Multi-scale modelling: As it has been said, one of the main advantages of CityGML is its capability to support different LoDs. The LoDs are necessary to adjust the detail of the information to the requirements of each application, facilitating visualization and analysis of data. CityGML represents the same object with different LoD simultaneously. This allows analyzing and displaying the same object with different degrees of resolution (See Figure 43). LoDs defined in CityGML are:

- → **LoD0:** the digital terrain model in two and a half dimensions. A map or aerial image can be represented by this level.
- → **LoD1:** the block model including buildings represented as simple blocks with flat roofs.
- → **LoD2:** differentiates between the surfaces of façades and roof, as well as the type of the roof. Vegetation objects can also be represented.
- → **LoD3:** detailed architectural models with walls, roofs, openings (windows and doors). High resolution textures can be applied to these structures. In addition, detailed vegetation and transportation objects can be represented at this level.
- → **LoD4:** completes LoD3 adding interior structures. For example, buildings are composed of rooms, doors, stairs and furniture.

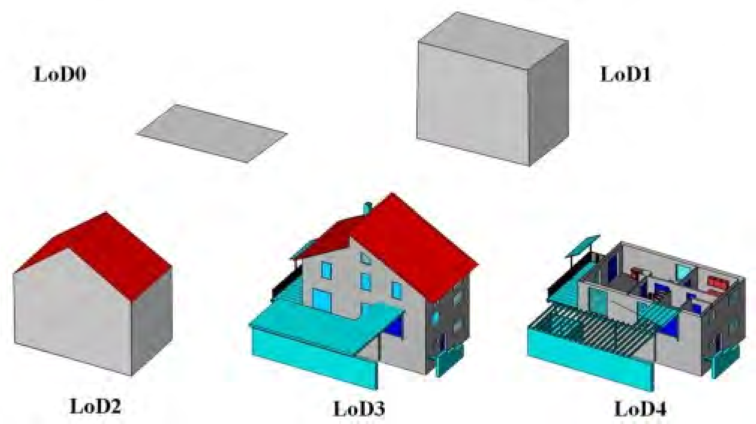

Figure 43: LoDs in CityGML. Source: (Gröger et al. 2012)

Coherence between semantics and geometry: CityGML represents the graphical appearance of city models and also semantic and thematic properties, taxonomies and aggregations. One of the most important design principles of CityGML is the coherent modelling of the semantic and geometrical properties. At the semantic level, real-world entities are represented by features such as buildings, walls, windows or rooms. The description also includes the attributes, relationships and hierarchies of aggregation between features. Thus, part of the relations between features can be obtained from the semantic level without geometry. The model consists of two hierarchies: semantics and geometric objects which are linked by relationships. The following figure shows this coherence.

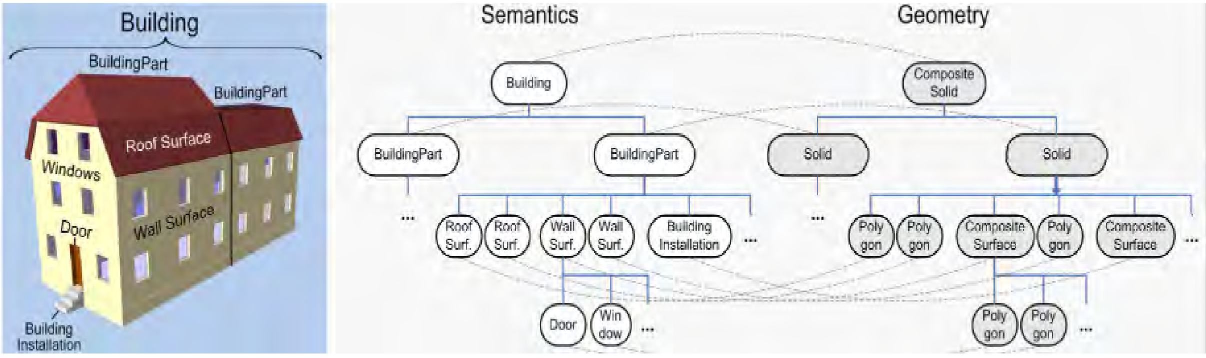

Figure 44 Coherence between semantics and geometry in CityGML. Source: (Gröger et al. 2012)

Extensibility: CityGML has been designed as a universal model of topographic information that defines the most general types of objects and attributes that are included in the applications at urban scale. However, in real applications of the model, objects or attributes that are not explicitly defined in CityGML can be necessary. This is covered by the extension of CityGML. CityGML provides two different ways for the extensibility of the model:

- → Generic objects and attributes: This concept allows the extension of CityGML applications without modifying the schema. Any object can be extended by additional attributes, whose names, data types and values can be provided by an application without any change in the CityGML schema. Similarly, the features that are not represented in CityGML predefined themes can be modeled using generic objects defined in CityGML.
- → Application Domain Extension (ADE): ADE extensions specify the additions to the CityGML data model required for a specific domain. Such additions include the introduction of new features to existing classes of CityGML (e.g. the number of inhabitants of a building or the definition of new objects types). The difference between ADEs and generic objects and attributes is that an ADE has to be defined in a new file that defines the XML schema with its own namespace. This file has to import explicitly the XML schema definition of the extended CityGML modules. The advantage of this approach is that the extension is formally specified. Extended documents can be validated against the schema of CityGML and ADE.

Interoperability: CityGML has many tools that allow viewing, editing, parsing, storing, importing, and exporting CityGML files. Some of the most relevant aspects of CityGML interoperability are shown in the following figure:

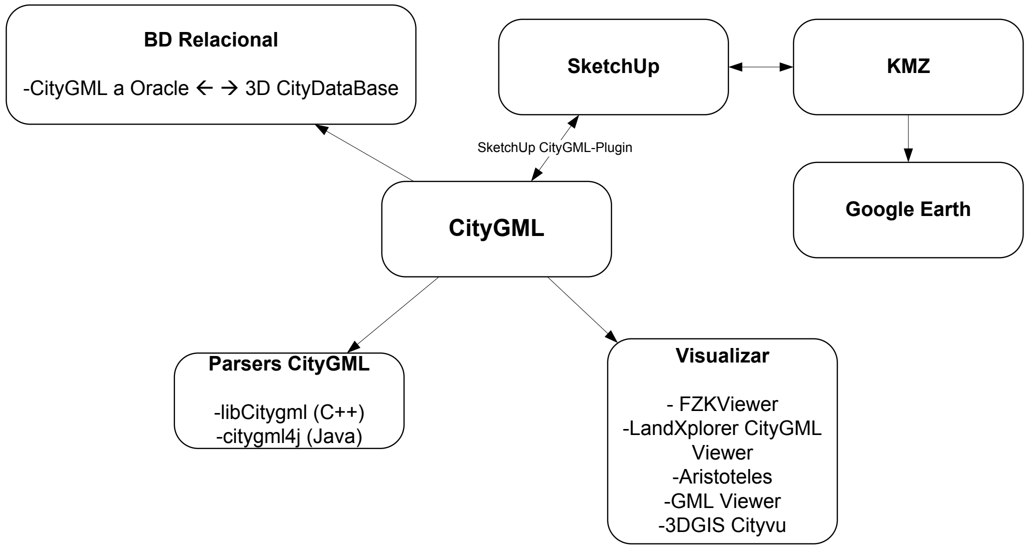

Figure 45: Interoperability of CityGML. Source : (Iñaki Prieto et al. 2012)

3.3 Identification of available data sources

In the EFFESUS project, within the task 1.1"Identification and collection of existing data"[56], the existing data sources on European historic building and urban stock were identified. Data sources were described, evaluated and listed. Based on that work, some considerations could be made about the data sources with applicability to the EFFESUS data model:

→ Information provided by the identified data sources can be classified into four main categories: geometric, building, energy and climate.

→ Most of the data sources at Worldwide or EU level provide statistical data. These data are disaggregated at country level, in any case presents statistics at regional or municipal level. National data sources provide information at regional or municipal level of detail.

→ There are several software platforms that provide images and geometry of buildings worldwide. The most relevant platforms are, Google Earth[57], Google Maps[58], Street View[59], Microsoft Virtual Earth 3D , Bing Maps[60] and OpenStreetMap[61]

→ The main source for the geometric information of the buildings is managed at national level and it is the cadastre of each country. Cadastre provides mostly information in 2D that can be displayed in a web browser. Cadastre information is mostly provided through the geographic

[56] EFFESUS (2013). Deliverable D1.1 – European building and urban stock data collection. EFFESUS Project (FP7/2012-2016 grant agreement n° 314678), 2014
[57] http://www.google.com/earth/
[58] https://www.google.es/maps
[59] https://www.google.com/maps/views/streetview
[60] http://www.microsoft.com/maps/
[61] https://www.openstreetmap.org

information services such as WMS (Web Map Service[62]) or WFS (Web Feature Service[63]). In some cases it is also possible to download some of the information in shape file format (SHP). This service is generally available in local language. The information associated with the geometry of the footprints is quite similar for all European countries but with specific structure for each country.

→ Regarding 3D geometric information, when exists, it is city-wide and is managed by the city itself. In Germany, most cities have a geometric model of the buildings in 3D, but in other countries this information is not so common. In any case these 3D city models are mainly geometric models and lack of semantics associated with such geometry. When the 3D model exists geometry can be used as a basis for the EFFESUS data model generation, in other cases the 3D model generation will use 2D data sources.

→ Different data sources analysed collect data with the inventory of historic buildings. Information collected in these data sources include, listed buildings, sites and monuments, the interventions carried out in the buildings, specific restrictions on buildings or historic sites, etc. Generally, this information is usually contained in reports of the municipal property and in some cases part of the information is accessible on request, although there are more and more cases where this information is accessible to the public by web platforms, frequently georeferenced.

→ The majority of energy data correspond to statistics or databases resulting from European projects completed or under development (ODYSSEE-MURE[64], REEGLE[65], TABULA-EPISCOPE[66], etc.). At the national level it is also possible to find statistical databases and other information about the different RES, suppliers, etc. In general, EP Certificates are not public available. The same is true for data from heating, gas, or energy providers. Therefore information can be collected only by asking building owners directly.

→ Each country has climate information through meteorological agencies. These agencies have the data they collect from meteorological stations located along the geography of each country. The most useful information provided by this data source corresponds to the values of parameters such as temperature, rainfall, sunshine hours, relative humidity, wind, solar radiation, etc. The information collected may be provided with different time ranges, seasonal averages, daily averages, means in a time slot, etc. These agencies also provide meteorological services for future weather forecast.

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[62] WMS: http://www.opengeospatial.org/standards/wms
[63] WFS: http://www.opengeospatial.org/standards/wfs
[64] http://www.odyssee-mure.eu/
[65] http://www.reegle.info/
[66] *Ibid 36*

3.4 EFFESUS multiscale data model for energy retrofitting of historic districts

As discussed before, the strategy on the scale of information is one of the main issues regarding the energy retrofitting of HUDs. The main element of DM, the building, can be reached from different perspectives. When the LoD of the required information regarding the building (and its elements) is very high, the proper approach for the representation of information is the operative one, that means the use of BIM. If the required LoD of information is lower and such information will be used just for decisions at strategic level, the most suitable approach falls within the urban scale alternatives.

However, the proper approach for dealing with the sustainable improvements of HUDs, being both an operative and a strategic problem, is a multiscale one. The scale of representation is going to be urban but medium/highly detailed information at building scale is going to be required too. As seen in the previous section, currently the only alternative of those presented that allows the representation of information at different scales on a single data model is CityGML.

3.4.1 Data model within the overall strategy

In Section 1.5 the methodological framework has been described. The information management and the multiscale data model are fundamental for this framework. The following figure shows the role of the data model in the overall strategy:

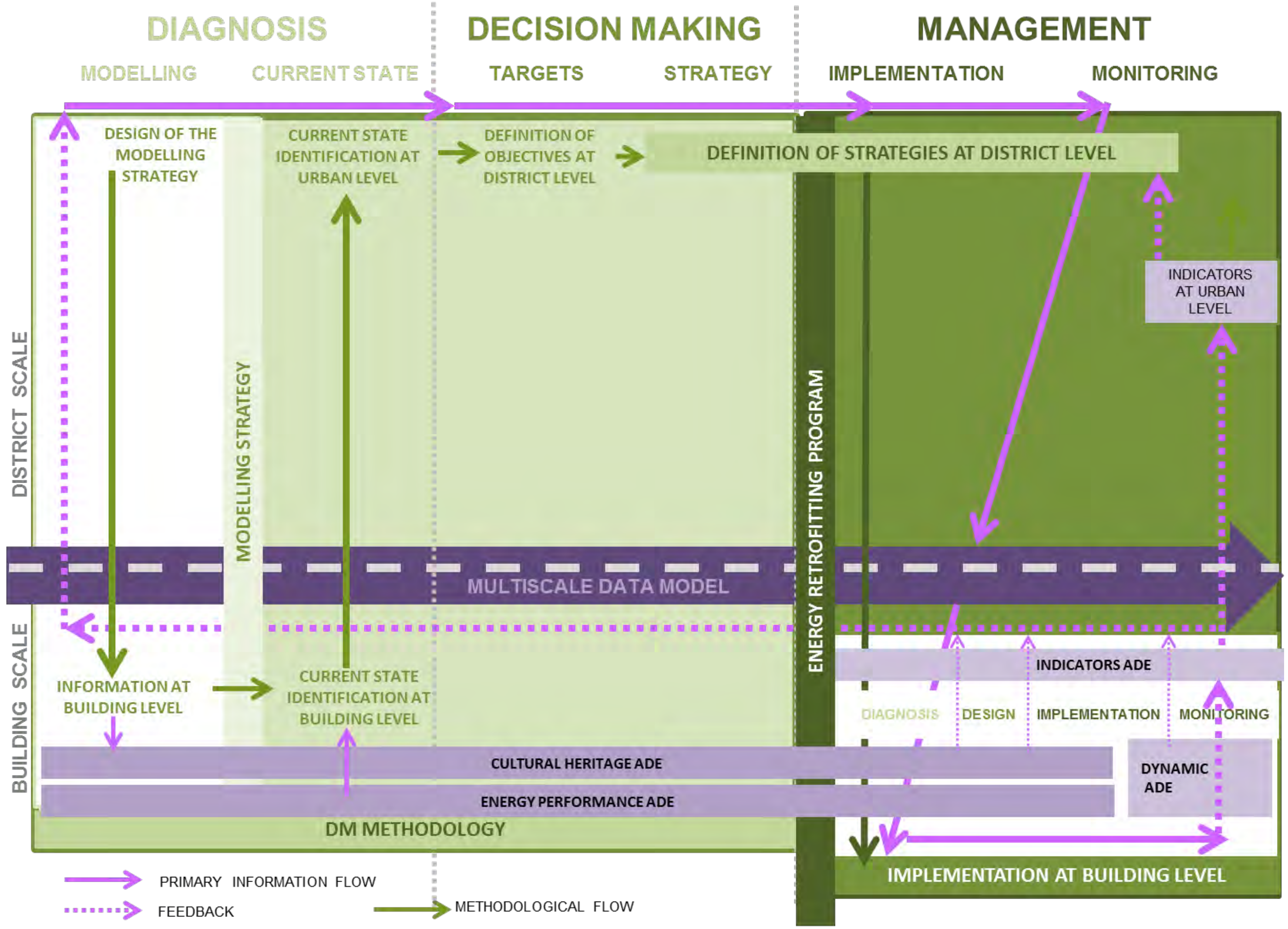


Figure 46: ADEs in overall methodology

Modelling phase

The first phase in the overall methodology is the modelling of the HUD. In Section 2.5 it has been discussed different strategies for modelling the HUD depending on the information availability. The first step for the modelling of the district through the use of the data model is always to generate the geometric information of the whole HUD in low detail. This can be made through a reasonably fast process as described in (Iñaki Prieto et al. 2012). After that, the semantic information will be introduced. The result of this step will allow the identification of building typologies and their representativeness for the extrapolation to district level. According to this identification the selection of sample buildings will be carried out in order to get a representation of each building typology. Once the representative buildings have been selected, next step is to complete the data model with detailed information for the sample buildings. The complete information of those buildings will be used to extrapolate the results to the whole district according to their representativeness.

The storage of all the required information is possible thanks to the implementation of domain extensions of the data model. As explained in Section 3.2.2, extensions can be implemented in the CityGML data model using the ADEs. There are two main disciplines involved in HUD´s energy retrofitting: cultural heritage and energy. Therefore, in order to support the framework and the DM methodology it is necessary specific extensions to organise the information regarding those two fields. Another two extensions have been designed with a more "utility" role in order to structure the information regarding indicators and dynamic data. In the modelling phase just three of them can be completed as the Dynamic data extension will be completed in the monitoring phase.

As a result of the modelling phase a multiscale data model of the historic district will be available. The model will provide enough representativeness of the district for the DM process and therefore for the definition of a retrofitting strategy at urban level.

Decision making phase

In the DM phase, the set of indicators are crucial for the definition of the objectives at urban level. Those indicators will be included also in the data model through an specific extension. The role that the data model plays in the DM process is to provide all the information that is necessary regarding the characteristics of the HUD, from urban level to component level. The information regarding the energy characteristics of the buildings, their HS values or the features of the fabric will be organized in the CH ADE and Energy ADE. Along with the information that the repository of solutions contains (see Section 3.5), this information will allow to assess the suitability and improvements of the different actions and to define the Energy Retrofitting Program at urban level. The multiscale nature of the model allows translating this strategy to the executive scale to set the objectives and the retrofitting strategy at this level.

Management phase

The Energy Retrofitting Program (see Section1.5.2) has to define the management phase. This phase includes the implementation of the strategies according to the previous phase and their monitoring. In this phase the data model will have a central role as the tool that ensures the continuous learning of the whole process. The strategies designed at urban level are translated to building level, setting the targets and the strategies for each building. With this information a detailed retrofitting project can be designed coherent with the overall strategy. The implementation of the strategies at building level will give the necessary feedback to the whole system in different ways using the multiscale data model as the core tool for the organization of this information. All the phases of the intervention at building level will generate new information about specific buildings that will complete the multiscale data model of the HUD as following:

→ The diagnosis carried out for the project will complete the information regarding the current state of the building in a very high detail. With enough numbers of buildings completed, the current state of the whole HUD could change and it could make possible to use DSS at LoDM III.

→ The design of the intervention will change the characteristics of the building so it has to be documented.

→ The implementation of the strategy will make possible the monitoring of the improvements using the indicators extension. This will allow the evaluation of the adopted strategies and therefore the refinement of the whole process (specially the DM phase).

The management phase will change the information stored in the different extensions, as the physical intervention in the buildings will change their characteristics, especially the extension for energy information, as the energy retrofitting is specially targeted to improve those characteristics. The extension regarding cultural heritage information could be also changed, as the analysis phase could change the HS assessment or correct the fabric compatibility assumptions.

The data model will keep the track of the different states of the buildings and the different interventions carried out. This feature (the fourth dimension) makes the data model an exceptional tool for the documentation of the HUD, one of the mandatory actions due to its cultural values. The following table shows the methods of monitoring of the different indicators in the management phase for the different LoDMs:

LEVELS OF DM						CRITERIA	MONITORING		
							MODEL		
Level		Accuracy		Scale		Category	Subcategory	Specific Indicator	Calculation
II	III	2	4	building		Habitability	Thermal comfort		Sensors
				building		Habitability	Acoustic comfort		Sensors
				building		Habitability	Visual comfort		Sensors
				building		Habitability	IAQ		Sensors
				building	district	Energy saving	Energy Saving		Billings
				building	district	Energy saving	Thermal energy use	Thermal energy use per m^2 building area	Billings
				building	district	Energy saving	Thermal energy use	Total use/year	Billings
				building	district	Energy saving	Electrical energy use	Total use/year	Billings
				building	district	Energy saving	Electrical energy use	Electricity use per m^2 building area	Billings
				building	district	Energy saving	CO_2 emissions	Total for a building or a district	DSS CALCULATION
				building	district	Economic feasibility	Cost of Retrofit Measures	Cost in euros	Not applied
				building	district	Economic feasibility	Value of energy saved	Value in euros	Billings
				building	district	Economic feasibility	Energy Payback Period	Payback time only taking account of cost of energy	DSS ESTIMATION
		3	5	building		Habitability	Thermal comfort	Temperature	Sensors/ simulation
				building		Habitability	Thermal comfort	Relative humidity	Sensors/ simulation
				building		Habitability	Thermal comfort	PMV	Simulation
				building		Habitability	Thermal comfort	PPD	with PMV
				building		Habitability	Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	Sensors/ simulation
				building		Habitability	Visual comfort	Mean maintained illuminance	Sensors
				building		Habitability	Visual comfort	Illuminance uniformity	Sensors
				building		Habitability	Visual comfort	Color rendering index (CRI) for lighting	Sensors
				building		Habitability	Visual comfort	Daylight factor	Sensors
				building		Habitability	IAQ	Pollutants	Sensors
				building		Habitability	IAQ	Microbial pollution	Sensors
				building		Habitability	IAQ	Ventilation rate	Sensors
				building	district	Energy saving	Thermal energy use	Total use/year	Billings/sensors
				building	district	Energy saving	Thermal energy use	Thermal energy use per m^2	DSS CALCULATION
				building	district	Energy saving	Electrical energy use	Total use/year	Billings/sensors
				building	district	Energy saving	Electrical energy use	Electricity use per m^2 building	Billings/sensors
				building	district	Energy saving	CO_2 emissions	Total for a building or a district	Sensors
				building	district	Energy saving	Peak power demand	Total for a building or a district	Sensors
				building	district	Energy saving	% RES	Fraction of energy supply from RES	Sensors
				building	district	Energy saving			
				building	district	Energy saving			
				building	district	Energy saving			
				building	district	Energy saving			
				building	district	Economic feasibility			
				building	district	Economic feasibility	Value of energy saved	Value in euros	Billings
				building	district	Economic feasibility	LCA (Life Cycle Analysis)	Combined Environmental Impact Indicator	Complex assessment procedure
				building	district	Economic feasibility	NPV (Net Present Value)	Value over time	Billings
				building	district	Economic feasibility	ROI	Efficiency of investment	Billings
				building	district	Economic feasibility	Overall Payback Period	Payback time taking account of all benefits	Billings
				building	district	Economic feasibility	Energy Payback Period	Payback time only taking account of cost of energy	Billings

Table 30: Indicators in the management phase

3.4.2 Information requirements for the EFFESUS data model

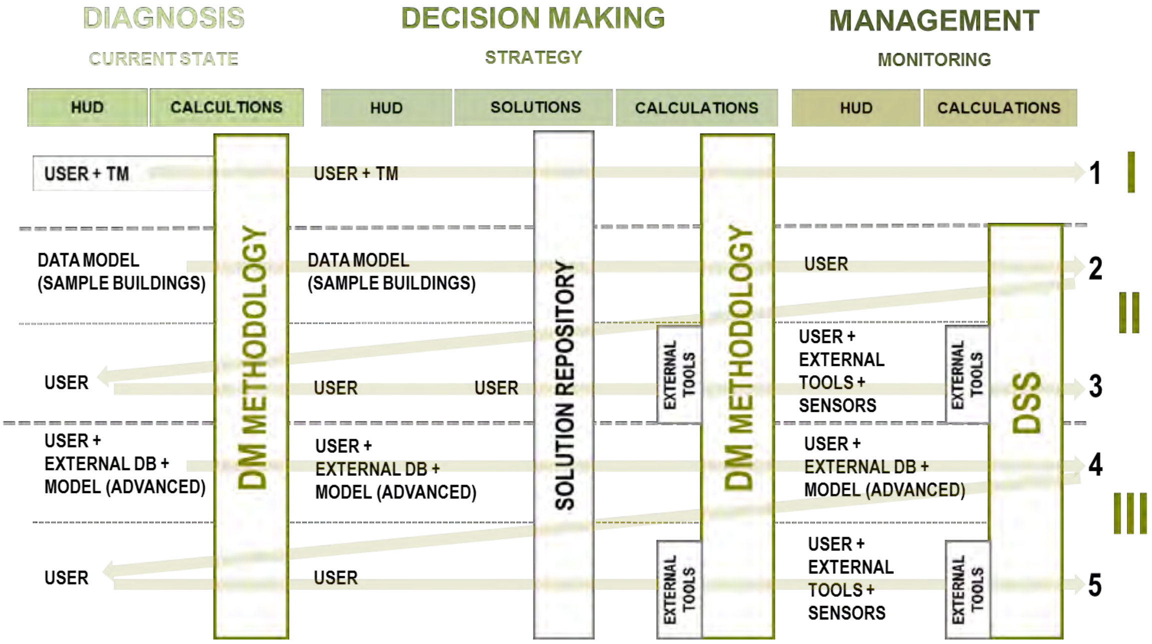


Figure 44: Information sources in different LoDM and accuracy levels

One of the main features of a CityGML data model, as explained before, is the coexistence between semantic information and geometry information at different levels. The geometric information could be stored in different LoDs and likewise the storage of semantic information could be of different natures. The different LoDs have been already explained in Section 3.2.2. The different categories of semantic information are the followings:

- **Generic information** regarding the HUD at urban, building or component level (e.g. year of construction, cadastre reference…)
- **Thematic information**, the static information regarding the cultural heritage and energy fields that usually will not change unless an intervention occurred.
- Information regarding **Indicators** necessary to compare the different scenarios and monitorize and assess the success of the implemented strategies at urban level.
- **Dynamic information** that usually change frequently as the data provided by sensors.

The geometric information and the generic semantic information could be added to the CityGML model itself, but the other three semantic categories required a specific extension to be included in the data model. As explained in Section 3.2.2, the generic CityGML model can be extended through ADEs with the information required for a specific domain. Accordingly four specific extensions are necessary to structure and store all the required information for the modelling, DM process and posterior management: two ADEs for the thematic information regarding EP and cultural heritage, another one for information regarding indicators and the fourth one for dynamic information.

In the next sections these four ADEs will be described in more detail.

Information requirements at LoDM II

At LoDM II the multiscale data model has to support the DM process through the identification of sample buildings besides of providing the data required for the methodology. At this level the information requirements are the followings:

→ Regarding the geometry the multiscale data model has to contain the geometric information of the whole historic district in low detail. At LoDM II from LoD0 to LoD2 can be required.

→ The model must include, at least, the information necessary for modelling purposes at this level. This information has to be enough to run the modelling strategy (see Section 2.5). consequently, the following parameters are required:

- Number of storeys
- Ground floor area
- Number of facades
- Year of construction
- Level of protection
- Use

→ In order to support the methodology, this level needs to have thematic information regarding energy and cultural heritage. That means that the information of the energy and cultural heritage extensions has to be completed for the sample buildings.

Information requirements at level III

At this level the methodology will be focused on buildings groups. Once the building group is selected, the Cultural Heritage and EP ADEs have to be fulfilled for a significant numbers of buildings within the group.

3.4.3 Application domain required information

As mentioned earlier, the required information for the whole methodological framework demands four specific extensions or ADEs:

→ The EP Domain Extension (Energy ADE)

→ The Cultural Heritage Domain Extension (Cultural Heritage ADE)

→ The Indicators Domain Extension (Indicators ADE)

→ The Dynamic Domain Extension (Dynamic ADE)

Energy Performance Domain Extension (Energy ADE)

The Energy ADE has the main purpose to store the information regarding the energetic parameters that will support the DM.

The Table 31 shows the main parameters identified for the Energy ADE, as well as representative information for each parameter (name of the variable, element at which the variable has effect, short description of the variable, main source for the data completion, values that the variable can take, only when they are a set of predefined values and unit in which the variable is measured)and if the parameter is part of the required minimum information (mandatory or not).

Category	Variable	Element	Description	Source	Values	Unit	Mandatory
Energy	Latitude	District	Latitude of the centroid of the district	Geometric		º	Yes
Energy	Longitude	District	Longitude of the centroid of the district	Geometric		º	Yes
Energy	Outside Min Temperature	District	Outside Min Temperature of the district	Climatic Database		ºC	Yes
Energy	Outside Max Temperature	District	Outside Max Temperature of the district	Climatic Database		ºC	Yes
Energy	Outside Average Temperature	District	Outside Average Temperature of the district	Climatic Database		ºC	Yes
Energy	Outside Average Temperature	District	Outside Average Temperature of the district	Climatic Database		ºC	Yes
Energy	Solar Radiation	District	Irradiation on horizontal surface	Climatic Database		W/m2	Yes
Energy	Average annual precipitation	District	Average annual precipitation of the district	Climatic Database		mm	Yes
Energy	Average relative humidity	District	Average relative humidity of the district	Climatic Database		%	Yes
Energy	Average annual number of sunshine hours	District	Average annual number of sunshine hours of the district	Climatic Database			Yes
Energy	Number of floors	Building	Number of floors of the building	Geometric			Yes
Energy	Foot print area	Building	Foot print area of the building	Geometric		m2	Yes
Energy	Volume	Building	Volume of the building	Geometric		m3	Yes
Energy	Thermal mass	Building	Thermal mass of the building	Expert Judgement	very light, light, medium, high, very light		Yes
Energy	Adjoining wall?	Boundary Surface/Wall	The wall is an adjoining wall?	Geometric			Yes
Energy	Wall Orientation	Boundary Surface/Wall	Orientation of the wall	Geometric			Yes
Energy	Wall Area	Boundary Surface/Wall	Area of the wall	Geometric		m3	Yes

Category	Variable	Element	Description	Source	Values	Unit	Mandatory
Energy	Wall Opaque Average U	Boundary Surface/Wall	Opaque Average U of the wall	Expert Judgement/ data base		W/m2·K	Yes
Energy	Wall Opening Average U	Boundary Surface/Wall	Opening Average U of the wall	Expert Judgement/ data base		W/m2·K	Yes
Energy	Wall % Openings	Boundary Surface/Wall	% Openings of the wall	Expert Judgement			Yes
Energy	Wall Thermal bridge	Boundary Surface/Wall	Thermal bridge of the wall	Expert Judgement/ data base			No
Energy	Wall Window Predominant Type	Boundary Surface/Wall	Window Predominant Type of the wall	Expert Judgement			No
Energy	Wall G-value	Boundary Surface/Wall	G-value of the wall	Expert Judgement/ data base			No
Energy	Roof Type	Boundary Surface/Roof	Type of the roof	Geometric			No
Energy	Roof Orientation	Boundary Surface/Roof	Orientation of the roof	Geometric			No
Energy	Roof Area	Boundary Surface/Roof	Area of the roof	Geometric		m3	Yes
Energy	Roof Opaque Average U	Boundary Surface/Roof	Opaque Average U of the roof	Expert Judgement/ data base		W/m2·K	Yes
Energy	Roof Opening Average U	Boundary Surface/Roof	Opening Average U of the roof	Expert Judgement/ data base		W/m2·K	Yes
Energy	Roof % Openings	Boundary Surface/Roof	% Openings of the roof	Expert Judgement			Yes
Energy	Roof Window Predominant Type	Boundary Surface/Roof	Window Predominant Type of the roof	Expert Judgement			No

Category	Variable	Element	Description	Source	Values	Unit	Mandatory
Energy	Roof G-value	Boundary Surface/Roof	G-value of the roof	Expert Judgement/ data base			No
Energy	Is the under roof floor climatizated?	Boundary Surface/Roof	Is the under roof floor climatizated?	Expert Judgement	Yes/No		Yes
Energy	Roof Slope	Boundary Surface/Roof	Roof Slope	Geometric			No
Energy	Ground Area	Boundary Surface/Ground	Area of the ground	Geometric		m3	Yes
Energy	Ground Opaque Average U	Boundary Surface/Ground	Opaque Average U of the ground	Expert Judgement/ data base		W/m2·K	Yes
Energy	Ground Minoration Coefficient	Boundary Surface/Ground	Minoration Coefficient of the ground	Expert Judgement/ data base			No
Energy	Comfort Tº (winter)	District	Comfort Tº (winter) of the district	Expert Judgement		ºC	Yes
Energy	Comfort Tº (summer)	District	Comfort Tº (summer) of the district	Expert Judgement		ºC	Yes
Energy	Set back Tº (winter)	District	Set back Tº (winter) of the district	Expert Judgement		ºC	Yes
Energy	Set back Tº (summer)	District	Set back Tº (summer) of the district	Expert Judgement		ºC	Yes
Energy	Use	Building	Use of the building	Expert Judgement/ data base			Yes
Energy	Ventilation strategy	Building	Building has a ventilation strategy?	Expert Judgement	Yes/No		No
Energy	Shadow strategy	Building	Building has a shadow strategy?	Expert Judgement	Yes/No		No
Energy	Occupancy	Building	Building occupancy	Expert Judgement /data base		people/m2	No

Category	Variable	Element	Description	Source	Values	Unit	Mandatory
Energy	Exist? Heating	IntBuildingInstallation	Exists heating?	Expert Judgement /data base	Yes/No		Yes
Energy	Heating Primary Energy	IntBuildingInstallation	Heating Primary Energy	Expert Judgement /data base	Biomass/Electricity/Gas		Yes
Energy	Heating Individual/Centralised	IntBuildingInstallation	Is Heating Centralised?	Expert Judgement /data base	Yes/No		Yes
Energy	Heating Efficiency	IntBuildingInstallation	Heating Efficiency	Expert Judgement /data base			No
Energy	Heating Type	IntBuildingInstallation	Heating Type	Expert Judgement /data base	Biomass - Cogenerator, Electricity - Heat pump with fan coil units, Electricity - Heat pump with ductwork, Electricity - Heat pump with underfloor heating, Gas - Low temperature boiler with radiators, Gas - Low temperature boiler with underfloor heating, Gas - Condensing boiler with radiators, Gas - Condensing boiler with underfloor heating, Gas - Boiler instant, Gas - Cogenerator		Yes
Energy	Exist? Cooling	IntBuildingInstallation	Exists cooling?	Expert Judgement	Yes/No		Yes

Category	Variable	Element	Description	Source	Values	Unit	Mandatory
				/data base			
Energy	Cooling Individual/Centralised	IntBuildingInstallation	Is Cooling Centralised?	Expert Judgement /data base	Yes/No		Yes
Energy	Cooling Efficiency	IntBuildingInstallation	Cooling Efficiency	Expert Judgement /data base			No
Energy	Cooling Type	IntBuildingInstallation	Cooling Type	Expert Judgement /data base	Electricity - Heat pump with fan coil units, Electricity - Heat pump with ductwork, Electricity - Heat pump with underfloor cooling		Yes
Energy	Exist? DHW	IntBuildingInstallation	Exists DHW	Expert Judgement /data base	Yes/No		No
Energy	DHW Primary Energy	IntBuildingInstallation	DHW Primary Energy	Expert Judgement /data base	Gasoil/Electricity/Gas		No
Energy	DHW Individual/Centralised	IntBuildingInstallation	Is DHW Centralised?	Expert Judgement	Yes/No		No
Energy	DHW Efficiency	IntBuildingInstallation	DHW Efficiency	Expert Judgement /data base			No
Energy	DHW Type	IntBuildingInstallation	DHW Type	Expert Judgement /data base	Electricity - Heat pump, Electricity - Caldera, Electricity - Instant hot, Electricity - Thermo instant, Electricity - Thermo by accumulation, Gas - boiler		No

Category	Variable	Element	Description	Source	Values	Unit	Mandatory
					with accumulator, Gas - Boiler mixed, Gas - Instant hot, Gas - Cogenerator, Diesel - Single		
Energy	Exist? RES	IntBuildingInstallation	Exists RES	Expert Judgement /data base	Yes/No		No
Energy	RES Type	IntBuildingInstallation	REST type	Expert Judgement /data base			No
Energy	RES % DHW demand covered	IntBuildingInstallation	RES % DHW demand covered	Expert Judgement			No
Energy	RES % heating demand covered	IntBuildingInstallation	RES % heating demand covered	Expert Judgement			No

Table 31: Application Domain Required Information for Energy Performance Extension

Cultural Heritage Domain Extension (CH ADE)

In this extension, it will be structured all information necessary to protect the cultural values of the HUD and to ensure that the chosen retrofitting strategy is compatible with its nature. The preservation of cultural values, the compatibility limits and regulations will be the constraints for the DM. So the role of this ADE, if fully completed, is to provide all information essential to avert choosing solutions that are detrimental for HS of the HUD, that are technically of physically incompatible or are not allowed.

Due to the complexity and importance of these issues a strategy for the simplification of the necessary data can be counterproductive. From this perspective, the identification of the required information in the cultural heritage domain has been focused on structuring and including all the data identified as essential in this sense. The user will have to take the decision about the level of completion of these data taking into account his/her expert judgement, the characteristics of the given HUD and the availability of the data. Anyway some guidelines could be provided to facilitate the task:

→ Usually it is not necessary to make the HS significance assessment regarding all possible values (visual, physical and spatial values). Selecting the most restrictive one could be necessary.

→ Most of the retrofit measures impact just in the whole building or in some of the main element. Frequently, the HS could be limited to those elements without losing significant information regarding the DM process at first stage. Those elements are the followings:

Scale	Total HS
District	0-4
Building	0-4
External wall	0-4
Roofs	0-4
Windows	0-4
Doors	0-4
Internal walls	0-4
Installations	0-4

Table 32: Simplified HS assessment

→ The fabric and building compatibility information is going to be used in LoDM III so it is not mandatory in the previous levels.

- In most of the cases, the regulations are going to be coherent with the HS assessment As the latter is more detailed, if no contradiction is detected, the process can run without the regulation information at a first stage.

The information that has been included falls within the following categories:

- information about the cultural value of the HUD at urban, building and component level
- information regarding the compatibility with the HUD
- general information regarding the regulations
- information necessary for the modelling strategies

The following table shows the main parameters identified for the CH ADE, as well as representative information for each parameter: name of the variable, element at which the variable has effect, short description of the variable, main source for the data completion and values that the variable can take, only when they are a set of predefined values a range.

Category	Variable	Element	Description	Source	Values
Historic	Name of the building	Building	Name of the building	Available Database	
Historic	Year of construction	Building	Year of construction of the building	Available Database	
Historic	Reference number	Building	Unique reference number of the building	Available Database	
Historic	Historic type	Building	Historic type of the building	Expert Judgement /data base	
Historic	Historic category	Building	Historic category of the building	Expert Judgement /data base	
Historic	Main material	Building	Main material of the building	Expert Judgement /data base	
Historic	Main Material	Boundary Surface	Main material of the boundary surface	Expert Judgement /data base	
Historic	Main construction techniques	Building	Main construction techniques of the building	Expert Judgement /data base	
Historic	Construction techniques	Boundary Surface	Construction techniques of the boundary surface	Expert Judgement /data base	
Historic	Coating material	Boundary Surface	Coating material of the boundary surface	Expert Judgement /data base	
Historic	Integrity of the building	Building	Integrity of the building	Expert Judgement /data base	demolished, ruined, rehabilitated
Historic	Physical state of the building	Building	Physical state of the building	Expert Judgement /data base	good, medium, poor

Category	Variable	Element	Description	Source	Values
Historic	Historical summary	Building	Historical summary of the building	Expert Judgement /data base	
Historic	Visual value Settlement pattern	District	Visual value of the Settlement pattern	Expert Judgement /data base	0-4
Historic	Physical value Settlement pattern	District	Physical value of the Settlement pattern	Expert Judgement /data base	0-4
Historic	Spatial value Settlement pattern	District	Spatial value of the Settlement pattern	Expert Judgement /data base	0-4
Historic	Visual value Roof-scape	District	Visual value of the Roof-scape	Expert Judgement /data base	0-4
Historic	Physical value Roof-scape	District	Physical value of the Roof-scape	Expert Judgement /data base	0-4
Historic	Spatial value Roof-scape	District	Spatial value of the Roof-scape	Expert Judgement /data base	0-4
Historic	Visual value River / canal / waterfront / seascape	District	Visual value of the River / canal / waterfront / seascape	Expert Judgement /data base	0-4
Historic	Physical value River / canal / waterfront / seascape	District	Physical value of the River / canal / waterfront / seascape	Expert Judgement /data base	0-4
Historic	Spatial value River / canal / waterfront / seascape	District	Spatial value of the River / canal / waterfront / seascape	Expert Judgement /data base	0-4
Historic	Visual value Streetscape	District	Visual value of the Streetscape	Expert Judgement /data base	0-4

Category	Variable	Element	Description	Source	Values
Historic	Physical value Streetscape	District	Physical value of the Streetscape	Expert Judgement /data base	0-4
Historic	Spatial value Streetscape	District	Spatial value of the Streetscape	Expert Judgement /data base	0-4
Historic	Visual value Public open spaces	District	Visual value of the Public open spaces	Expert Judgement /data base	0-4
Historic	Physical value Public open spaces	District	Physical value of the Public open spaces	Expert Judgement /data base	0-4
Historic	Spatial value Public open spaces	District	Spatial value of the Public open spaces	Expert Judgement /data base	0-4
Historic	Visual value Curtilage	District	Visual value of the Curtilage	Expert Judgement /data base	0-4
Historic	Physical value Curtilage	District	Physical value of the Curtilage	Expert Judgement /data base	0-4
Historic	Spatial value Curtilage	District	Spatial value of the Curtilage	Expert Judgement /data base	0-4
Historic	Visual value Walls	Building	Visual value Walls of the Building	Expert Judgement /data base	0-4
Historic	Physical value Walls	Building	Physical value Walls of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Walls	Building	Spatial value Walls of the Building	Expert Judgement /data base	0-4
Historic	Visual value Roofs	Building	Visual value Roofs of the Building	Expert Judgement /data base	0-4
Historic	Physical value Roofs	Building	Physical value Roofs of the Building	Expert Judgement /data base	0-4

Category	Variable	Element	Description	Source	Values
Historic	Spatial value Roofs	Building	Spatial value Roofs of the Building	Expert Judgement /data base	0-4
Historic	Visual value Roof features	Building	Visual value Roof features of the Building	Expert Judgement /data base	0-4
Historic	Physical value Roof features	Building	Physical value Roof features of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Roof features	Building	Spatial value Roof features of the Building	Expert Judgement /data base	0-4
Historic	Visual value Windows	Building	Visual value Windows of the Building	Expert Judgement /data base	0-4
Historic	Physical value Windows	Building	Physical value Windows of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Windows	Building	Spatial value Windows of the Building	Expert Judgement /data base	0-4
Historic	Visual value Shading devices	Building	Visual value Shading devices of the Building	Expert Judgement /data base	0-4
Historic	Physical value Shading devices	Building	Physical value Shading devices of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Shading devices	Building	Spatial value Shading devices of the Building	Expert Judgement /data base	0-4
Historic	Visual value Doors	Building	Visual value Doors of the Building	Expert Judgement /data base	0-4
Historic	Physical value Doors	Building	Physical value Doors of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Doors	Building	Spatial value Doors of the Building	Expert Judgement /data base	0-4

Category	Variable	Element	Description	Source	Values
Historic	Visual value Balconies	Building	Visual value Balconies of the Building	Expert Judgement /data base	0-4
Historic	Physical value Balconies	Building	Physical value Balconies of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Balconies	Building	Spatial value Balconies of the Building	Expert Judgement /data base	0-4
Historic	Visual value Porches	Building	Visual value Porches of the Building	Expert Judgement /data base	0-4
Historic	Physical value Porches	Building	Physical value Porches of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Porches	Building	Spatial value Porches of the Building	Expert Judgement /data base	0-4
Historic	Visual value Shopfront	Building	Visual value Shopfront of the Building	Expert Judgement /data base	0-4
Historic	Physical value Shopfront	Building	Physical value Shopfront of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Shopfront	Building	Spatial value Shopfront of the Building	Expert Judgement /data base	0-4
Historic	Visual value Building General	Building	Visual value of the Building	Expert Judgement /data base	0-4
Historic	Physical value Building General	Building	Physical value of the Building	Expert Judgement /data base	0-4
Historic	Spatial value Building General	Building	Spatial value of the Building	Expert Judgement /data base	0-4
Historic	Visual value common use space	Common Areas	Visual value of the common use space	Expert Judgement /data base	0-4

Category	Variable	Element	Description	Source	Values
Historic	Physical value common use space	Common Areas	Physical value of the common use space	Expert Judgement /data base	0-4
Historic	Spatial value common use space	Common Areas	Spatial value of the common use space	Expert Judgement /data base	0-4
Historic	Visual value common use interior finishes	Common Areas	Visual value of the common use interior finishes	Expert Judgement /data base	0-4
Historic	Physical value common use interior finishes	Common Areas	Physical value of the common use interior finishes	Expert Judgement /data base	0-4
Historic	Spatial value common use interior finishes	Common Areas	Spatial value of the common use interior finishes	Expert Judgement /data base	0-4
Historic	Visual value common use internal walls	Common Areas	Visual value of the common use internal walls	Expert Judgement /data base	0-4
Historic	Physical value common use internal walls	Common Areas	Physical value of the common use internal walls	Expert Judgement /data base	0-4
Historic	Spatial value common use internal walls	Common Areas	Spatial value of the common use internal walls	Expert Judgement /data base	0-4
Historic	Visual value common use ceilings	Common Areas	Visual value of the common use ceilings	Expert Judgement /data base	0-4
Historic	Physical value common use ceilings	Common Areas	Physical value of the common use ceilings	Expert Judgement /data base	0-4
Historic	Spatial value common use ceilings	Common Areas	Spatial value of the common use ceilings	Expert Judgement /data base	0-4
Historic	Visual value common use doors	Common Areas	Visual value of the common use doors	Expert Judgement /data base	0-4
Historic	Physical value common use doors	Common Areas	Physical value of the common use doors	Expert Judgement /data base	0-4

Category	Variable	Element	Description	Source	Values
Historic	Spatial value common use doors	Common Areas	Spatial value of the common use doors	Expert Judgement /data base	0-4
Historic	Visual value private use space	Dwelling	Visual value of the private use space	Expert Judgement /data base	0-4
Historic	Physical value private use space	Dwelling	Physical value of the private use space	Expert Judgement /data base	0-4
Historic	Spatial value private use space	Dwelling	Spatial value of the private use space	Expert Judgement /data base	0-4
Historic	Visual value private use interior finishes	Dwelling	Visual value of the private use interior finishes	Expert Judgement /data base	0-4
Historic	Physical value private use interior finishes	Dwelling	Physical value of the private use interior finishes	Expert Judgement /data base	0-4
Historic	Spatial value private use interior finishes	Dwelling	Spatial value of the private use interior finishes	Expert Judgement /data base	0-4
Historic	Visual value private use internal walls	Dwelling	Visual value of the private use internal walls	Expert Judgement /data base	0-4
Historic	Physical value private use internal walls	Dwelling	Physical value of the private use internal walls	Expert Judgement /data base	0-4
Historic	Spatial value private use internal walls	Dwelling	Spatial value of the private use internal walls	Expert Judgement /data base	0-4
Historic	Visual value private use ceilings	Dwelling	Visual value of the private use ceilings	Expert Judgement /data base	0-4
Historic	Physical value private use ceilings	Dwelling	Physical value of the private use ceilings	Expert Judgement /data base	0-4
Historic	Spatial value private use ceilings	Dwelling	Spatial value of the private use ceilings	Expert Judgement /data base	0-4

Category	Variable	Element	Description	Source	Values
Historic	Visual value private use doors	Dwelling	Visual value of the private use doors	Expert Judgement /data base	0-4
Historic	Physical value private use doors	Dwelling	Physical value of the private use doors	Expert Judgement /data base	0-4
Historic	Spatial value private use doors	Dwelling	Spatial value of the private use doors	Expert Judgement /data base	0-4
Historic	Presence of water-soluble salts in concerned fabric	Boundary Surface	Presence of water-soluble salts in concerned fabric	Expert Judgement	Neglectable, Minimal, Somewhat, Significant
Historic	Presence of water-soluble salts in concerned environments	Boundary Surface	Presence of water-soluble salts in concerned environments	Expert Judgement	Neglectable, Minimal, Somewhat, Significant
Historic	Presence of metals in concerned fabric	Boundary Surface	Presence of metals in concerned fabric	Expert Judgement	Neglectable, Minimal, Somewhat, Significant
Historic	Presence of corrosion-causing substances in the concerned fabric	Boundary Surface	Presence of corrosion-causing substances in the concerned fabric	Expert Judgement	Neglectable, Minimal, Somewhat, Significant
Historic	Presence of moisture in the concerned environment	Boundary Surface	Presence of moisture in the concerned environment	Expert Judgement	Neglectable, Minimal, Somewhat, Significant
Historic	Capability of vapour transport of concerned fabric	Boundary Surface	Capability of vapour transport of concerned fabric	Available Database	Neglectable, Minimal, Somewhat, Significant
Historic	Capability of liquid transport of concerned fabric	Boundary Surface	Capability of liquid transport of concerned fabric	Available Database	Neglectable, Minimal, Somewhat, Significant
Historic	Salt resistance of concerned fabric	Boundary Surface	Salt resistance of concerned fabric	Available Database	Neglectable, Minimal, Somewhat, Significant

Category	Variable	Element	Description	Source	Values
Historic	Frost resistance of near surface layer of concerned exterior fabric	Boundary Surface	Frost resistance of near surface layer of concerned exterior fabric	Available Database	Neglectable, Minimal, Somewhat, Significant
Historic	Spare load capacity of concerned fabric	Boundary Surface	Spare load capacity of concerned fabric	Available Database	Neglectable, Minimal, Somewhat, Significant
Historic	Thermal expansion coefficient of concerned fabric	Boundary Surface	Thermal expansion coefficient of concerned fabric	Available Database	Neglectable, Minimal, Somewhat, Significant
Historic	Resistance to mechanical damage of concerned fabric	Boundary Surface	Resistance to mechanical damage of concerned fabric	Available Database	Neglectable, Minimal, Somewhat, Significant
Historic	Formal protection	Building	Formal protection of the building	Regulations	Listed, General Law, District plans, None
Historic	Formal protection	Boundary Surface	Formal protection of the boundary surface	Regulations	Listed, General Law, District plans, None
Historic	CH Law Restrictions	Building	CH Law Restrictions of the building	Regulations	Allowed, No changes, Some visible/material changes may be allowed, No restrictions
Historic	CH Law Restrictions	Boundary Surface	CH Law Restrictions of the boundary surface	Regulations	Allowed, No changes, Some visible/material changes may be allowed, No restrictions

Table 33: Application Domain Required Information for Cultural Heritage Extension

Indicators extension

As explained before, the indicators regarding *building and urban fabric compatibility* and *HS and conservation principles* have been considered as constraints for the DM process since they are no characteristics to be "improved" or that could be trade off in the DM process rather than aspects that have to be maintained and assured. The information these indicators provide barely would be altered during the rehabilitation process due to its nature, although could be updated due to more accurate information. Thus, they have been included as required information of the CH ADE, as properties of the own building/district.

The role of the Indicators Extension is to structure the indicators of the other categories (Indoor environmental conditions, Embodied energy, Operational energy and Economic return) at building and at district level in order to compare the different scenarios and assess the success of the implemented strategies at urban level. The information provided by the indicators can be interdependent to other indicators from other extensions. Therefore, this extension will not function as separated group and their information would be dependent on continuous feedback from the other extensions.

The Table 35 shows the main parameters identified for the Indicators ADE, as well as representative information for each parameter as: category of the variable, name of the variable, element at which the variable has effect, short description of the variable, main source for the data completion and values that the variable can take (only when they are a set of predefined values a range).

Category	Variable	Element	Description	Source	Values
Indoor Environmental Conditions	Temperature	Dwelling	Room temperature	Dynamic	
Indoor Environmental Conditions	Relative humidity	Dwelling	Room relative humidity	Dynamic	
Indoor Environmental Conditions	Predicted mean vote (PMV)	Dwelling	Predicts the mean response of a larger group of people according to the ASHRAE thermal sensation scale	Dynamic	From -3 to +3
Indoor Environmental Conditions	Predicted percentage dissatisfied (PPD)	Dwelling	The PPD is a function of PMV	Predicted Mean Value (PMV)	0-100
Indoor Environmental Conditions	Indoor ambient noise levels in unoccupied spaces	Dwelling	Average sound pressure level over 30 minutes	Dynamic	
Indoor Environmental Conditions	Mean maintained illuminance	Dwelling	Average value of illuminance on a surface	Dynamic	
Indoor Environmental Conditions	Illuminance uniformity	Dwelling	Ratio between minimum and average illuminance on a surface	Dynamic	
Indoor Environmental Conditions	Colour rendering index (CRI) for lighting	Dwelling	Effect of light source on perceived colours of objects ad surfaces	Expert Judgement	100 point scale
Indoor Environmental Conditions	Daylight factor	Dwelling	Ratio between illuminance from skylight on horizontal surface within the room and illuminance from skylight on horizontal plane exposed to skylight	Dynamic	
Indoor Environmental Conditions	TVOC Pollutants	Dwelling	Measurement of TVOC concentration	Dynamic	
Indoor Environmental Conditions	Carbon Pollutants	Dwelling	Measurement of CO and CO2 concentrations	Dynamic	

Category	Variable	Element	Description	Source	Values
Indoor Environmental Conditions	Nitrogen Pollutants	Dwelling	Measurement of NO2 concentration	Dynamic	
Indoor Environmental Conditions	PM Pollutants	Dwelling	Measurement of PM2,5 and PM10 concentrations	Dynamic	
Indoor Environmental Conditions	Microbial pollution (perceived by dampness)	Dwelling	Perception of persistent dampness and/or presence of condensation on surfaces or in structures	Expert Judgement	0-4
Indoor Environmental Conditions	Microbial pollution (perceived by odour)	Dwelling	Microbial growth, visible or odour perceived of mould	Expert Judgement	0-4
Indoor Environmental Conditions	Microbial pollution (perceived by water damage)	Dwelling	History of water damage, leakages or penetrations	Expert Judgement	0-4
Indoor Environmental Conditions	Ventilation rate	Dwelling	Ventilation for pollution	Dynamic	
Embodied Energy	Building Total primary energy consumption (over 100 years)	Building	Primary energy consumption on the building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	Building Total primary energy consumption (over 100 years) per year	Building	Primary energy consumption on the building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	Building Total carbon emissions (over 100 years)	Building	Carbon emissions related building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	Building Total carbon emissions (over 100 years) per year	Building	Carbon emissions related building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	Building Total primary energy saving (over 100 years)	Building	Primary energy saved due to the interventions. New interventions should be added.	Available Database	

Category	Variable	Element	Description	Source	Values
Embodied Energy	Building Total primary energy saving (over 100 years) per year	Building	Primary energy saved due to the interventions. New interventions should be added.	Available Database	
Embodied Energy	Building Total carbon saving (over 100 years)	Building	Carbon emissions saved due to the interventions. New interventions should be added.	Available Database	
Embodied Energy	Building Total carbon saving (over 100 years) per year	Building	Carbon emissions saved due to the interventions. New interventions should be added.	Available Database	
Operational Energy	Building Electrical energy use per year	Building	The information will be taken from the electricity meters	Dynamic	
Operational Energy	Building Electrical energy use per year and per m2 building area	Building	The information will be taken from the electricity meters and building information	Dynamic	
Operational Energy	Building Thermal energy use (heating and cooling) per year	Building	Electricity/gas/fuel consumption is needed (related to heating and cooling). Devices' database.	Dynamic	
Operational Energy	Building Thermal energy use (heating and cooling) per year and per m2 building area	Building	Electricity/gas/fuel consumption is needed (related to heating and cooling). Devices' database.	Dynamic	
Operational Energy	Building CO2 emissions	Building	This index is calculated by means of database and energy use	Dynamic	
Operational Energy	Building Peak power demand	Building	Hourly power demand	Dynamic	
Operational Energy	Building %RES: Electric	Building	Fraction of electrical energy supply from renewable energy sources.	Dynamic	
Operational Energy	Building %RES: Thermal	Building	Fraction of thermal energy supply from renewable energy sources.	Dynamic	
Embodied Energy	District Total primary energy	District	Primary energy consumption on the building/district erection. Subsequent	Available Database	

Category	Variable	Element	Description	Source	Values
	consumption (over 100 years)		interventions are included.		
Embodied Energy	District Total primary energy consumption (over 100 years) per year	District	Primary energy consumption on the building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	District Total carbon emissions (over 100 years)	District	Carbon emissions related building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	District Total carbon emissions (over 100 years) per year	District	Carbon emissions related building/district erection. Subsequent interventions are included.	Available Database	
Embodied Energy	District Total primary energy saving (over 100 years)	District	Primary energy saved due to the interventions. New interventions should be added.	Available Database	
Embodied Energy	District Total primary energy saving (over 100 years) per year	District	Primary energy saved due to the interventions. New interventions should be added.	Available Database	
Embodied Energy	District Total carbon saving (over 100 years)	District	Carbon emissions saved due to the interventions. New interventions should be added.	Available Database	
Embodied Energy	District Total carbon saving (over 100 years) per year	District	Carbon emissions saved due to the interventions. New interventions should be added.	Available Database	
Operational Energy	District Electrical energy use per year	District	The information will be taken from the electricity meters	Dynamic	
Operational Energy	District Electrical energy use per year and per m2 building area	District	The information will be taken from the electricity meters and building information	Dynamic	
Operational Energy	District Thermal energy use (heating and cooling) per year	District	Electricity/gas/fuel consumption is needed (related to heating and cooling). Devices' database.	Dynamic	

Category	Variable	Element	Description	Source	Values
Operational Energy	District Thermal energy use per year and per m2 building area	District	Electricity/gas/fuel consumption is needed (related to heating and cooling). Devices' database.	Dynamic	
Operational Energy	District CO2 emissions	District	This index is calculated by means of database and energy use	Dynamic	
Operational Energy	District Peak power demand	District	Hourly power demand	Dynamic	
Operational Energy	District %RES: Electric	District	Fraction of electrical energy supply from renewable energy sources.	Dynamic	
Operational Energy	District %RES: Thermal	District	Fraction of thermal energy supply from renewable energy sources.	Dynamic	
Economic Return	Cost of retrofit measures	Building	Cost in euros of the retrofit measures	Available Database	
Economic Return	Value of energy saved	Building	Value in euros saved by means of the retrofit measures	Available Database	
Economic Return	Life cycle analysis (LCA)	Building	Combined environmental impact indicator	Available Database	
Economic Return	Net Present Value (NPV)	Building	Measures the total amount and investment is expected to increase	Available Database	
Economic Return	Return on Investment (ROI)	Building	This indicator measures the efficiency of the investment	Available Database	
Economic Return	Overall payback period	Building	Payback time taking account of all the benefits	Available Database	
Economic Return	Energy payback period	Building	Payback time only taking account of cost of energy	Available Database	
Economic Return	Public domain benefits: GDP	Building	Value of the influence of the interventions in the GDP	Available Database	
Economic Return	Public domain benefits: Health care costs	Building	Value of the influence of the interventions in the health care costs	Available Database	
Economic Return	Public domain benefits: health benefits	Building	Value of the influence of the interventions in the health benefits	Available Database	

Table 34: Application Domain Required Information for Indicators Extension

Dynamic data Extension

Domain specific requirements for the data model (See Section 3.1.3) identified as requirement the feature of representing temporal information to track changes, updates or interventions along the time. The dynamic nature of those data suggest to create an independent extension This extension aims to structure the dynamic data that change frequently and that feed some of the indicators used to monitor the compliance of the objectives defined within the retrofitting strategy.

The frequency of updating these data will vary depending on the data and have to be established in the Energy Retrofitting Program in the management phase. Most of the dynamic indicators are directly related to indoor environmental conditions and they are usually assessed by sensors installed within the buildings. It could be interesting to carry out a continuous monitoring of the indoor conditions in order to elaborate a historical chart of the indoor conditions of the entire district. Some of these dynamic indicators could even be the aim of the implemented rehabilitation measures, e.g. the relative humidity of rooms. The rest of the indicators identified for the dynamic data extension are related to energy use.

The following table shows the main parameters identified for the dynamic data extension, as well as representative information for each parameter (name of the variable, element at which the variable has effect, short description of the variable, main source for the data completion and values that the variable can take (only when they are a set of predefined values a range).

Category	Variable	Element	Description	Source	Values	Unit
Dynamic	Air Temperature	Dwelling	There are several ways to measure the room temperature. Some variables consider the effect of the wetness or radiation.	Device - Dry Bulb Thermometer	10-40	ºC
Dynamic	Wet-bulb Temperature (Twb)	Dwelling	There are several ways to measure the room temperature. Some variables consider the effect of the wetness or radiation.	Device - Wet Bulb Thermometer	10-40	ºC
Dynamic	Relative Humidity	Dwelling	Modern electronic devices use temperature of condensation (the dew point), or changes in electrical capacitance or resistance to measure humidity differences.	Device - Hygrometer	0-100	
Dynamic	Mean Radiant Temperature	Dwelling	The black-globe thermometer consists of a black globe in the center of which is placed a temperature sensor such as the bulb of a mercury thermometer, a thermocouple or a resistance probe.	Device - Black Globe Thermometer	10-40	ºC
Dynamic	Air velocity	Dwelling	Depending on the type of application, air velocity meters are made as hot wire air velocity meters or pocket weather air velocity meters, both of which can measure air speed and air pressure	Device - Air velocity meter	0-5	
Dynamic	Superficial Temperature	Dwelling	This parameter it is necessary to assess several indicators, such as radiant temperature asymmetry or Heat Stress Index	Device - Superficial Thermometer	0-40	
Dynamic	Indoor ambient noise levels in unoccupied spaces	Dwelling	Measures sound pressure level	Device - Sound level meter	0-120	
Dynamic	Reverberation Time	Dwelling	It is the time required for reflections of a direct sound to decay 60 dB. Reverberation time is frequently stated as a single value, however, it can be measured more precisely in narrow bands.	Device - Chronometer		

Category	Variable	Element	Description	Source	Values	Unit
Dynamic	Structural vibration at low frequencies	Dwelling	Structural vibration can be measured by electronic sensors that convert vibration motion into electrical signals. By analysing the electrical signals, you can learn about the nature of the vibration. Signal analysis is generally divided into time and frequency domains; each domain provides a different view and insight into the nature of the vibration.	Device - Electronic sensors		
Dynamic	Frequency-Weighted Acceleration	Dwelling	The frequency-weighted acceleration calculates how intensive mechanical vibrations affect the human body at the workplace or in vehicles. The result values are a frequency-weighted vibration signal or a floating root mean square, also called K-value.	Device - Electronic sensors		
Dynamic	Illuminance	Dwelling	Illuminance is the total luminous flux incident on a surface, per unit area. It is a measure of how much the incident light illuminates the surface, wavelength-weighted by the luminosity function to correlate with human brightness perception.	Device - Lux meter		
Dynamic	Luminance	Dwelling	Luminance is the measure of light radiating from a source, measured in candela per square meter. Luminance is perceived by the human viewer as the brightness of a light source. In the assessment of light pollution, luminance can be used to assess glare, up-light and spill-light.	Device - Digital camera		
Dynamic	Organic and inorganic pollutants concentration	Dwelling	Each pollutant has a different sensor to be measured.	Device - Pollution measuring instruments		
Dynamic	Ventilation rate	Dwelling	Tracer gases can be used to measure the ventilation rate in buildings. The gases used are odourless, nontoxic and typically used at concentrations in the range of parts per billion (ppb) to part per million (ppm).	Device - Blower door, tracer gas, flow hoods, and VAV box measurements		
Dynamic	Electrical energy use	Dwelling	It measures the amount of electric energy consumed by a residence, business,	Device - Electricity meter		

Category	Variable	Element	Description	Source	Values	Unit
			or an electrically powered device.			
Dynamic	Gas/butane/propane energy use	Dwelling	Flow measurement is the quantification of bulk fluid movement. Flow can be measured in a variety of ways. Positive-displacement flow meters accumulate a fixed volume of fluid and then count the number of times the volume is filled to measure flow	Device - Flow measurement		
Dynamic	Fuel energy use	Dwelling	Flow measurement is the quantification of bulk fluid movement. Flow can be measured in a variety of ways. Positive-displacement flow meters accumulate a fixed volume of fluid and then count the number of times the volume is filled to measure flow	Device - Flow measurement		

Table 35: Application Domain Required Information for Dynamic Extension

3.5 Repository of solutions

The structure of the repository of EEIM and RES described in Section 2.2.2 has to be coherent with the whole methodology but specially with the multiscale data model in order to enable a logical match of information. The information regarding the HUD (included in the data model) and the information regarding the possible actions (repository) have to share a common architecture in order to evaluate the suitability of specific actions for specific HUDs.

The matching points are going to be of two kinds:

- → Spatial: each solution that is stored in the repository has to be linked to the element it has impact on, so the system can match actions with HUD elements.
- → Semantic: an attribute from a measure within the repository will impact in corresponding attributes in a building or element. Usually this attribute is the one it is intended to improve for its consequences in the EP or other criteria. For example, the insulation of a wall will change the U value of this wall improving its thermal characteristics. The base value of the U will come from the attributes of this wall in the multiscale data model; the repository will provide the new U value for the estimation of the improvements.

The following table shows the minimum information requirements for each action of the repository:

	CRITERIA	INDICATORS	INFORMATION IN THE REPOSITORY
		Element of impact	Element where the measure is going to impact
INDICATORS	Habitability and indoor environment quality	Thermal comfort	0-4 scale
		Acoustic comfort	0-4 scale
		Visual comfort	0-4 scale
		IAQ	0-4 scale
	Energy saving	Energy use	New value of the U
			New value of the U
			New thermal bridge
			New type
			New G value
			New value of the U
			New value of the U
			New type
			New G value
			The solution climatized the under roof?
			The solution is a ventilation strategy?
			The solution is a shadow strategy?
			The solution is a heating system?
			New heating primary energy
			The solution is a centralised heating system?
			New heating efficiency
			New heating type
			The solution is a cooling system?
			The solution is a centralised cooling system?
			New cooling efficiency
			New cooling type
			The solution is a DHW system?
			New DHW primary energy
			The solution is a centralised DHW system?
			New DHW efficiency
			New DHW type
		RES	The solution is a RES
			New RES type
			New RES %
	Economic feasibility	Cost in euros	Relative Cost
		Value in euros	Energy Saving Potential
CONSTRAINTS	HS	Impact on visual HS	0-4
		Impact on spatial HS	0-4
		Impact on physical HS	0-4
	Compatibility	Reactivity of measure when in contact with salts	0-4
		Content of corrosive materials in the measure	0-4
		Reactivity of corroding and/or corrosive substances at measure surface	0-4
		Capability of liquid transport of concerned measure	0-4
		Capability of vapour permeability of concerned measure	0-4
		Impact on hygrothermal performance	0-4
		Weight of the measure	0-4
		Flexibility of the measure	0-4
		Damage caused by removal of measure	0-4

Table 36: Information requirements in the repository

3.6 Implementation of the data model

The EFFESUS data model has been implemented within the EFFESUS project[67] for the case study of Santiago de Compostela. In the Chapter 4 it can be seen in detail the implementation in of the model and the results (see specifically Section 4.8.1 for the results).

[67] EFFESUS (2014). Deliverable D1.5 –Multiscale data model. EFFESUS Project (FP7/2012-2016 grant agreement n° 314678), 2014

4 IMPLEMENTATION

I may not have gone where I intended
to go, but I think I have ended up
where I needed to be
Douglas Adams,
The Long Dark Tea-Time of the Soul

4.1 The case study of Santiago de Compostela

Santiago de Compostela has been selected as the case study for the implementation of the methodology. Santiago de Compostela is a city located in the north-west of Spain with around 100.000 inhabitants, whose historic centre was declared World Heritage Site by UNESCO in 1985.

4.1.1 Scope and urban context

The area selected as case study is the area traditionally called the "Almendra" due its form and it coincides with the area that was historically inside the walls (see Figure 47). Initially 819 buildings have been considered within this area.

Figure 47: Historic District of Santiago de Compostela (Source: Google)

4.1.2 Regulations

A detailed description of the regulations regarding the preservation of the buildings of the HUD of Santiago de Compostela can be found in Section 2.1 of (Liñares Mendez 2012). An analysis regarding the heritage constrains and restrictions for the architectural integration of photovoltaic systems in the same area can also be found in (Lucchi et al. 2014). The following milestones can be highlighted:

- → In December of 1985 the historic centre of Santiago de Compostela was declared Cultural Asset of Universal Interest by UNESCO.
- → In 1994 the "Oficina de rehabilitación de la Ciudad Histórica de Santiago" was created. This Technical Office was born with the mission of designing and developing the rehabilitation program for the urban renovation of the historic city centre. Some of the fundamental principles that guided this project were a strong citizen-centred vision, the natural integration of the rehabilitation policies in the everyday life, the attempt to avoid solely repressive policies and the trust on a culture of maintenance (Ramos Guallart et al. 2002).
- → In 1997, it was approved the "Plan especial de protección e rehabilitación da cidade histórica" (Special Protection and Rehabilitation Plan for the Historic City Core of Santiago de Compostela) although the diagnosis and the basic information was generated previous to 1990. This plan was developed following what was established in the Spanish Historical Heritage Law (1985) and in the aforementioned "Plan General Municipal de Ordenación de Santiago de Compostela" (1989). The goal was to address the preservation, and the restructuration of the old town. The plan defined a comprehensive rehabilitation program where the *preservation of housing and improvement of the living conditions of the citizens* and the *conservation of the built heritage* were two of its main goals.

Regarding the objectives of this research it is important to highlight the way that these regulations classified the level of protection of the buildings as they can be linked to the HS. The *Plan Especial* (PE) classifies the buildings in five levels of protection from 0 to 4. The buildings considered as level 0 of protection are considered as not listed and are divided in two categories in compliance or not with the urban image of the HUD (type 1 and 2). The other four categories are the buildings considered as listed and the level of protection goes from 1 (the highest) to the 4 (the lowest) as following:

- → Monumental buildings of outstanding value are classified with a value of 1.
- → Buildings of singular features and of major value are protected within the level 2.
- → The buildings with special features regarding architecture and environment have a level of protection of 3.
- → And finally, the interesting buildings in the urban context are classified as a level of protection of 4.

The following table summarizes the intervention allowed according to the protection of the building as seen in (Liñares Mendez 2012):

Protection level / Interventions (I)	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Type	*Restauración*	*Restauración* *Conservación* *Rehabilitación*	*Conservación* *Rehabilitación*	*Conservación* *Rehabilitación* Partial *Reestructuración* Global *Reestructuración*
General I allowable	*Rehabilitación* Partial *Reestructuración*	Partial *Reestructuración* Global *Reestructuración* for restitution	Partial *Reestructuración* Global *Reestructuración* (spreadsheet)	Global *Reestructuración* (spreadsheet)
Conservation		Entrance Stairs	Entrance (spreadsheet) Stairs (spreadsheet)	Entrance (spreadsheet) Stairs (spreadsheet)
State of ruin		Global *Reestructuración*	*Reestructuración total* Replacement structural elements	Global *Reestructuración* Replacement structural elements *Ampliación* (*PE*)
Particular I allowed	Partial *Restauración*	Partial *Conservación* *Rehabilitación* *Consolidación*	Partial *Conservación* *Rehabilitación* Volumetric reconfiguration (spread)	Partial *Conservación* *Rehabilitación* Volumetric reconfiguration (spread)

Table 37: Interventions allowed according to protection of buildings. Source: (Liñares Mendez 2012))

4.1.3 Description of the elements

District

The clear layout of the historic part of Santiago of Compostela is a reflection of its topography with the main streets going along the more easy topography (North/South) crossed by the secondary streets with an East/West direction.

Buildings

A detailed analysis about the original constructive type of the buildings of Santiago de Compostela and its evolution can be found in (Guallart Ramos et al. 2002). In the second chapter the two main urban layouts are described: the *rueiro* housing and the *medieval* housing. In the selected area there are mainly buildings of the second type. The buildings were built within two granitic walls that form a layout of parallel lines perpendicular to the main streets. Those buildings have usually two or three floors with a width that ranges from 4 to 7 meters. The original structural concept was based on a light structure of wood (often reused wood) within the granitic walls. The facade was of masonry in the first floor and of wood in the upper floors. The pitched roofs, wooden structures covered with tiles, had originally their gables facing the streets but later a parallel solution was adopted as a better solution for the collection of rain.

Elements

The following table summarised the description of the different elements of the building of the HUD of Santiago using the information of (Guallart Ramos et al. 2002) as seen in (Méndez, 2012).

Element	Material	Description	Observations	Thickness (m)	U value (W/m²C)
Facade	Granite stone	Two layers of masonry with a filling of earth or small pieces	Sometimes they have a protecting external finishing of lime mortar	0,6	2,3
	Timber walls			0,044	2,75
Adjoining wall	Granite stone	Pieces of granite stone mixed with smalls pieces to fill the gaps *(Cachotes)*	Very altered from their origins	0,6	2,3
Roof	Wooden structure covered with tile			0,124	1,31
Windows	Singled glazing without framing	External aligned with the facade	High infiltrations but wooden shutters produces a buffering effect	0,1	5,6
	Singled glazing with wooden frame	Internal window	High infiltration lower buffering effect	0,1	5,6

Table 38: Description of the HUD´s elements of Santiago de Compostela

4.2 List of solutions

As described in Section 2.2.3 in EFFESUS project a repository of solutions was developed in order to provide the information about the different EEIM and RES technologies to the DM process. For testing purposes, a simplified adaptation of this repository has been used, with the technologies that fit better to our case. For simplification reasons the RES have not been considered. The structure of the EFFESUS repository has been adapted to the methodology and the resulting strategies for potential scenario generation (see Section 2.7.4) are the following:

CODE	STRATEGY	CODE	SUB-STRATEGY
1	**People and management**	11	Improve the energy management
2	**Passive solutions**	21	Improve the airtightness
		22	Insulation of the walls
		23	Improve the windows
		24	Insulation of the roof
3	**Active solutions**	31	HVAC enhancement
		32	Electric equipment

Table 39: Structure of the solutions for the generation of scenarios

In the next table the considered solutions are shown with their impact on the HS and in the different criteria:

RETROFIT MEASURE					IMPACT ON THE BUILDING					IMPACT ON INDICATORS				
ID	STRATEGY	SUB-STRATEGY	CODE	RETROFIT MEASURE	Element of impact	Visual impact	Physical impact	Spatial impact	TOTAL IMPACT	LIS	TC	IAQ	ES	Cost
1	1	11	**111**	**Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants**	Building general	0	0	0	**0**	4	2	2	2	2
2	1	11	**112**	**Instal energy monitoring and management system**	Building general	1	0	0	**1**	3	2	0	3	4
3	2	21	**212**	**Sealimg of all openings and joints**	Building general	0	2	0	**2**	2	1	3	2	4
4	2	21	**213**	**Airtightness of windows**	Windows	2	2	0	**2**	2	1	3	1	3
5	2	21	**214**	**Chimney dampers and closers**	Building general	0	0	0	**0**	4	2	1	1	4
6	2	21	**215**	**Instal draught lobby at external doors**	Doors	3	3	4	**4**	0	1	1	1	3
7	2	21	**216**	**Airtightness membrane to underside roof**	Roofs	1	2	0	**2**	2	1	0	1	3
8	2	22	**221**	**Exterior insulation with a composite system 10 cm**	External wall	3	4	3	**4**	0	4	0	4	1
9	2	22	**222**	**Exterior insulation with ventilated cavity**	External wall	4	2	4	**4**	0	4	0	4	0
10	2	22	**223**	**Exterior insulation with insulation plaster 5 cm**	External wall	3	4	1	**4**	0	2	0	2	2
11	2	22	**224**	**Diffusion closed interior insulation 10 cm (mineral wool)**	Internal wall	3	4	2	**4**	0	3	0	4	1
12	2	22	**225**	**Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm**	Internal wall	3	4	2	**4**	1	3	0	3	2
13	2	22	**226**	**Insulation of an existing cavity 5cm (perlite)**	External wall	0	1	0	**1**	3	2	0	2	2
14	2	23	**231**	**Instal high performance window and glazing systems**	Windows	4	3	1	**4**	0	3	3	3	1
15	2	23	**232**	**Install secondary double glazing with wooden frame and shutters**	Windows	3	2	2	**3**	1	3	3	1	3
16	2	24	**241**	**Thermal insulation of the rooftop (20 mm)**	Roofs	0	1	1	**1**	2	0	0	4	2
17	2	24	**242**	**Thermal insulation of the rooftop (40 mm)**	Roofs	0	1	1	**1**	2	0	0	4	1
18	3	31	**311**	**Install a new gas boiler**	Installations	0	2	2	**2**	2	0	0	3	2
19	3	31	**312**	**Install a condensing boiler**	Installations	0	2	2	**2**	2	0	0	1	3
20	3	32	**321**	**Instal low energy lighting**	Installations	3	2	2	**3**	1	0	0	2	2
21	3	32	**322**	**Instal low energy appliances**	Installations	3	2	2	**3**	1	0	0	2	2
22	3	32	**323**	**Instal power conditioner / voltage optimiser**	Building general	0	0	0	**0**	4	0	0	1	1

Table 40: List of solutions

4.3 Calculation Assumptions

The main data source for the completion of the information has been the information contained in the PE, especially the database created as result of the updating of the information contained in the PE that was made in September of 2009. As complementary data source the research of (Liñares Mendez 2012) has been used.

4.3.1 Heritage significance

HUD has to be assessed regarding its HS at urban, building and element scale and regarding their visual, spatial and physical values. As seen in Section 2.4.2, the scale goes from 0 to 4 as follows:

- → 0= Neutral or negative significance
- → 1= Minor significance
- → 2= Major significance
- → 3= Outstanding significance
- → 4= Exceptionally outstanding significance

This assessment has to be done by expert judgement. In the case of Santiago in order to carry on this assessment mainly the data from PE has been used. For urban values it has been considered de maximum as Santiago de Compostela is an UNESCO site. The following table shows the correlation between the source values (PE and UNESCO) and the adopted value for the DM methodology:

Scale	Source	Considered source value		Adopted HS value for DM	Comments
District	UNESCO	UNESCO site		4	
Building	PE	Monumental buildings of outstanding value	1	4	
	PE	Building of singular features and of major value	2	3	
	PE	Buildings with special features regarding architecture and environment	3	2	
	PE	Interesting buildings in the urban context	4	1	
	PE	Not listed	0	0	
Elements	PE	Exceptional	E	3	
	PE	Common	C	2	If the global HS of the building is 4, 3 or 2
	PE	Common	C	1	If the global HS of the building is 1 or 0
	PE	Missing Value	N	0	
	PE	Decontextualized Value	D	0	

Table 41: Correlation between source values and values adopted for DM methodology

4.3.2 Energy performance and savings

As mentioned in the methodology the energy performance of the building has been assessed considering mainly the international standard ISO 13790:2008 ("Energy performance of buildings- Calculation of energy use for space heating and cooling"), based on a quasi-steady state monthly method. The following assumptions have been made:

- → The building has been treated as a single zone and with residential use.
- → Due to the residential use and the characteristic of the case study low internal gains have been considered (2W/m^2).
- → For the *thermal transmission properties* of the envelope the values found in (Liñares Mendez 2012)have been used.
- → For climate data monthly typical day values have been used.
- → For the *Thermal Mass* value a four values scale has been considered: very low (100 kJ/m2·K), low (200 kJ/m2·K), medium (300 kJ/m2·K) and high (400 kJ/m2·K).
- → For *Air Infiltration* a five values scale has been used considering the airtightness of the building: very high (0.2 air changes), high (0.75 air changes), usual (1 air changes), low (1.5 air changes) and very low (3 air changes). It has been taken into account that a traditional building needs to be ventilated at a higher rate than a modern building, usually around 0.8 to 1.0 air changes (English Heritage 2008), therefore high levels of airtightness have been not been pursued.
- → The *Thermal Bridge factor* has been considered to have no impact, therefore a value of 1 (f=1) has been used.
- → Regarding the electric demand, just lighting has been considered for simplification purposes. An estimation of 2 kWh/m^2 has been considered based on the type of building and the climatic zone (Idae 2011).

4.4 Modelling the Historic Urban District of Santiago de Compostela

4.4.1 Generation of 3D geometry

Within the EFFESUS project a multiscale data model of Santiago de Compostela has been implemented. The 3D geometry generation was generated following the methodology described in (Iñaki Prieto et al. 2012). Data used for the generation of the 3D geometry and data sources are presented in the following table:

Data	Institution	Source
Digital Terrain Model (DTM)	Spanish National Geographic Institute	CNIG[68]
Orthophotographs	Spanish National Geographic Institute	PNOA[69]
Building Footprints	Spanish Cadaster	General Directorate for Cadaster[70]
Constructions Data	Spanish Cadaster	General Directorate for Cadaster
LiDAR	Spanish National Geographic Institute	CNIG
Roads	Spanish National Geographic Institute	Cartociudad[71]
Green Areas	Spanish National Geographic Institute	Cartociudad
Textured 3D Models		Freelance modeler

Table 42 Data sources for 3D urban model of the historic district of Santiago de Compostela

Although, the whole process is described in detail in one of the deliverables of the project EFFESUS ("D1.5: Multiscale data management model"[72], it is worthy to describe the approach for generating the geometry of the buildings due to its importance for the methodology:

→ **Building Footprints:** it has been developed the 3D models of the buildings for the whole city of Santiago de Compostela in LoD1 (See Figure 48) but the buildings of the HUD have been generated in LoD2 (See Figure 50).

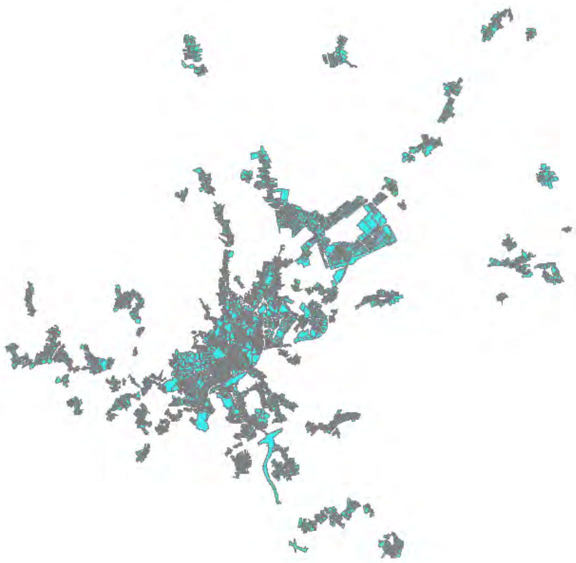


Figure 48: Parcel of the Municipality of Santiago de Compostela

[68] Centro Nacional de Información Geográfica: https://www.cnig.es/
[69] Plan Nacional de Ortofotografía Aerea: http://www.ign.es/PNOA/
[70] Dirección General del Catastro: http://www.catastro.meh.es/
[71] Cartociudad: http://www.cartociudad.es/visor/
[72] *Ibid 67*

Figure 49: Buildings in the HUD of Santiago de Compostela

Figure 50: Footprints of buildings for LoD2

→ **Construction data:** Several useful data about the buildings are provided by Spanish cadastre for each municipality. Among others, this file contains information on the number of floors of each building. From 2D geometry building walls are generated (assuming an average height of 3 meters on each floor) and also the building roof. This information has been used for the development of the whole city of Santiago de Compostela in LoD1.

→ **LiDAR:** It includes the point cloud defining the surface (including vegetation and buildings), with an average density of 0.5 points/m2 (1 point every 2 m^2). LiDAR data has been obtained for the whole city of Santiago de Compostela. File format has been converted to ASCII file with x, y and z coordinates. This information has been used only for the development of the LoD2 of the buildings of the HUD. LiDAR information is especially useful for identification of roof typologies.

As a result of the generation process the following geometric information is included in the EFFESUS data model of Santiago de Compostela:

Element	LoD	Description
Digital Terrain Model (DTM)	LoD0	Textured DTM of the urban area of Santiago de Compostela and its surroundings
Roads	LoD0	Roads / Streets of the urban area of Santiago de Compostela and its surroundings
Green Areas	LoD0	Green areas of the urban area of Santiago de Compostela and its surroundings
Buildings	LoD1	All parcels of the city of Santiago de Compostela represented by building cubes with the average height of the buildings in the parcel. EFFESUS data model includes 18.298 buildings in LoD1.
	LoD2	All buildings of the historic district of Santiago de Compostela represented by independent facades and roof (including typology). EFFESUS data model includes 1.249 buildings in LoD2. Roof type and building height have been obtained from the LiDAR data. For the generation of the LoD2 of the buildings geometry it has been used the platform novaF ACTORY[73], which is being developed into the i-scope[74] project.

Table 43: Summary of the geometric information included in the EFFESUS data model of Santiago

[73] NovaFACTORY: http://www.moss.de/english/products/novafactory/3d-pro-module/
[74] I-scope Project: http://www.iscopeproject.net/

4.4.2 Generation of semantic data

In the multiscale urban information model, as important as the geometric information is the multiscale semantic information. In a first stage, this information has to be already available or easily acquired. Official public databases usually are the best source to get the information regarding the buildings in this first stage.

In September 2009 it was updated and enriched the information regarding the buildings of the HUD of Santiago that was contained in the "Plan Especial de Protección e Rehabilitación da Cidade Histórica" and in the "Ordenación Urbanística e Catálogo do Plan Especial" (1992-1993). The result was a very comprehensive database containing very specific and complete information for each building of Santiago´s HUD. In this first stage, it has been used just a little percentage of this information. Just the information that will be easily found in the majority of the European HUDs as it has been seen in Section 3.3. The other main data source at building level has been Spanish cadastre. Some of its data have been processed to automatically be included in the data model.

Most of the parameters at district level are obtained from the climate database of the Spanish meteorological agency and are manually introduced into the data model. Part of the semantic data introduced in the data model are included in the CityGML core, some of them are included into the domain extensions (EP and Cultural Heritage). Some of the data included are the following:

- → **Reference number:** Each building has a unique reference number called cadastral reference and it is used as the unique identifier of the building. The reference number of the building has been obtained from the Spanish cadastre database.
- → **Footprint Area:** Represents the total area of the building footprint. The area of the building is the addition of the areas of all the construction elements of the parcel with height higher than 0 meters (excluding garden, porch, pool, etc.).
- → **Volume:** Represents the volume of the building. To calculate the volume of the building the area has been multiplied with the average height of the construction elements of the building.
- → **Storeys above ground:** Represents the number of storeys of the building. This information is obtained from the PE data base. This data is the average value of the number of floors of each of the construction elements that make up the building.
- → **Measured height:** Represents the average height of the building. For buildings in LoD1, this information has been estimated taking as reference that each building floor is an average of three meters high. For those buildings in LoD2, the value has been obtained from LiDAR.
- → **Year of construction:** Year of construction of each building is obtained from the PE database

- **Class, Function, Use:** These three data represents the type of building in CityGML. In order to assign a CityGML class, function and usage values a matching between Spanish cadastre usage and CityGML code lists (Gröger et al. 2012) has been made.
- **Name, description of the building:** Name and description of the building contains the same information at this moment. The description of the building includes the following information: type of street, name of the street, house number, municipality, province and cadastral parcel. (*e.g. RU CIDADETRANSPORTEF 10 - SANTIAGODECOMPOSTELA - ACORUÑA - 9714430NH3591D*
- **Roof type:** Building in LoD2 contains information about the roof type (flat roof, monopitch roof, gabled roof, hipped roof, etc.).
- **Roof Slope:** Building in LoD2 contains information about the slope of the roof.
- **Latitude and Longitude:** The latitude and longitude have been manually introduced for the district using the data provided by cadaster.
- **Outside Min, Max and Average Temperature:** Represent average values for temperatures in the district. Data have been taken during 30 years from the nearest weather station to the historic city of Santiago de Compostela.
- **Average Annual Precipitation, Average Relative Humidity and Average Annual Number of Sunshine Hours:** Represent average values for other climatic values in the district. Data have been taken during 30 years from the nearest weather station to the historic city of Santiago de Compostela.
- **Level of protection:** Level of protection of each building is obtained from the PE database.

Table 44 summarizes the semantic those data included in the EFFESUS data model of Santiago de Compostela and presents the following information for each of the semantic data included in the EFFESUS data model of Santiago:

- element at which the parameter has effect
- extension to which the parameter belongs
- name of the parameter in EFFESUS data model (included in extensions or CityGML core)
- database from which the parameter has been obtained
- specific data source which provided the parameter
- if the data was automatically process or manually introduced into the data model
- key parameters for the categorization of the buildings and typology generation

Element	Extension	Parameter	Database	Source	Process	Categorization
Building	Heritage	Reference Number	Spanish Cadaster	General Directorate for Cadaster[75]	Automatically	
Building	Energy	Footprint Area	Spanish Cadaster	General Directorate for Cadaster	Automatically	
Building	Energy	Volume	Spanish Cadaster	General Directorate for Cadaster	Automatically	Key parameter
Building	CityGML Core	Storeys Above Ground	Plan Especial	Santiago Municipality	Automatically	Key parameter
Building	CityGML Core	Measured Height	Spanish Cadaster	General Directorate for Cadaster	Automatically	
			Spanish Geographic Institute	CNIG[76]	Automatically	
Building	Heritage	Year Of Constructions	Plan Especial	Santiago Municipality	Automatically	Key parameter
Building	CityGML Core	Class	Spanish Cadaster	General Directorate for Cadaster	Automatically	
Building	CityGML Core	Function	Spanish Cadaster	General Directorate for Cadaster	Automatically	
Building	Energy	Use	Plan Especial	Santiago Municipality	Automatically	Key parameter
Building	Heritage	Name of the building	Spanish Cadaster	General Directorate for Cadaster	Automatically	
Building	CityGML Core	Description	Spanish Cadaster	General Directorate for Cadaster	Automatically	
Building	CityGML Core	Roof Type	Spanish	CNIG	Automatically	Key parameter

[75] Dirección General del Catastro: http://www.catastro.meh.es/
[76] Centro Nacional de Información Geográfica: https://www.cnig.es/

Element	Extension	Parameter	Database	Source	Process	Categorization
			Geographic Institute			
Building	CityGML Core	Roof Slope	Spanish Geographic Institute	CNIG	Automatically	
Building	Heritage	Level of protection	Plan Especial	Santiago Municipality	Automatically	Key parameter
District	Heritage	Latitude	Spanish Cadaster	General Directorate for Cadaster	Manually	
District	Heritage	Longitude	Spanish Cadaster	General Directorate for Cadaster	Manually	
District	Energy	Outside Min Temperature	Climate DB	Spanish Meteorological Agency[77]	Manually	
District	Energy	Outside Max Temperature	Climate DB	Spanish Meteorological Agency	Manually	
District	Energy	Outside Average Temperature	Climate DB	Spanish Meteorological Agency	Manually	
District	Energy	Average Annual Precipitation	Climate DB	Spanish Meteorological Agency	Manually	
District	Energy	Average Relative Humidity	Climate DB	Spanish Meteorological Agency	Manually	
District	Energy	Average Annual Number Of Sunshine Hours	Climate DB	Spanish Meteorological Agency	Manually	

Table 44: Semantic data included in the EFFESUS data model of Santiago de Compostela

[77] AEMET: http://www.aemet.es/

4.4.3 Statistical overview of the historic urban district for parameters and threshold selection

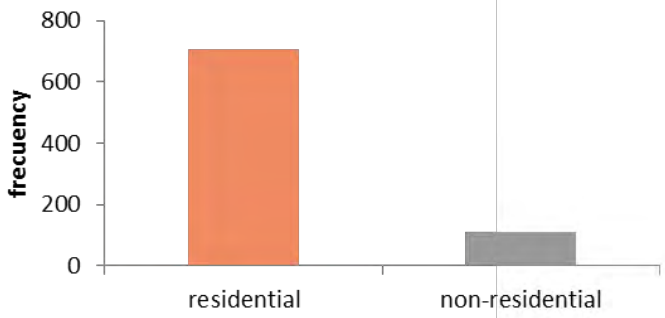
Once the semantic information has been completed some of the parameters will be used for the building categorization and typology generation. As seen in Section 2.7.2, the first step is to have an overview of the HUD regarding the key parameters that have influence in the HS and the EP. As it was justified in the abovementioned section those parameters are the followings: use of the building, number of facades, year of construction, volume, and level of protection.

Each HUD has its own building stock characteristics distribution; therefore it is necessary to choose the right parameters and threshold to obtain a right number of typologies with a good representatively of the building stock. As explained before the tool for this process will be histograms of the frequency of each parameter and maps to see the geographic distributions.

In the following sections each parameter will be analysed for the case of Santiago in order to select the final parameters and thresholds.

Use of the building

The use of each building has been classified in residential and non-residential. In the following figures it can be seen the frequency and the spatial distribution of this parameter.



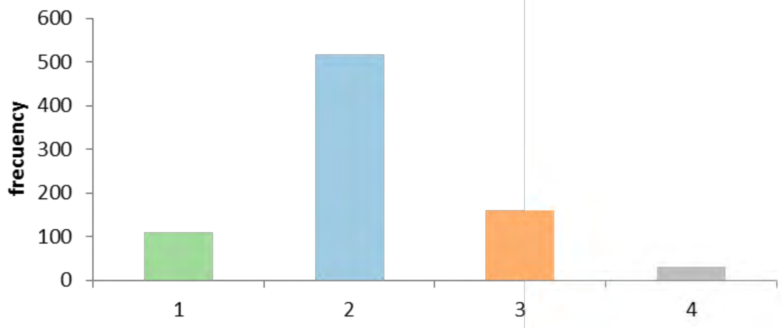
use	number of buildings	code	colour
residential	707	1	
non-residential	112	2	

Figure 51: Frequency and spatial distributions of the residential and non-residential buildings

As this research is focused in residential buildings this parameter has been used to discard the non-residential buildings (112 buildings)

Number of facades

The following figures show the frequency and the spatial distribution of this parameter:

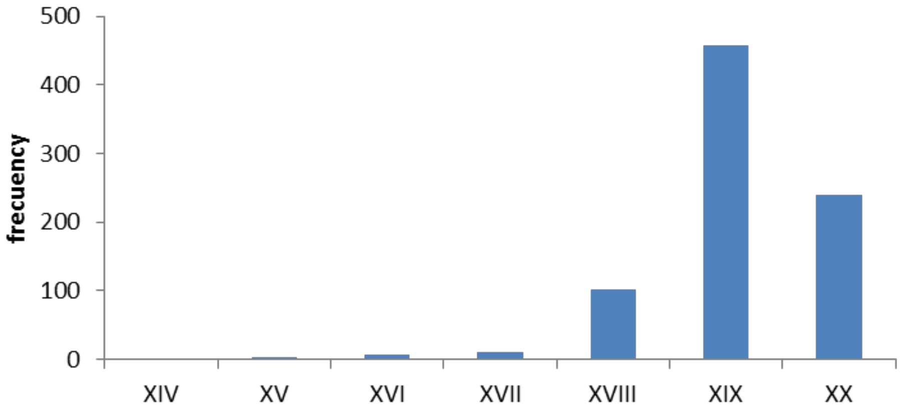


number of facades	number of buildings	code	colour
1	110	1	green
2	518	2	blue
3	159	3	orange
>3	32	4	grey

Table 45: Frequency and spatial distributions of the number of facades parameter

Year of construction

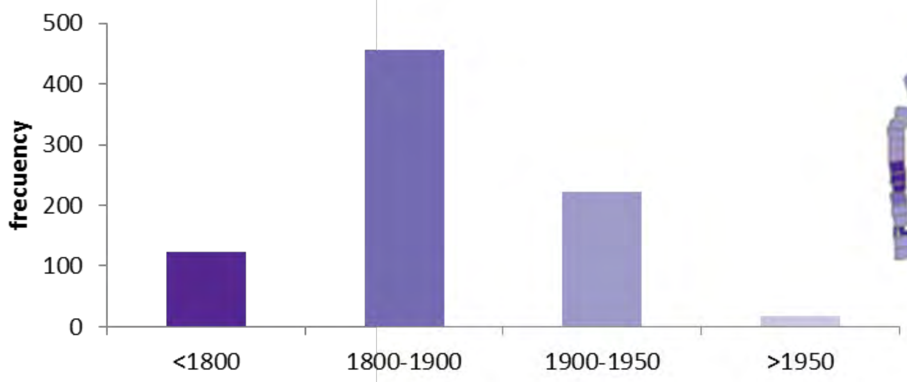
The buildings that have not this data have been discarded and the rest have been classified by century. Year of construction is one of the cases where the threshold between ranges is not direct. One possible approach is to overview the frequency of the parameter by centuries, as in the next figure:



century of construction	number of buildings
XIV	1
XV	2
XVI	7
XVII	11
XVIII	101
XIX	457
XX	240

Table 46: Frequency of the century of construction

Once, the overview is analysed it is necessary to make more representative groups. It is necessary to distinguish also the historical buildings. The year 1950 will be used as threshold. The following figures show the frequency and the spatial distribution of this parameter:

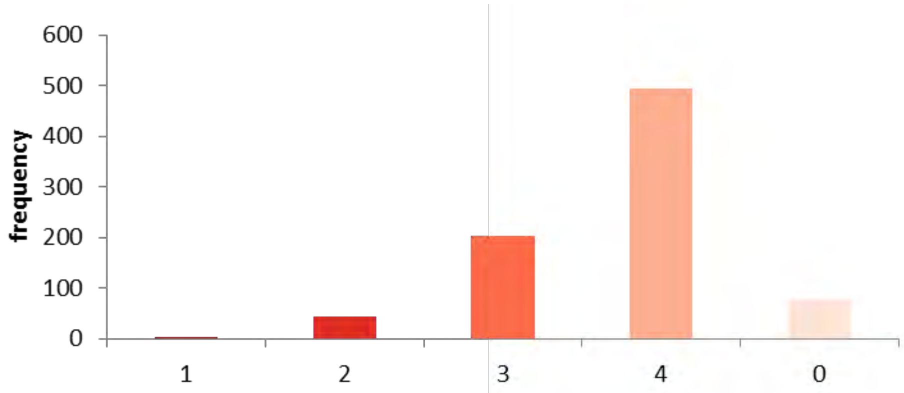


year of construction	number of buildings	code	colour
<1800	122	1	
1800-1900	457	2	
1900-1950	223	3	
>1950	17	4	

Table 47: Frequency and spatial distribution of the year of construction

Level of protection

The following figures show the frequency and the spatial distribution of this parameter. It has to be noted that the scale of 0-4 in the level of protection used in Santiago is not the same as it is used in this research (see Section 4.3.1 for the correlation):



level of protection	number buildings	code	colour
1	1	1	
2	45	2	
3	202	3	
4	495	4	
0 (not protected)	76	0	

Table 48: Frequency and spatial distribution of the level of protection

4.4.4 Generation and selection of the typologies

In the case of Santiago the non-historical (post 1950) and the non-residential buildings have been discarded due to the scope of this research (see Section 2.7.1 for the definition of the scope). As it has been seen before the final parameters for the generation of typologies have to balance the representativeness with a manageable number of typologies.

The volume is an indicator for the EP of the buildings, but in the case of Santiago, as seen in the previous section, this parameter is too homogeneous for being significant. Therefore the final used parameters are the following: use, number of facades, year of construction and level of protection.

Finally, the threshold used for the minimum representation has been established in 3%. The following table shows the process of the generation of typologies:

use	number of facades	year of construction	level of protection	typlogy code	number of buildings	total buildings	historical and residential buildings	selected tipologies (3% threshold)
Residential	1	<1800	3	1113	2	0,24%	0,29%	
			4	1114	9	1,10%	1,30%	
			0	1110	1	0,12%	0,14%	
		1800-1900	2	1122	1	0,12%	0,14%	
			3	1123	4	0,49%	0,58%	
			4	1124	46	5,62%	6,64%	1
			0	1120	1	0,12%	0,14%	
		1900-1950	3	1133	3	0,37%	0,43%	
			4	1134	26	3,17%	3,75%	2
			0	1130	8	0,98%	1,15%	
		>1950	4	1144	1	0,12%		
	2	<1800	2	1212	1	0,12%	0,14%	
			3	1213	30	3,66%	4,33%	3
			4	1214	22	2,69%	3,17%	4
		1800-1900	2	1222	2	0,24%	0,29%	
			3	1223	66	8,06%	9,52%	5
			4	1224	194	23,69%	27,99%	6
			0	1220	2	0,24%	0,29%	
		1900-1950	2	1232	1	0,12%	0,14%	
			3	1233	20	2,44%	2,89%	
			4	1234	69	8,42%	9,96%	7
			3	1230	32	3,91%	4,62%	8
		>1950	4	1244	2	0,24%		
			0	1240	8	0,98%		
	3	<1800	2	1312	10	1,22%	1,44%	
			3	1313	10	1,22%	1,44%	
			4	1314	8	0,98%	1,15%	
			0	1310	1	0,12%	0,14%	
		1800-1900	2	1322	3	0,37%	0,43%	
			3	1323	26	3,17%	3,75%	9
			4	1324	47	5,74%	6,78%	10
		1900-1950	2	1332	1	0,12%	0,14%	
			3	1333	7	0,85%	1,01%	
			4	1334	10	1,22%	1,44%	
			0	1330	10	1,22%	1,44%	
		>1950	4	1344	3	0,37%		
	4	<1800	2	1412	5	0,61%	0,72%	
			3	1413	3	0,37%	0,43%	
		1800-1900	2	1422	1	0,12%	0,14%	
			3	1423	3	0,37%	0,43%	
			4	1424	4	0,49%	0,58%	
		1900-1950	2	1432	1	0,12%	0,14%	
			4	1434	3	0,37%	0,43%	
Non residential					112	13,68%		
							selected tipologies	10
							selected buildings	558
							representativity	80,52%

Table 49: Generation of typologies

The following table summarized the selected typologies:

USE	NUMBER OF FACADES	YEAR OF CONSTRUCTION	LEVEL OF PROTECTION	TYPOLOGY	REPRESENTATIVITY	NUMBER OF BUILDINGS	CODE
RESIDENTIAL	1	1800-1900	4	1124	6,64%	46	1
		1900-1950	4	1134	3,75%	26	2
	2	<1800	3	1213	4,33%	30	3
			4	1214	3,17%	22	4
		1800-1900	3	1223	9,52%	66	5
			4	1224	27,99%	194	6
		1900-1950	4	1234	9,96%	69	8
			0	1230	4,62%	32	7
	3	1800-1900	3	1323	3,75%	26	9
			4	1324	6,78%	47	10
					80,52% total representativity	558 total building considered	10 number of tipologies

Table 50: Selected typologies and their representativeness

With these 10 typologies 80.52% of representativity has been reached. This proportion of number of typologies and representatitivity obtained could be considered optimal. The following figure shows the spatial distribution of the typologies:

use	number facades	year construction	level protection	typology		number buildings	code	colour
residential	1	1800-1900	4	**1124**	6,64%	46	1	
		1900-1950	4	**1134**	3,75%	26	2	
	2	<1800	3	**1213**	4,33%	30	3	
			4	**1214**	3,17%	22	4	
		1800-1900	3	**1223**	9,52%	66	5	
			4	**1224**	27,99%	194	6	
		1900-1950	4	**1234**	9,96%	69	7	
			0	**1230**	4,62%	32	8	
	3	1800-1900	3	**1323**	3,75%	26	9	
			4	**1324**	6,78%	47	10	
						Not selected typologies	0	
						Not considered buildings	-1	

Figure 52: Geographical distribution of typologies

Three typologies have been selected in order to test the validity of the proposal, the typologies with the 1223, 1224 and 1324 codes. High representativity typologies (more than 6%) have been selected to allow a pairwise comparison to see the effect of key parameters in the final results. As key parameters it has been chosen the number of facades (determinant in the EP of the buildings) and the level of protection (key in their HS). The following table shows the selected typologies for the implementation.

USE	NUMBER OF FACADES	YEAR OF CONSTRUCTION	LEVEL OF PROTECTION	TYPOLOGY	REPRESENTATIVITY	NUMBER OF BUILDINGS	CODE
RESIDENTIAL	1	1800-1900	4	1124	6,64%	46	1
		1900-1950	4	1134	3,75%	26	2
	2	<1800	3	1213	4,33%	30	3
			4	1214	3,17%	22	4
		1800-1900	3	1223	9,52%	66	5
			4	1224	27,99%	194	6
		1900-1950	4	1234	9,96%	69	8
			0	1230	4,62%	32	7
	3	1800-1900	3	1323	3,75%	26	9
			4	1324	6,78%	47	10

Table 51: Selected typologies for implementation in the case study

When it comes to select the sample buildings, the three different possibilities will be explored too (see the implications of the sample building selection in Section 2.7.2):

- → The main elements of the sample building have a higher HS than the level protection of the typology (typology 1223).
- → The main elements of the sample building have a lower HS than the level protection of the typology (typology 1224).
- → The main elements of the sample building have the same HS than the level protection of the typology (typology 1324).

4.5 Decision making in Typology 1223

USE	FACADES	CONSTRUCTION	PROTECTION	TYPOLOGY	REPRESENTATIVITY	BUILDINGS	CODE
RESIDENTIAL	**2**	**1800-1900**	**3**	**1223**	9,52%	66	5

4.5.1 Modelling

Selection of the sample building

One of the buildings contained within this typology (Rua Nova 22) was used as case study in (Liñares Mendez 2012) where it was study its EP and the different possibilities for a refurbishment process. It has been considered useful to select the same building in order to compare the results.

Figure 53: Rua Nova 22. Source: Google Street

Completion of the information

As it has been said before, the information will be completed using the databases of the municipality (contained in the PE).

Cultural Heritage ADE

Variable	Element	Value
Year of construction	Building	1800
Reference number	Building	7376909NH3477E
Main material	Building	Granite
Main Material (External Walls)	External Walls	Stone
Main construction techniques	Building	Stone walls and timber structure roof
Construction techniques	External Walls	Two layers of masonry filled
Coating material	External Walls	Plaster
Physical state of the building	Building	Good
Visual value Settlement pattern	District	4
Physical value Settlement pattern	District	4
Spatial value Settlement pattern	District	4
Visual value Roof-scape	District	4
Physical value Roof-scape	District	4
Spatial value Roof-scape	District	4
Visual value Streetscape	District	4
Physical value Streetscape	District	4
Spatial value Streetscape	District	4
Visual value Public open spaces	District	4
Physical value Public open spaces	District	4
Spatial value Public open spaces	District	4
Visual value Walls	External wall	3
Physical value Walls	External wall	3
Spatial value Walls	External wall	3
Visual value Roofs	Roofs	2
Physical value Roofs	Roofs	2
Spatial value Roofs	Roofs	2
Visual value Roof features	Roofs	2
Physical value Roof features	Roofs	2

Variable	Element	Value
Spatial value Roof features	Roofs	2
Visual value Windows	Windows	2
Physical value Windows	Windows	2
Spatial value Windows	Windows	2
Visual value Doors	Doors	2
Physical value Doors	Doors	2
Spatial value Doors	Doors	2
Visual value Building General	Building	2
Physical value Building General	Building	2
Spatial value Building General	Building	2
Visual value common use space	Common Areas	0
Physical value common use space	Common Areas	0
Spatial value common use space	Common Areas	0
Visual value common use interior finishes	Internal walls	0
Physical value common use interior finishes	Internal walls	0
Spatial value common use interior finishes	Internal walls	0
Visual value common use internal walls	Internal walls	0
Physical value common use internal walls	Internal walls	0
Spatial value common use internal walls	Internal walls	0

Table 52: CH ADE (Rua Nova 22)

Energy ADE

At district level:

Variable	Element	Santiago HUD	Source	Unit
Latitude	District	42°52'40"N	Geometric	º
Longitude	District	8°32'40"W	Geometric	º
Outside Min Temperature	District	-1.4	Climatic Database	ºC
Outside Max	District	33.6	Climatic Database	ºC

Variable	Element	Santiago HUD	Source	Unit
Temperature				
Outside Average Min Temperature	District	8.2	Climatic Database	ºC
Outside Average Max Temperature	District	17.6	Climatic Database	ºC
Solar Radiation	District	3.76	Climatic Database	kWh/m²d
Average annual precipitation	District	1895	Climatic Database	mm
Average relative humidity	District	80	Climatic Database	%
Average annual number of sunshine hours	District	1978	Climatic Database	
Comfort Tº (winter)	District	20	Expert Judgement	ºC
Comfort Tº (summer)	District	25	Expert Judgement	ºC
Set back Tº (winter)	District	17	Expert Judgement	ºC
Set back Tº (summer)	District	25	Expert Judgement	ºC

Table 53: Energy ADE at district level

At building level:

Variable	Element	Rua Nova 22-Building	Source	Unit
Number of floors	Building	4	Geometric	
Foot print area	Building	161	Geometric	m2
Volume	Building	2093	Geometric	m3
Thermal mass	Building	High	Expert Judgement	
Use	Building	Residential	Existing Database	
Ventilation strategy	Building	No	Expert Judgement	
Shadow strategy	Building	No	Expert Judgement	
Exist? Heating	IntBuildingInstallation	Yes	Expert Judgement	
Heating Energy	IntBuildingInstallation	Electricity	Expert Judgement	
Heating Individual/Centralised	IntBuildingInstallation	Individual	Expert Judgement	
Heating Efficiency	IntBuildingInstallation	1	Expert Judgement	
Heating Type	IntBuildingInstallation	Electric	Expert Judgement	

Variable	Element	Rua Nova 22-Building	Source	Unit
Exist? Cooling	IntBuildingInstallation	No	Expert Judgement	
Cooling Individual/Centralised	IntBuildingInstallation	No	Expert Judgement	
Cooling Efficiency	IntBuildingInstallation		Expert Judgement	
Cooling Type	IntBuildingInstallation	Cooling Type	Expert Judgement	
Exist? RES	IntBuildingInstallation	No	Expert Judgement	
RES Type	IntBuildingInstallation	-	Expert Judgement	
RES % heating demand covered	IntBuildingInstallation	-	Expert Judgement	

Table 54: Energy ADE at building level (Rua Nova 22)

At building element level:

Variable	Element	Rua Nova 22- East Facade	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	East	Geometric	
Wall Area	Boundary Surface/Wall	96,72	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,40	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	-	Expert Judgement	

Table 55: Energy ADE at element level (Rua Nova 22)

Variable	Element	Rua Nova 22- West Facade	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	West	Geometric	
Wall Area	Boundary Surface/Wall	120,77	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,75	Expert Judgement/Default	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,40	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0	Expert Judgement	

Table 56: Energy ADE at element level (Rua Nova 22)

Variable	Element	Rua Nova 22-South adjoining wall	Source	Unit
Adjoining wall?	Boundary Surface/Wall	Yes	Geometric	
Wall Orientation	Boundary Surface/Wall	South	Geometric	
Wall Area	Boundary Surface/Wall	306,54	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	0	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0,5	Expert Judgement	

Table 57: Energy ADE at element level (Rua Nova 22)

Variable	Element	Rua Nova 22-North Adjoining Wall	Source	Unit
Adjoining wall?	Boundary Surface/Wall	Yes	Geometric	
Wall Orientation	Boundary Surface/Wall	North	Geometric	
Wall Area	Boundary Surface/Wall	306,54	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	0	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0,50	Expert Judgement	

Table 58: Energy ADE at element level (Rua Nova 22)

Variable	Element	Rua Nova 22-Roof	Source	Unit
Roof Area	Boundary Surface/Roof	161	Geometric	m3
Roof Opaque Average U	Boundary Surface/Roof	131	Expert Judgement	W/m2·K
Roof Opening Average U	Boundary Surface/Roof	0	Expert Judgement	W/m2·K
Roof % Openings	Boundary Surface/Roof	0	Expert Judgement	
Is the under roof floor climatizated?	Boundary Surface/Roof	No	Expert Judgement	

Table 59: Energy ADE at element level (Rua Nova 22)

Variable	Element	Rua Nova 22-Ground	Source	Unit
Ground Area	Boundary Surface/Ground	161	Geometric	m3
Ground Opaque Average U	Boundary Surface/Ground	1,4	Expert Judgement	W/m2·K

Table 60: Energy ADE at element level (Rua Nova 22)

Current state identification

At this point the current state will be identified regarding the EP and the constraints (HS).

Energy Performance Assessment

The results of this analysis are the following:

				Energy Demand				Final Energy				Primary energy				CO2 emissions			
				SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY	
		CONSIDERED AREA	EXCLUDED AREA		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVINGS		SAVING	TOTAL IMPACT	SAVINGS
		(m2)	(m2)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(gr/m2)	(%)	Ton	(%)
CURRENT SITUATION																			
	THERMAL	24885,7		137,00		3409340,90		137,00		3409340,90		357,57		8898379,75		232062,93		57750,48	
	ELECTRICITY	24885,7		2,00		49771,40		2,00		49771,40		5,22		129903,35		3387,78		843,07	
	TOTAL							139,00		3459112,30		362,79		9028283,10		235450,71		58593,56	

Table 61: Energy Savings Indicators for case study (Rua Nova 22)

For the calculation of the heated area of the typology it has been used the coefficient of 0.7 (see the Impact Adjustment Section in 2.7.4)

It is worthy to remark , that the estimations for the energy demand for the same building in (Liñares Mendez 2012) are 142.36 kWh/m2, a difference of 3.7%.

Heritage Significance Assessment

The assessment regarding the HS could be directly obtained for the Cultural Heritage ADE. The final results are the following:

	Scale	Building or urban element	Impact area	Rua Nova 22
HS And Conservation Principles	**Urban**	Settlement pattern	Visual	4
			Physical	4
			Spatial	4
		Roof-scape	Visual	4
			Physical	4
			Spatial	4
		Street-scape	Visual	4
			Physical	4
			Spatial	4
		Public spaces	Visual	4
			Physical	4
			Spatial	4
	Building exterior	Walls	Visual	3
			Physical	3
			Spatial	3
		Roofs	Visual	2
			Physical	2
			Spatial	2
		Windows	Visual	2
			Physical	2
			Spatial	2
		Doors	Visual	2
			Physical	2
			Spatial	2
		Building general	Visual	2
			Physical	2
			Spatial	2
	Building interior	Common use space	Visual	0
			Physical	0
			Spatial	0
		Common Internal Walls	Visual	0

	Scale	Building or urban element	Impact area	Rua Nova 22
			Physical	0
			Spatial	0
		Private Internal Walls	Visual	0
			Physical	0
			Spatial	0

Table 62: HS and Conservation Principles (Rua Nova 22)

Current State Identification

Taking into account the results shown in Table 61, the energy class of the building will be E that is a very poor EP.

For HS the obtained results are the following:

Scale	HS
District	4
Building	2
External wall	3
Roofs	2
Windows	2
Doors	2
Internal walls	0
Installations	0

Table 63: Current State regarding HS (Rua Nova 22)

4.5.2 Decision making

Filtered list of solutions according to the constraints:

As explained in the methodology the list of solutions will be filtered according to their applicability. In this case, according to the HS of the building, it has been decided to be discarded. The following table shows the applicability of all the solutions:

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	0
5	2	21	214	Chimney dampers and closers	0
10	2	22	223	Exterior insulation with insulation plaster 5 cm	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	0
18	3	31	311	Install a new gas boiler	0
19	3	31	312	Install a condensing boiler	0
20	3	32	321	Instal low energy lighting	0
21	3	32	322	Instal low energy appliances	0
22	3	32	323	Instal power conditioner / voltage optimiser	0
2	1	11	112	Instal energy monitoring and management system	1
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	1
16	2	24	241	Thermal insulation of the rooftop (20 mm)	1
17	2	24	242	Thermal insulation of the rooftop (40 mm)	1
3	2	21	212	Sealimg of all openings and joints	2
4	2	21	213	Airtightness of windows	2
7	2	21	216	Airtightness membrane to underside roof	2
15	2	23	232	Install secondary double glazing with wooden frame and shutters	2
6	2	21	215	Instal draught lobby at external doors	3
8	2	22	221	Exterior insulation with a composite system 10 cm	3
9	2	22	222	Exterior insulation with ventilated cavity	3
14	2	23	231	Instal high performance window and glazing systems	3

Table 64: Filtered list of solutions for Rua Nova 22

After the automatic filtering it is necessary to discard other solutions due to the technical difficulties as the 226 solution in this case (there is not a cavity).

Target definition

As seen in the current state, the Rua Nova 22 building has a very poor EP and a medium-high HS of its elements. In this step, with this information, the user has to show the preferences regarding the 5 criteria (Thermal Comfort, IAQ, Energy Saving, Cost and Low impact solutions). In order to explore different possibilities two scenarios has been considered. The user is going to be asked to compare the different criteria with the following scale:

- → Extremely preferred = 9
- → Very strongly preferred = 7
- → Strongly preferred = 5
- → Moderately preferred = 3
- → Equally preferred =1

In the scenario 1, it has been considered a user that has a strong preference for energy savings and secondarily for low budget solutions. In the scenario 2, it has been considered a user that has a strong preference for low impact solutions and for the thermal comfort of the inhabitants. The following table shows the results of the pairwise comparison of the different criteria for the two scenarios:

	Scenario 1			Scenario 2			
Thermal Comfort		1		7			IAQ
Thermal Comfort			5	5			Energy Saving
Thermal Comfort			5	5			Cost
Thermal Comfort		1		5			Low impact solutions
IAQ			9			7	Energy Saving
IAQ						3	Cost
IAQ			3			9	Low impact solutions
Energy Saving	7			5			Cost
Energy Saving	7					5	Low impact solutions
Cost		1				7	Low impact solutions

Table 65: Pairwise comparison for scenarios (Rua Nova 22)

With this information, the two comparison matrix could be built following AHP methodology (see 2.7.4):

Scenario 1	TC	IAQ	ES	Cost	LIS	
TS	1	1	0,2	0,2	1	**3,4**
IAQ	1	1	0,11	0,14	3	**5,25**
ES	5	9	1	7	7	**29**
Cost	5	7	0,14	1	1	**14,14**
LIS	1	0,33	0,14	1	1	**3,47**
	13	**18,33**	**1,59**	**9,34**	**13**	**55,26**

Table 66: Comparison matrix for scenario 1

Scenario 1	TC	IAQ	ES	Cost	LIS	
TS	1	7	5	5	5	**23**
IAQ	0,14	1	0,14	0,33	0,11	**1,72**
ES	0,2	7	1	5	0,2	**13,4**
Cost	0,2	3	0,2	1	0,14	**4,54**
LIS	0,2	9	5	7	1	**22,2**
	1,74	**27**	**11,34**	**18,33**	**6,45**	**64,86**

Table 67: Comparison matrix for scenario 2

And the final weights are obtained:

	Weights S1	Weights S2
TS	0,07	0,46
IAQ	0,09	0,03
ES	0,56	0,15
Cost	0,21	0,06
LIS	0,07	0,29

Table 68: Final weights for scenario 1 and 2

Ranked list of solutions

Each solution is already characterized regarding the 5 criteria considered by the methodology in this step (Thermal Comfort, IAQ, Energy Saving, Cost and Low impact solutions) according to a 0-4 scale. This characterization along with the weighted criteria allows ranking the different suitable solutions (applicability 0 or 1) for each scenario. In Section 4.2, it have been listed the possible solution that have been taken into account for test purposes. It can be seen also the characterization of each solution for each criterion. The total score will go from a minimum of 0 to a maximum of 4.

Ranked list of solutions for scenario 1

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S1	APPLICABILITY
2	1	11	112	Instal energy monitoring and management system	**2,867**	1
16	2	24	241	Thermal insulation of the rooftop (20 mm)	**2,794**	1
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	**2,653**	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	**2,586**	1
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	**2,376**	0
18	3	31	311	Install a new gas boiler	**2,236**	0
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	**2,144**	0
5	2	21	214	Chimney dampers and closers	**1,913**	0
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	**1,893**	1
10	2	22	223	Exterior insulation with insulation plaster 5 cm	**1,674**	0
20	3	32	321	Instal low energy lighting	**1,605**	0
21	3	32	322	Instal low energy appliances	**1,605**	0
19	3	31	312	Install a condensing boiler	**1,328**	0
22	3	32	323	Instal power conditioner / voltage optimiser	**1,058**	0

Table 69: Ranked list of solutions for scenario 1(Rua Nova 22)

Ranked list of solutions for scenario 2

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S2	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	**2,56**	0
5	2	21	214	Chimney dampers and closers	**2,5**	0
2	1	11	112	Instal energy monitoring and management system	**2,48**	1
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	**2,24**	0
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	**2,21**	1
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	**2,04**	0
22	3	32	323	Instal power conditioner / voltage optimiser	**1,37**	0
10	2	22	223	Exterior insulation with insulation plaster 5 cm	**1,34**	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	**1,3**	1
17	2	24	242	Thermal insulation of the rooftop (40 mm)	**1,24**	1
18	3	31	311	Install a new gas boiler	**1,15**	0
19	3	31	312	Install a condensing boiler	**0,91**	0
20	3	32	321	Instal low energy lighting	**0,71**	0
21	3	32	322	Instal low energy appliances	**0,71**	0

Table 70: Ranked list of solutions for scenario 2 (Rua Nova 22)

Strategy Generation

The strategies or packed solutions will be generated selecting a retrofit measure from each strategy, as described in Section 4.2. As shown in the methodology now it will be selected a solution for each strategy in order to generate the different retrofitting strategies. As it has been explained, the strategies considered in the case study are the followings:

CODE	STEP	CODE	STRATEGY
1	**People and management**	11	Improve the energy management
2	**Passive solutions**	21	Improve the airtightness
		22	Insulation of the walls
		23	Improve the windows
		24	Insulation of the roof
3	**Active solutions**	31	HVAC enhancement
		32	Electric equipment

Table 71: Retrofitting strategies

In this case it has been selected the first ranked solution of each strategy. Depending of the characteristics of the building some strategies could be not applicable at all. Therefore the number of solutions for strategies could vary with a maximum of 7.

Strategy for scenario 1

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S1	APPLICABILITY
2	1	11	112	Instal energy monitoring and management system	2,867	1
16	2	24	241	Thermal insulation of the rooftop (20 mm)	2,794	1
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	2,653	0
18	3	31	311	Install a new gas boiler	2,236	0
5	2	21	214	Chimney dampers and closers	1,913	0
20	3	32	321	Instal low energy lighting	1,605	0

Table 72: Strategy for scenario 1 (Rua Nova 22)

Strategy for scenario 2

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S2	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	2,56	0
5	2	21	214	Chimney dampers and closers	2,5	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	2,24	0
22	3	32	323	Instal power conditioner / voltage optimiser	1,37	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	1,3	1
18	3	31	311	Install a new gas boiler	1,15	0

Table 73: Strategy for scenario 2(Rua Nova 22)

Impact adjustment

The coefficients that are considered for the impact adjustment can be seen in the next table (see 2.7.4):

Impact adjustment	Percentage of reductions	Considered Area (m2)
Total area of the whole typology		35551,00
Total heated area	0,7	**24885,70**
Applicability of solutions	1	24885,70
Recent renovations	0,99	24636,84
Adjusted area		**24636,84**

Table 74: Impact adjustment for Rua Nova 22

Assessment of the Scenarios

The different scenarios are assessed against the energy indicators through the EE ADE. In the following table it is summarized the energy indicators for the two scenarios. It is included also the qualitative achievement for each criterion:

				Energy Demand				Final Energy				Primary energy				CO2 emissions								
				SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY						
		CONSIDERED AREA	EXCLUDED AREA		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVINGS		SAVING	TOTAL IMPACT	SAVINGS					
		(m2)	(m2)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(gr/m2)	(%)	Ton	(%)					
CURRENT SITUATION																								
	THERMAL	24885,7		137,00		3409340,90		137,00		3409340,90		357,57		8898379,75		232062,93		57750,48						
	ELECTRICITY	24885,7		2,00		49771,40		2,00		49771,40		5,22		129903,35		3387,78		843,07						
	TOTAL							139,00		3459112,30		362,79		9028283,10		235450,71		58593,56		TOTAL IMPACT IN INDICATORS				
																				HS	TC	IAQ	ES	COST
SCENARIO 1																								
IMPLEMENTED STRATEGIES	THERMAL	24636,843	248,857	47,20	65,55%	1162858,99	65,89%	53,82		1360044,37		54,36		1428194,26		11089,04		3309,49						
	ELECTRICITY	24636,843	248,857	1,70	15,00%	42380,35	14,85%	1,70		42380,35		4,44		110612,71		2879,61		717,88						
241/224/311/112/321	TOTAL							55,52	60,06%	1402424,71	59,46%	58,80	83,79%	1538806,97	82,96%	13968,65	94,07%	4027,37	93,13%	50,00%	29,17%	4,17%	70,83%	62,50%
SCENARIO 2																								
IMPLEMENTED	THERMAL	24636,843	248,857	54,40	60,29%	1374337,67	59,69%	62,03		1562308,07		62,65		1632480,607		12780,59		3726,24						
STRATEGIES	ELECTRICITY	24636,843	248,857	1,80	10,00%	44844,03	9,90%	1,80		44844,03		4,70		117042,922		3049,00		759,61						
111/214/225/323/241/311	TOTAL							63,83	54,08%	1607152,10	53,54%	67,35	81,44%	1749523,53	80,62%	15829,59	93,28%	4485,85	92,34%	70,83%	29,17%	12,50%	58,33%	54,17%

Table 75: Results for Rua Nova 2

4.6 Decision making in Typology 1224

USE	FACADES	CONSTRUCTION	PROTECTION	TYPOLOGY	REPRESENTATIVITY	BUILDINGS	CODE
RESIDENTIAL	2	1800-1900	4	1224	17,99%	194	6

4.6.1 Modelling

Selection of the sample building

Within the typology 1224 it has been selected the building located in Rua Nova 46. It has been considered to select a building where the elements (in this case the windows and the external walls) have a lower protection than the building in general.

Figure 54: Rua Nova 46. Source: Google Street

Completion of the information

As in the previous case, the information has been completed using the information contained in the PE.

Cultural Heritage ADE

Variable	Element	Description
Year of construction	Building	1800
Reference number	Building	7376921NH3477E
Main material	Building	Granite
Main Material	External Walls	Stone
Main construction techniques	Building	Stone walls and concrete structure roof
Construction techniques	External Walls	Cachoteria
Coating material	External Walls	Plaster
Physical state of the building	Building	Good
Visual value Settlement pattern	District	4
Physical value Settlement pattern	District	4
Spatial value Settlement pattern	District	4
Visual value Roof-scape	District	4
Physical value Roof-scape	District	4
Spatial value Roof-scape	District	4
Visual value Streetscape	District	4
Physical value Streetscape	District	4
Spatial value Streetscape	District	4
Visual value Public open spaces	District	4
Physical value Public open spaces	District	4
Spatial value Public open spaces	District	4
Visual value Walls	External wall	0
Physical value Walls	External wall	0
Spatial value Walls	External wall	0
Visual value Roofs	Roofs	1
Physical value Roofs	Roofs	1
Spatial value Roofs	Roofs	1

Variable	Element	Description
Visual value Roof features	Roofs	1
Physical value Roof features	Roofs	1
Spatial value Roof features	Roofs	1
Visual value Windows	Windows	0
Physical value Windows	Windows	0
Spatial value Windows	Windows	0
Visual value Doors	Doors	0
Physical value Doors	Doors	0
Spatial value Doors	Doors	0
Visual value Building General	Building	1
Physical value Building General	Building	1
Spatial value Building General	Building	1
Visual value common use space	Common Areas	0
Physical value common use space	Common Areas	0
Spatial value common use space	Common Areas	0
Visual value common use interior finishes	Internal walls	0
Physical value common use interior finishes	Internal walls	0
Spatial value common use interior finishes	Internal walls	0
Visual value common use internal walls	Internal walls	0
Physical value common use internal walls	Internal walls	0
Spatial value common use internal walls	Internal walls	0

Table 76: CH ADE (Rua Nova 46)

Energy ADE

At district level:

Variable	Element	Santiago HUD	Source	Unit
Latitude	District	42°52'40"N	Geometric	º
Longitude	District	8°32'40"W	Geometric	º
Outside Min Temperature	District	-1.4	Climatic Database	ºC

Variable	Element	Santiago HUD	Source	Unit
Outside Max Temperature	District	33.6	Climatic Database	ºC
Outside Average Min Temperature	District	8.2	Climatic Database	ºC
Outside Average Max Temperature	District	17.6	Climatic Database	ºC
Solar Radiation	District	3.76	Climatic Database	kWh/m²d
Average annual precipitation	District	1895	Climatic Database	mm
Average relative humidity	District	80	Climatic Database	%
Average annual number of sunshine hours	District	1978	Climatic Database	
Comfort Tº (winter)	District	20	Expert Judgement	ºC
Comfort Tº (summer)	District	25	Expert Judgement	ºC
Set back Tº (winter)	District	17	Expert Judgement	ºC
Set back Tº (summer)	District	25	Expert Judgement	ºC

Table 77: Energy ADE at district level

At building level:

Variable	Element	Rua Nova 46-Building	Source	Unit
Number of floors	Building	5	Geometric	
Foot print area	Building	75	Geometric	m2
Volume	Building	1125	Geometric	m3
Thermal mass	Building	High	Expert Judgement	
Use	Building	Residential	Existing Database	
Ventilation strategy	Building	No	Expert Judgement	
Shadow strategy	Building	No	Expert Judgement	
Exist? Heating	IntBuildingInstallation	Yes	Expert Judgement	
Heating Energy	IntBuildingInstallation	Electricity	Expert Judgement	
Heating Individual/Centralised	IntBuildingInstallation	Individual	Expert Judgement	
Heating Efficiency	IntBuildingInstallation	1	Expert Judgement	

Variable	Element	Rua Nova 46-Building	Source	Unit
Heating Type	IntBuildingInstallation	Electric	Expert Judgement	
Exist? Cooling	IntBuildingInstallation	No	Expert Judgement	
Cooling Individual/Centralised	IntBuildingInstallation	No	Expert Judgement	
Cooling Efficiency	IntBuildingInstallation		Expert Judgement	
Cooling Type	IntBuildingInstallation	Cooling Type	Expert Judgement	
Exist? RES	IntBuildingInstallation	No	Expert Judgement	
RES Type	IntBuildingInstallation	-	Expert Judgement	
RES % heating demand covered	IntBuildingInstallation	-	Expert Judgement	

Table 78: Energy ADE at building level (Rua Nova 46)

At element level:

Variable	Element	Rua Nova 46- South East Facade	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	South East	Geometric	
Wall Area	Boundary Surface/Wall	124,50	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,50	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	-	Expert Judgement	

Table 79: Energy ADE at element level (Rua Nova 46)

Variable	Element	Rua Nova 46- North West Facade	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	North West	Geometric	
Wall Area	Boundary Surface/Wall	62,4	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,50	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0	Expert Judgement	

Table 80: Energy ADE at element level (Rua Nova 46)

Variable	Element	Rua Nova 46-South West adjoining wall	Source	Unit
Adjoining wall?	Boundary Surface/Wall	Yes	Geometric	
Wall Orientation	Boundary Surface/Wall	South West	Geometric	
Wall Area	Boundary Surface/Wall	134,25	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	0	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0,5	Expert Judgement	

Table 81: Energy ADE at element level (Rua Nova 46)

Variable	Element	Rua Nova 46-NorthEast Adjoining Wall	Source	Unit
Adjoining wall?	Boundary Surface/Wall	Yes	Geometric	
Wall Orientation	Boundary Surface/Wall	NorthEast	Geometric	
Wall Area	Boundary Surface/Wall	134.25	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	0	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0,50	Expert Judgement	

Table 82: Energy ADE at element level (Rua Nova 46)

Variable	Element	Rua Nova 46-Roof	Source	Unit
Roof Area	Boundary Surface/Roof	75	Geometric	m3
Roof Opaque Average U	Boundary Surface/Roof	131	Expert Judgement	W/m2·K
Roof Opening Average U	Boundary Surface/Roof	0	Expert Judgement	W/m2·K
Roof % Openings	Boundary Surface/Roof	0	Expert Judgement	
Is the under roof floor climatizated?	Boundary Surface/Roof	Yes	Expert Judgement	

Table 83: Energy ADE at element level (Rua Nova 46)

Variable	Element	Rua Nova 46-Ground	Source	Unit

Variable	Element	Rua Nova 46-Ground	Source	Unit
Ground Area	Boundary Surface/Ground	75	Geometric	m3
Ground Opaque Average U	Boundary Surface/Ground	1,4	Expert Judgement	W/m2·K

Table 84: Energy ADE at element level (Rua Nova 46)

Current state identification

At this point the current state will be identified regarding the EP and HS.

Energy Performance Assessment

The results of this assessment are the following:

				Energy Demand				Final Energy				Primary energy				CO2 emissions			
				SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY	
		CONSIDERED AREA	EXCLUDED AREA		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVINGS		SAVING	TOTAL IMPACT	SAVINGS
		(m2)	(m2)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(gr/m2)	(%)	Ton	(%)
CURRENT SITUATION																			
	THERMAL	44769,55		175,58		7860637,59		175,58		7860637,59		458,26		20516264,11		297413,21		133150,55	
	ELECTRICITY	44769,55		2,00		89539,10		2,00		89539,10		5,22		233697,05		3387,78		1516,69	
	TOTAL							**177,58**		**7950176,69**		**463,48**		**20749961,16**		**300800,99**		**134667,25**	

Table 85: Energy Savings Indicators for case study (Rua Nova 46)

Heritage Significance Assessment

The assessment regarding the HS could be directly obtained for the Cultural Heritage ADE:

	Scale	Building or urban element	Impact area	Rua Nova 22
HS And Conservation Principles	**Urban**	Settlement pattern	Visual	4
			Physical	4
			Spatial	4
		Roof-scape	Visual	4
			Physical	4
			Spatial	4
		Street-scape	Visual	4
			Physical	4
			Spatial	4
		Public spaces	Visual	4
			Physical	4
			Spatial	4
	Building exterior	Walls	Visual	0
			Physical	0
			Spatial	0
		Roofs	Visual	1
			Physical	1
			Spatial	1
		Windows	Visual	0
			Physical	0
			Spatial	0
		Doors	Visual	0
			Physical	0
			Spatial	0
			Spatial	
		Building general	Visual	1
			Physical	1
			Spatial	1
	Building interior	Common use space	Visual	0
			Physical	0
			Spatial	0
		Common Internal Walls	Visual	0
			Physical	0
			Spatial	0
		Private Internal Walls	Visual	0
			Physical	0
			Spatial	0

Table 86: HS and Conservation Principles (Rua Nova 46)

Current State Identification

Taking into account the results shown the energy class of the building will be E that is a very poor EP.

For HS the obtained results are the following:

Scale	HS
District	4
Building	1
External wall	0
Roofs	1
Windows	0
Doors	0
Internal walls	0
Installations	0

Table 87: Current State regarding HS (Rua Nova 46)

4.6.2 Decision making

Filtered list of solutions according to the constraints:

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	0
2	1	11	112	Instal energy monitoring and management system	0
4	2	21	213	Airtightness of windows	0
5	2	21	214	Chimney dampers and closers	0
6	2	21	215	Instal draught lobby at external doors	0
8	2	22	221	Exterior insulation with a composite system 10 cm	0
9	2	22	222	Exterior insulation with ventilated cavity	0
10	2	22	223	Exterior insulation with insulation plaster 5 cm	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	0
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	0
14	2	23	231	Instal high performance window and glazing systems	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	0
18	3	31	311	Install a new gas boiler	0
19	3	31	312	Install a condensing boiler	0
20	3	32	321	Instal low energy lighting	0
21	3	32	322	Instal low energy appliances	0
22	3	32	323	Instal power conditioner / voltage optimiser	0
3	2	21	212	Sealimg of all openings and joints	1
7	2	21	216	Airtightness membrane to underside roof	1

Table 88: Filtered list of solutions for Rua Nova 46

After the automatic filtering it is necessary to discard other solutions due to the technical difficulties as the 221 and 222.

Target definition

As seen in the current state, the Rua Nova 46 building has a very poor EP and a medium HS of its elements. It will be used the same scenarios defined in the previous case:

	Scenario 1	Scenario 2
Thermal Comfort	0,071	0,46
IAQ	0,089	0,03
Energy Saving	0,558	0,15
Cost	0,38	0,06
Low impact solutions	0,073	0,29

Table 89: Final weights for scenario 1 and 2

Ranked list of solutions

Ranked list of solutions for scenario 1

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S1	APPLICABILITY
2	1	11	112	Instal energy monitoring and management system	**2,867**	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	**2,794**	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	**2,653**	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	**2,586**	0
3	2	21	212	Sealimg of all openings and joints	**2,432**	1
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	**2,376**	0
14	2	23	231	Instal high performance window and glazing systems	**2,362**	0
18	3	31	311	Install a new gas boiler	**2,236**	0
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	**2,144**	0
5	2	21	214	Chimney dampers and closers	**1,913**	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	**1,735**	0
10	2	22	223	Exterior insulation with insulation plaster 5 cm	**1,674**	0
4	2	21	213	Airtightness of windows	**1,666**	0
20	3	32	321	Instal low energy lighting	**1,605**	0
21	3	32	322	Instal low energy appliances	**1,605**	0
7	2	21	216	Airtightness membrane to underside roof	**1,399**	1
6	2	21	215	Instal draught lobby at external doors	**1,342**	0
19	3	31	312	Install a condensing boiler	**1,328**	0
22	3	32	323	Instal power conditioner / voltage optimiser	**1,058**	0

Table 90: Ranked list of solutions for scenario 1 (Rua Nova 46)

Ranked list of solutions for scenario 2

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S2	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	2,56	0
5	2	21	214	Chimney dampers and closers	2,5	0
2	1	11	112	Instal energy monitoring and management system	2,48	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	2,24	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	2,09	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	2,04	0
14	2	23	231	Instal high performance window and glazing systems	1,98	0
3	2	21	212	Sealimg of all openings and joints	1,67	1
4	2	21	213	Airtightness of windows	1,46	0
7	2	21	216	Airtightness membrane to underside roof	1,37	1
10	2	22	223	Exterior insulation with insulation plaster 5 cm	1,34	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	1,3	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	1,24	0
18	3	31	311	Install a new gas boiler	1,15	0
19	3	31	312	Install a condensing boiler	0,91	0
6	2	21	215	Instal draught lobby at external doors	0,82	0
20	3	32	321	Instal low energy lighting	0,71	0
21	3	32	322	Instal low energy appliances	0,71	0
22	3	32	323	Instal power conditioner / voltage optimiser	1,37	0

Table 91: Ranked list of solutions for scenario 2 (Rua Nova 46)

Strategy Generation

Strategy for scenario 1

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S1	APPLICABILITY
2	1	11	112	Instal energy monitoring and management system	2,867	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	2,794	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	2,653	0
3	2	21	212	Sealimg of all openings and joints	2,432	1
14	2	23	231	Instal high performance window and glazing systems	2,362	0
18	3	31	311	Install a new gas boiler	2,236	0
20	3	32	321	Instal low energy lighting	1,605	0

Table 92: Strategy for scenario 1 (Rua Nova 46)

Strategy for scenario 2

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S2	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	2,56	0
5	2	21	214	Chimney dampers and closers	2,5	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	2,24	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	2,09	0
22	3	32	323	Instal power conditioner / voltage optimiser	1,37	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	1,3	0
18	3	31	311	Install a new gas boiler	1,15	0

Table 93: Strategy for scenario 2 (Rua Nova 46)

Impact adjustment

The coefficients that are considered for the impact adjustment can be seen in the next table (see 2.7.4):

Impact adjustment	Percentage of reductions	Considered Area (m2)
Total area of the whole typology		63956,50
Total heated area	0,7	**44769,55**
Applicability of solutions	0,36	16117,04
Recent renovations	0,99	15955,87
Adjusted area		**15955,87**

Table 94: Impact adjustment for Rua Nova 46

Assessment of the Scenarios

In the following table it is shown the results of the two scenarios:

				Energy Demand				Final Energy				Primary energy				CO2 emissions								
				SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY						
		CONSIDERED AREA	EXCLUDED AREA		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVINGS		SAVING	TOTAL IMPACT	SAVINGS					
		(m2)	(m2)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(gr/m2)	(%)	Ton	(%)					
CURRENT SITUATION																								
	THERMAL	44769,55		175,58		7860637,59		175,58		7860637,59		458,26		20516264,11		297413,21		133150,55						
	ELECTRICITY	44769,55		2,00		89539,10		2,00		89539,10		5,22		233697,05		3387,78		1516,69						
	TOTAL							177,58		7950176,69		463,48		20749961,16		300800,99		134667,25		TOTAL IMPACT IN INDICATORS				
																				HS	TC	IAQ	ES	COST
SCENARIO 1																								
IMPLEMENTED	THERMAL	15955,87	28813,68	25,60	85,42%	5467576,56	30,44%	29,19		5524864,86		29,48		13674683,67		6014,39		86655,35						
STRATEGIES	ELECTRICITY	15955,87	28813,68	1,70	15,00%	84752,34	5,35%	1,70		84752,34		4,44		221203,61		905,15		1120,57						
112/241/224/212/231/311/321	TOTAL							30,89	82,60%	5609617,20		33,92	92,68%	13895887,28	33,03%	6919,54	97,70%	87775,91	34,82%	35,71%	32,14%	21,43%	75,00%	57,14%
SCENARIO 2																								
IMPLEMENTED	THERMAL	15955,87	28813,68	37,40	78,70%	5655855,80	28,05%	42,65		5739550,42		43,07		13891516,09		8786,65		87097,68						
STRATEGIES	ELECTRICITY	15955,87	28813,68	1,80	10,00%	86347,93	3,56%	1,80		86347,93		4,70		225368,0881		958,39		1129,06						
111/214/225/232/341/311	TOTAL							44,45	74,97%	5825898,35	26,72%	47,77	89,69%	14116884,18	31,97%	9745,05	96,76%	88226,75	34,49%	64,29%	35,71%	21,43%	53,57%	57,14%

Table 95: Results of Rua Nova 46

4.7 Decision making in Typology 1324

USE	FACADES	CONSTRUCTION	PROTECTION	TYPOLOGY	REPRESENTATIVITY	BUILDINGS	CODE
RESIDENTIAL	**3**	**1800-1900**	**4**	**1324**	6,78%	47	10

4.7.1 Modelling

Selection of the sample building

Within the typology 1324 it has been selected the building located in Plaza do Toural 3. It has been considered to select a building where the elements have the same protection than the building in general.

Figure 55: Plaza Toural 3. Source: Google Street

Completion of the information

As in the previous case, the information has been completed using the information contained in the PE database:

Cultural Heritage ADE

Variable	Element	Description
Year of construction	Building	1800
Reference number	Building	7375205NH3477E

Variable	Element	Description
Main material	Building	Granite
Main Material	External Walls	Stone
Main construction techniques	Building	Stone walls and timber roof
Construction techniques	External Walls	Mansonry
Coating material	External Walls	Plaster
Physical state of the building	Building	Good
Visual value Settlement pattern	District	4
Physical value Settlement pattern	District	4
Spatial value Settlement pattern	District	4
Visual value Roof-scape	District	4
Physical value Roof-scape	District	4
Spatial value Roof-scape	District	4
Visual value Streetscape	District	4
Physical value Streetscape	District	4
Spatial value Streetscape	District	4
Visual value Public open spaces	District	4
Physical value Public open spaces	District	4
Spatial value Public open spaces	District	4
Visual value Walls	External wall	1
Physical value Walls	External wall	1
Spatial value Walls	External wall	1
Visual value Roofs	Roofs	1
Physical value Roofs	Roofs	1
Spatial value Roofs	Roofs	1
Visual value Roof features	Roofs	1
Physical value Roof features	Roofs	1
Spatial value Roof features	Roofs	1
Visual value Windows	Windows	1
Physical value Windows	Windows	1

Variable	Element	Description
Spatial value Windows	Windows	1
Visual value Doors	Doors	0
Physical value Doors	Doors	0
Spatial value Doors	Doors	0
Visual value Building General	Building	1
Physical value Building General	Building	1
Spatial value Building General	Building	1
Visual value common use space	Common Areas	0
Physical value common use space	Common Areas	0
Spatial value common use space	Common Areas	0
Visual value common use interior finishes	Internal walls	0
Physical value common use interior finishes	Internal walls	0
Spatial value common use interior finishes	Internal walls	0
Visual value common use internal walls	Internal walls	0
Physical value common use internal walls	Internal walls	0
Spatial value common use internal walls	Internal walls	0

Table 96: CH ADE (Toural 3)

Energy ADE

At district level:

Variable	Element	Santiago HUD	Source	Unit
Latitude	District	42°52'40"N	Geometric	º
Longitude	District	8°32'40"W	Geometric	º
Outside Min Temperature	District	-1.4	Climatic Database	ºC
Outside Max Temperature	District	33.6	Climatic Database	ºC
Outside Average Min Temperature	District	8.2	Climatic Database	ºC
Outside Average Max Temperature	District	17.6	Climatic Database	ºC
Solar Radiation	District	3.76	Climatic Database	kWh/m²d

Variable	Element	Santiago HUD	Source	Unit
Average annual precipitation	District	1895	Climatic Database	mm
Average relative humidity	District	80	Climatic Database	%
Average annual number of sunshine hours	District	1978	Climatic Database	
Comfort Tº (winter)	District	20	Expert Judgement	ºC
Comfort Tº (summer)	District	25	Expert Judgement	ºC
Set back Tº (winter)	District	17	Expert Judgement	ºC
Set back Tº (summer)	District	25	Expert Judgement	ºC

Table 97: Energy ADE at district level

At building level

Variable	Element	Rua Nova 46-Building	Source	Unit
Number of floors	Building	3	Geometric	
Foot print area	Building	278	Geometric	m2
Volume	Building	2502	Geometric	m3
Thermal mass	Building	High	Expert Judgement	
Use	Building	Residential	Existing Database	
Ventilation strategy	Building	No	Expert Judgement	
Shadow strategy	Building	No	Expert Judgement	
Exist? Heating	IntBuildingInstallation	Yes	Expert Judgement	
Heating Primary Energy	IntBuildingInstallation	Electrical	Expert Judgement	
Heating Individual/Centralised	IntBuildingInstallation	Individual	Expert Judgement	
Heating Efficiency	IntBuildingInstallation	1	Expert Judgement	
Heating Type	IntBuildingInstallation	Electric	Expert Judgement	
Exist? Cooling	IntBuildingInstallation	No	Expert Judgement	
Cooling Individual/Centralised	IntBuildingInstallation	No	Expert Judgement	
Cooling Efficiency	IntBuildingInstallation		Expert Judgement	
Cooling Type	IntBuildingInstallation	Cooling Type	Expert Judgement	

Variable	Element	Rua Nova 46-Building	Source	Unit
Exist? RES	IntBuildingInstallation	No	Expert Judgement	
RES Type	IntBuildingInstallation	-	Expert Judgement	
RES % heating demand covered	IntBuildingInstallation	-	Expert Judgement	

Table 98: Energy ADE at building level (Toural 3)

At element level:

Variable	Element	Rua Nova 46- West	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	West	Geometric	
Wall Area	Boundary Surface/Wall	95,13	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,40	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	-	Expert Judgement	

Table 99: Energy ADE at element level (Toural 3)

Variable	Element	Rua Nova 46- South East Facade	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	South East	Geometric	
Wall Area	Boundary Surface/Wall	94,14	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K

Variable	Element	Rua Nova 46- South East Facade	Source	Unit
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,40	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0	Expert Judgement	

Table 100: Energy ADE at element level (Toural 3)

Variable	Element	Rua Nova 46- South	Source	Unit
Adjoining wall?	Boundary Surface/Wall	No	Geometric	
Wall Orientation	Boundary Surface/Wall	South	Geometric	
Wall Area	Boundary Surface/Wall	185,94	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K
Wall Opening Average U	Boundary Surface/Wall	5,60	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0,40	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	-	Expert Judgement	

Table 101: Energy ADE at element level (Toural 3)

Variable	Element	Rua Nova 46-North	Source	Unit
Adjoining wall?	Boundary Surface/Wall	Yes	Geometric	
Wall Orientation	Boundary Surface/Wall	North	Geometric	
Wall Area	Boundary Surface/Wall	284,46	Geometric	m3
Wall Opaque Average U	Boundary Surface/Wall	2,30	Expert Judgement/Default	W/m2·K

Variable	Element	Rua Nova 46-North	Source	Unit
Wall Opening Average U	Boundary Surface/Wall	0	Expert Judgement	W/m2·K
Wall % Openings	Boundary Surface/Wall	0	Expert Judgement	
Minoration Coefficient	Boundary Surface/Ground	0,50	Expert Judgement	

Table 102: Energy ADE at element level (Toural 3)

Variable	Element	Rua Nova 46-Roof	Source	Unit
Roof Area	Boundary Surface/Roof	278	Geometric	m3
Roof Opaque Average U	Boundary Surface/Roof	1,31	Expert Judgement	W/m2·K
Roof Opening Average U	Boundary Surface/Roof	0	Expert Judgement	W/m2·K
Roof % Openings	Boundary Surface/Roof	0	Expert Judgement	
Is the under roof floor climatizated?	Boundary Surface/Roof	No	Expert Judgement	

Table 103: Energy ADE at element level (Toural 3)

Variable	Element	Rua Nova 46-Ground	Source	Unit
Ground Area	Boundary Surface/Ground	278	Geometric	m3
Ground Opaque Average U	Boundary Surface/Ground	1,4	Expert Judgement	W/m2·K

Table 104: Energy ADE at element level (Toural 3)

Current state identification

The current state identification will be as in the previous cases:

				Energy Demand				Final Energy				Primary energy				CO2 emissions			
				SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY	
		CONSIDERED AREA	EXCLUDED AREA		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVINGS		SAVING	TOTAL IMPACT	SAVINGS
		(m2)	(m2)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(gr/m2)	(%)	Ton	(%)
CURRENT SITUATION																			
	THERMAL	12420,8		157,00		1950065,60		157,00		1950065,60		409,77		5089671,22		265940,73		33031,97	
	ELECTRICITY	12420,81		2,00		24841,60		2,00		24841,60		5,22		64836,63		3387,78		420,79	
	TOTAL							**159,00**		**1974907,20**		**414,99**		**5154507,84**		**269328,51**		**33452,76**	

Table 105: Energy Savings Indicators for case study (Toural 3)

Heritage Significance Assessment

The assessment regarding the HS is directly obtained for the CH ADE. The final results are the following:

	Scale	Building or urban element	Impact area	Rua Nova 22
HS And Conservation Principles	**Urban**	Settlement pattern	Visual	4
			Physical	4
			Spatial	4
		Roof-scape	Visual	4
			Physical	4
			Spatial	4
		Street-scape	Visual	4
			Physical	4
			Spatial	4
		Public spaces	Visual	4
			Physical	4
			Spatial	4
	Building exterior	Walls	Visual	1
			Physical	1
			Spatial	1
		Roofs	Visual	1
			Physical	1
			Spatial	1
		Windows	Visual	1
			Physical	1
			Spatial	1
		Doors	Visual	0
			Physical	0
			Spatial	0
			Spatial	
		Building general	Visual	1
			Physical	1
			Spatial	1
	Building interior	Common use space	Visual	0
			Physical	0
			Spatial	0
		Common Internal Walls	Visual	0
			Physical	0
			Spatial	0
		Private Internal Walls	Visual	0
			Physical	0
			Spatial	0

Table 106: HS and Conservation Principles (Toural 3)

Current State Identification

Taking into account the results shown in the previous tables, the energy class of the building will be E that is a very poor EP.

For HS the obtained results are the following:

Scale	HS
District	4
Building	1
External wall	1
Roofs	1
Windows	1
Doors	0
Internal walls	0
Installations	0

Table 107: Current State regarding HS (Toural 3)

4.7.2 Decision making

Filtered list of solutions according to the constraints:

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	0
5	2	21	214	Chimney dampers and closers	0
2	1	11	112	Instal energy monitoring and management system	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	0
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	0
22	3	32	323	Instal power conditioner / voltage optimiser	0
10	2	22	223	Exterior insulation with insulation plaster 5 cm	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	0
18	3	31	311	Install a new gas boiler	0
19	3	31	312	Install a condensing boiler	0
6	2	21	215	Instal draught lobby at external doors	0
20	3	32	321	Instal low energy lighting	0
21	3	32	322	Instal low energy appliances	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	1
3	2	21	212	Sealimg of all openings and joints	1
4	2	21	213	Airtightness of windows	1
7	2	21	216	Airtightness membrane to underside roof	1
8	2	22	221	Exterior insulation with a composite system 10 cm	2
9	2	22	222	Exterior insulation with ventilated cavity	2
14	2	23	231	Instal high performance window and glazing systems	2

Table 108: Filtered list of solutions for Toural 3

Target definition

As seen in the current state, the Toural 3 building has a very poor EP and a medium HS of its elements. It will be used the same scenarios used previously.

	Scenario 1	Scenario 2
Thermal Comfort	0,071	0,46
IAQ	0,089	0,03
Energy Saving	0,558	0,15
Cost	0,38	0,06
Low impact solutions	0,073	0,29

Table 109: Final weights for scenario 1 and 2

Ranked list of solutions

Ranked list of solutions for scenario 1

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S1	APPLICABILITY
2	1	11	112	Instal energy monitoring and management system	2,867	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	2,794	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	2,653	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	2,586	0
3	2	21	212	Sealimg of all openings and joints	2,432	1
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	2,376	0
18	3	31	311	Install a new gas boiler	2,236	0
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	2,144	0
5	2	21	214	Chimney dampers and closers	1,913	0
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	1,893	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	1,735	1
10	2	22	223	Exterior insulation with insulation plaster 5 cm	1,674	0
4	2	21	213	Airtightness of windows	1,666	1
20	3	32	321	Instal low energy lighting	1,605	0
21	3	32	322	Instal low energy appliances	1,605	0
7	2	21	216	Airtightness membrane to underside roof	1,399	1
6	2	21	215	Instal draught lobby at external doors	1,342	0
19	3	31	312	Install a condensing boiler	1,328	0
22	3	32	323	Instal power conditioner / voltage optimiser	1,058	0

Table 110: Ranked list of solutions for scenario 1 (Toural 3)

Ranked list of solutions for scenario 2

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S2	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	2,56	0
5	2	21	214	Chimney dampers and closers	2,5	0
2	1	11	112	Instal energy monitoring and management system	2,48	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	2,24	0
13	2	22	226	Insulation of an existing cavity 5cm (perlite)	2,21	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	2,09	1
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	2,04	0
3	2	21	212	Sealimg of all openings and joints	1,67	1
4	2	21	213	Airtightness of windows	1,46	1
7	2	21	216	Airtightness membrane to underside roof	1,37	1
22	3	32	323	Instal power conditioner / voltage optimiser	1,37	0
10	2	22	223	Exterior insulation with insulation plaster 5 cm	1,34	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	1,3	0
17	2	24	242	Thermal insulation of the rooftop (40 mm)	1,24	0
18	3	31	311	Install a new gas boiler	1,15	0
19	3	31	312	Install a condensing boiler	0,91	0
6	2	21	215	Instal draught lobby at external doors	0,82	0
20	3	32	321	Instal low energy lighting	0,71	0
21	3	32	322	Instal low energy appliances	0,71	0

Table 111: Ranked list of solutions for scenario 2 (Toural 3)

Strategy Generation

Strategy for scenario 1

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S1	APPLICABILITY
2	1	11	112	Instal energy monitoring and management system	2,867	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	2,794	0
11	2	22	224	Diffusion closed interior insulation 10 cm (mineral wool)	2,653	0
3	2	21	212	Sealimg of all openings and joints	2,432	1
18	3	31	311	Install a new gas boiler	2,236	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	1,735	1
20	3	32	321	Instal low energy lighting	1,605	0

Table 112: Strategy for scenario 1(Toural 3)

Strategy for scenario 2

ID	STEP	STRATEGY	CODE	RETROFIT MEASURE	TOTAL SCORE S2	APPLICABILITY
1	1	11	111	Implement energy mgmt procedures for EE and education program related to energy saving actions for occupants	2,56	0
5	2	21	214	Chimney dampers and closers	2,5	0
12	2	22	225	Diffusion-open, capillary-active interior insulation systems 5cm IQ-Therm	2,24	0
15	2	23	232	Install secondary double glazing with wooden frame and shutters	2,09	1
22	3	32	323	Instal power conditioner / voltage optimiser	1,37	0
16	2	24	241	Thermal insulation of the rooftop (20 mm)	1,3	0
18	3	31	311	Install a new gas boiler	1,15	0

Table 113: Strategy for scenario 2 (Toural 3)

Impact adjustment

The coefficients that are considered for the impact adjustment can be seen in the next table (see 2.7.4):

Impact adjustment	Percentage of reductions	Considered Area (m2)
Total area of the whole typology		**17744,00**
Total heated area	0,7	12420,80
Applicability of solutions	1	12420,80
Recent renovations	0,99	12296,59
Adjusted area		**12296,59**

Table 114: Impact adjustment for Toural 3

Assessment of the Scenarios

In the following table it is shown the results of the two scenarios:

				Energy Demand				Final Energy				Primary energy				CO2 emissions								
				SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY		SAMPLE BUILDING		TIPOLOGY						
		CONSIDERED AREA	EXCLUDED AREA		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVING		SAVING	TOTAL IMPACT	SAVINGS		SAVING	TOTAL IMPACT	SAVINGS					
		(m2)	(m2)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(kWh/m2)	(%)	(kWh/year)	(%)	(gr/m2)	(%)	Ton	(%)					
CURRENT SITUATION																								
	THERMAL	12420,8		157,00		1950065,60		157,00		1950065,60		409,77		5089671,22		265940,73		33031,97						
	ELECTRICITY	12420,81		2,00		24841,60		2,00		24841,60		5,22		64836,63		3387,78		420,79						
	TOTAL							159,00		1974907,20		414,99		5154507,84		269328,51		33452,76		TOTAL IMPACT IN INDICATORS				
																				HS	TC	IAQ	ES	COST
SCENARIO 1																								
IMPLEMENTED	THERMAL	12296,56	124,24	39,20	75,03%	482025,15	75,28%	44,70		549910,83		45,14		606035,71		9209,54		1462,86						
STRATEGIES	ELECTRICITY	12296,56	124,25	1,70	15,00%	21152,63	14,85%	1,70		21030,40		4,44		55208,42		2879,61		358,30						
112/241/224/212/311/232/321	TOTAL							46,40	70,82%	570941,23		49,58	88,05%	661244,13	87,17%	12089,15	95,51%	1821,16	94,56%	39,29%	32,14%	21,43%	67,86%	64,29%
SCENARIO 2																								
IMPLEMENTED	THERMAL	12296,56	124,24	51,00	67,52%	646630,24	66,84%	58,15		734585,00		58,73		773139,9338		11981,80		1803,75						
STRATEGIES	ELECTRICITY	12296,56	124,25	1,80	10,00%	22382,31	9,90%	1,80		22382,31		4,70		58417,82388		3049,00		379,13						
	TOTAL							59,95	62,29%	756967,30	61,67%	63,43	84,71%	831557,76	83,87%	15030,80	94,42%	2182,89	93,47%	64,29%	35,71%	21,43%	53,57%	57,14%

Table 115: Results of Toural 3

4.8 Results of the case study

4.8.1 Multiscale data model of Santiago

The following figures present the implementation of the EFFESUS multiscale data model developed within the EFFESUS project[78]. The Figure 56 partially shows the 3D geometric model of the city of Santiago de Compostela including textured DTM, roads, green areas and buildings in LoD1.

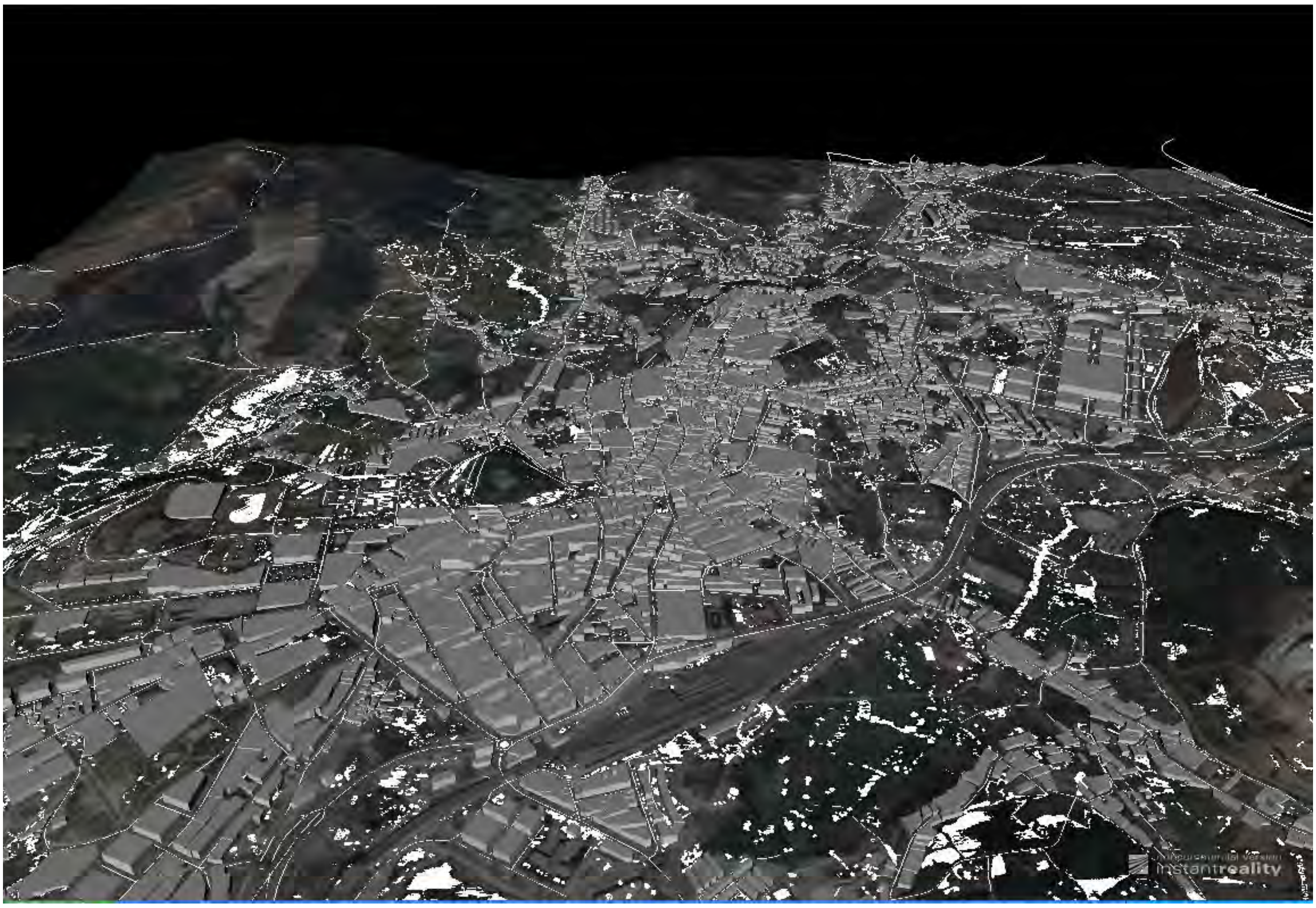


Figure 56: 3D Geometric model of Santiago de Compostela in LoD1

The next figure presents the historic centre of Santiago de Compostela with building in LoD2, textured DTM, roads and green areas in 3D for web format (x3d).

[78] *Ibid 67*

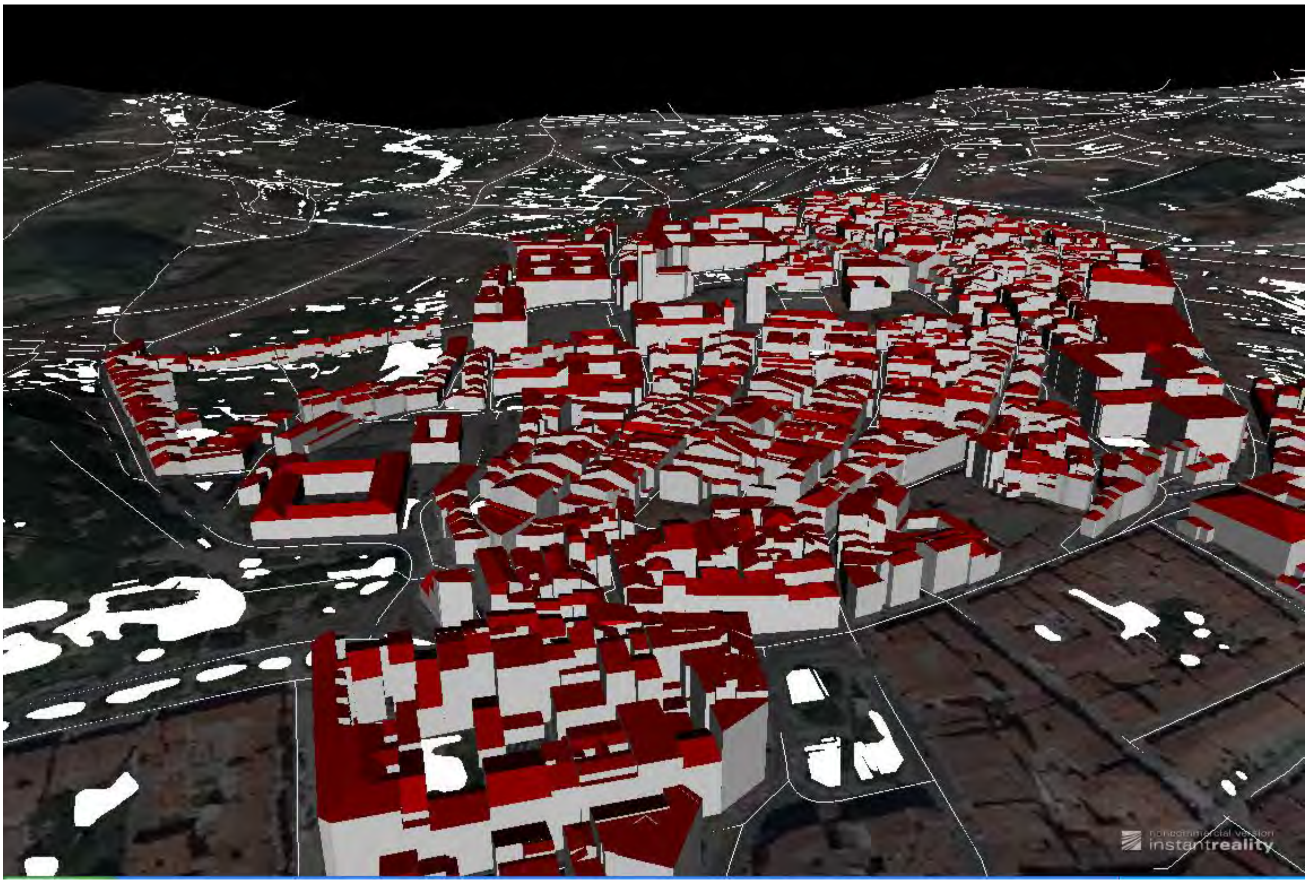


Figure 57: HUD of Santiago with building in LoD2

4.8.2 Comparison of results

The following table shows the comparison of the results of the three typologies that have been studied. The conclusions of the implementations will be made in Section 5.5. The energy savings and the percentages of indicator achievement have been coloured with the following code:

Code	Percentage	
	<30%	Minor energy savings and improvements
	30%-60%	Moderate energy savings and improvements
	60%-90%	Major energy savings and improvements
	>90%	Deep energy savings and improvements

Table 116: Energy savings and indicator improvements for comparison of results

	Rua Nova 22	Rua Nova 46	Toural 3
USE	RESIDENTIAL	RESIDENTIAL	RESIDENTIAL
NUMBER OF FACADES	2	2	3
YEAR OF CONSTRUCTION	1800-1900	1800-1900	1800-1900
LEVEL OF PROTECTION	3	4	4
TYPOLPOGY ID.	1223	1224	1324
REPRESENTATIVITY	9,52%	27,99%	6,78%
NUMBER OF BUILDINGS	66	194	47
CONSIDERED AREA (M2)	24885,7	44769,55	12420,8
IMPACT AREA (M2)	24636,84 (99%)	15955,86 (35,64%)	12296,56 (99%)
SAMPLE BUILDING	Rua Nova 22	Rua Nova 46	Toural 3

CURRENT SITUATION

	Rua Nova 22 Sample	Rua Nova 22 Tipology	Rua Nova 46 Sample	Rua Nova 46 Tipology	Toural 3 Sample	Toural 3 Tipology
Thermal energy demand	137 kWh/m2	3409341 kWh	175,56 kWh/m2	11229482,3 kWh	157 kWh/m2	1950066 kWh
Electricity demand	2 kWh/m2	49771,4 kWh	2 kWh/m2	127913 kWh	2 kWh/m2	24841,6 kWh
CO2 emissions	235450,71 gr/m2	58593,56 ton	300800,99 gr/m2	134667,25 ton	269328,51 gr/m2	33452,76 ton

STRATEGIES

Rua Nova 22 (1223)

S1	ES and low budget solutions prefered	S2	Low impact solutions and TC prefered
112	Instal energy monitoring and management system	111	Implement energy mgmt procedures for EE
241	Thermal insulation of the rooftop (20 mm)	214	Chimney dampers and closers
224	Diffusion closed interior insulation 10 cm	225	Diffusion-open, capillary-active interior insulation
311	Install a new gas boiler	323	Instal power conditioner / voltage optimiser
214	Chimney dampers and closers	241	Thermal insulation of the rooftop (20 mm)
321	Instal low energy lighting	311	Install a new gas boiler

Rua Nova 46 (1224)

S1	ES and low budget solutions prefered	S2	Low impact solutions and TC prefered
112	Instal energy monitoring and management system	111	Implement energy mgmt procedures for EE
241	Thermal insulation of the rooftop (20 mm)	214	Chimney dampers and closers
224	Diffusion closed interior insulation 10 cm	225	Diffusion-open, capillary-active interior insulation systems
212	Sealimg of all openings and joints	232	Install secondary double glazing
231	Instal high performance window	323	Instal power conditioner / voltage optimiser
311	Install a new gas boiler	241	Thermal insulation of the rooftop (20 mm)
321	Instal low energy lighting	311	Install a new gas boiler

Toural 3 (1324)

S1	ES and low budget solutions prefered	S2	Low impact solutions and TC prefered
112	Instal energy monitoring and management system	111	Implement energy mgmt procedures for EE
241	Thermal insulation of the rooftop (20 mm)	214	Chimney dampers and closers
224	Diffusion closed interior insulation 10 cm (mineral wool)	225	Diffusion-open interior insulation systems
212	Sealimg of all openings and joints	232	Install secondary double glazing
311	Install a new gas boiler	323	Instal power conditioner / voltage optimiser
232	Install secondary double glazing	241	Thermal insulation of the rooftop (20 mm)
321	Instal low energy lighting	311	Install a new gas boiler

IMPACT

Building	Strategy	Indicator	Sample building	Savings	Tipology	Savings
Rua Nova 22	S1	Thermal energy demand	47,2 kWh/m2	65,55%	1162859 kWh	65,00%
Rua Nova 22	S1	Electricity demand	1,7 kWh/m2	15,00%	42380,35 kWh	15,00%
Rua Nova 22	S1	CO2 emissions	13968,65 gr/m2	94%	4027,371 ton	93%
Rua Nova 22	S2	Thermal energy demand	54,4 kWh/m2	60,29%	1374337,67 kWh	59,69%
Rua Nova 22	S2	Electricity demand	1,8 kWh/m2	10,00%	44844,03 kWh	9,90%
Rua Nova 22	S2	CO2 emissions	15829,59 gr/m2	93,28%	4485,85 ton	92%
Rua Nova 46	S1	Thermal energy demand	25,6 kWh/m2	85,42%	5467576,6 kWh	30,44%
Rua Nova 46	S1	Electricity demand	1,7 kWh/m2	15,00%	84752,34 kWh	5,35%
Rua Nova 46	S1	CO2 emissions	6919,54 gr/m2	97,70%	5552328,9 ton	34,82%
Rua Nova 46	S2	Thermal energy demand	37,4 kWh/m2	78,70%	5655855,80 kWh	28,05%
Rua Nova 46	S2	Electricity demand	1,8 kWh/m2	10,00%	86347,93 kWh	3,56%
Rua Nova 46	S2	CO2 emissions	9745,05 gr/m2	96,76%	88226,75 ton	34,49%
Toural 3	S1	Thermal energy demand	39,20 kWh/m2	75,03%	482025,15 kWh	75%
Toural 3	S1	Electricity demand	1,70 kWh/m2	15,00%	21152,63 kWh	14,85%
Toural 3	S1	CO2 emissions	12089,15 gr/m2	95,51%	1821,16 ton	95%
Toural 3	S2	Thermal energy demand	51,00 kWh/m2	67,52%	646630,24 kWh	67%
Toural 3	S2	Electricity demand	1,80 kWh/m2	10,00%	22382,31 kWh	9,90%
Toural 3	S2	CO2 emissions	15030,80 gr/m2	94,42%	2182,89 ton	93%

Indicators

Building	Strategy	TC	IAQ	ES	Cost	LIS
Rua Nova 22	S1	29,17%	4,17%	70,83%	62,50%	50,00%
Rua Nova 22	S2	29,17%	12,50%	58,33%	54,17%	70,83%
Rua Nova 46	S1	32,14%	21,43%	75%	57,14%	35,71%
Rua Nova 46	S2	35,71%	21,43%	53,57%	57,14%	64,29%
Toural 3	S1	32,14%	21,43%	67,86%	64,29%	39,29%
Toural 3	S2	35,71%	21,43%	53,57%	57,14%	64,29%

Table 117: Comparison of results

5 CONCLUSIONS

A conclusion is simply the place
where you got tired of thinking
Dan Chaon,
Stay Awake

In this dissertation, a look at the Historic Urban Districts as complex energy and informational systems has been taken. HUDs face the same challenge of other more modern urban entities: the need to make the life in the cities more sustainable and more liveable for their citizens. This common goal is even more necessary for HUDs as their conservation as priceless cultural structures relies in their capacity of surviving as living cities. The appropriate energy management is one of the keystones for improving both the sustainability and the liveability of the HUDs and one of the premises of this research was that a strategic information management could be the answer.

Three main topics have been developed within this thesis: the comprehensive methodological framework, where the energy retrofitting of HUD is articulated from a multiscale approach, the DM methodology that allows the selection of the strategies, and the multiscale information management that supports the whole system. The historic city of Santiago de Compostela has been selected for the implementation.

5.1 Main contributions

The main contributions of this dissertation are the following:

- → A framework for energy retrofitting of HUDs that aims to be applicable in the majority of the European historic districts. The framework is based on a strategic information management and in a multiscale perspective in order to ensure the feasibility, efficiency, continuity and coherence of the whole energy retrofitting cycle at urban level.
- → A modelling strategy for HUDs based on a categorization of the building stock and the selection of sample buildings which takes into account the historic quality of the building stock as well as their energy characteristics. Easily acquired parameters have been proposed as well

as a method to carry out the categorization in a flexible way. Depending on the selection of the sample buildings and therefore in the applicability of the strategies *impact adjustment coefficients* have been proposed in order to correct the final impact.

→ Different levels of DM (LoDM) have been proposed for the decision making in order to accommodate the methodology to different possible scenarios of information availability.

→ Four criteria and two categories of constraints have been proposed in order to consider the important factors of the DM for energy retrofitting in historic environments. For the assessment of the constraints (HS and fabric compatibility) a method developed in the EFFESUS project has been adapted and for the multicriteria DM the use of the AHP method has been proposed.

→ Four extensions for a multiscale data model, based on a standard, have been proposed in order to support the strategic information management and the DM. Two of the extensions aim to use the extensibility of the data model to structure all the thematic information required regarding the energy and cultural characteristics of the buildings. The third one structures the information about the indicators in order to enable the monitoring and the fourth one deals with the dynamic data.

5.2 Conclusions about the methodological framework

Energy and functional requalification of HUDs is basically a matter of sustainable management of its evolution. It is about the design and the planning of the next steps in the continuous evolution of the HUDs towards the adaptation of their historic fabric to the requirements of each epoch. Sustainability and liveability are two modern concerns that are not unfamiliar to the historic cities as they are in the roots of any successful city that has survived until our times.

This first chapter had the aim to set the methodological framework for a comprehensive system that will support the energy retrofitting of HUDs in order to improve the liveability and the sustainability. Some conclusions could be made:

→ Updating of the HUDs is not only important from the cultural point of view, it is also important from global goals perspective as an important percentage of our existing building stock is preindustrial.

→ Preindustrial buildings have their own way to deal with the management of environmental conditions in order to answer efficiently to the liveability requirements. This nature of old buildings and old districts of being energy systems can be considered also as part of their cultural values and its understanding could help in the design and planning of new ways to preserve our urban heritage.

- → The operative scale of energy retrofitting and cultural heritage conservation is the building but the strategic scale is the district. Energy management is an interscalar topic where a multiscalar approach is necessary.
- → A framework that covers the whole cycle articulating the diagnosis, the DM, the implementation and the subsequent management and maintenance is necessary, but so far the frameworks and methodologies that were proposed have some limitations that the proposed methodology aims to overcome. First, they have been specifically tailored for a specific HUD making their replication not easy. The multiscalarity is not specifically addressed and moreover, they do not propose any kind of strategy for the management of information consistent to all the phases that will ensure the interconnection between scales and that will allow to the system to learn from itself.
- → The interconnection between scales can only be done managing the flow of information. A strategic information management is the principle for the feasibility of a comprehensive system in the long term. The efficient management of the information (regarding the energy and heritage characteristics of the buildings, the implications and impacts of the different measures, and indicators that measure and monitorize the important criteria…) is the only way to design, implement and maintain a coherent strategy over the time. It supports also the feedback regarding the real improvements of the strategies and therefore the system can learn from itself.
- → To facilitate the implementation, the framework is divided in two stages: a first one where the diagnosis is carried out and the strategy is defined through a DM methodology and a second one where the energy retrofitting program is designed. This research has been focused in the first stage.

5.3 Conclusions about decision making methodology

The second chapter intended to establish the methodology for supporting the DM to select the strategies for improving the EP and the liveability of HUDs while respecting their cultural values. Some conclusions:

- → The first step in any DM process is to identify what we want to achieve with that decision and consequently to select the optimum key influencing factors for that decision. The literature review shows us that various criteria have been used for improving energy efficiency of the buildings, but so far they have not been integrated in a harmonised way with the constraints of a cultural heritage environment. Three axes to integrate the improvement criteria as well as the constraints in a balanced way have been proposed: efficient resource management, improvement of liveability and preservation of cultural values. These axes lead us to four criteria (indoor environmental conditions, embodied energy, operational energy, economic return) and two constraints (HS and fabric compatibility) for DM.

→ DM is about which information we are going to use and how we are going to use it. In the information era, it is critical to decide on which information we are going to rely to model the HUD for the DM, due to the overflow of heterogeneous urban information (heterogeneous in quality, in veracity, in format, in purposes…). Different options have been analysed for this modelling and the sample buildings strategy has proved itself the most suitable as the main modelling strategy for our purposes, although others as buildings group or identification of priority areas could be used in different stages. The reason for selecting this strategy is that it is the only option that allows an incremental use of the information, takes into account the cultural values of the buildings and that can be used as first step for other kinds of more complete modelling.

→ A method to use the *sample building modelling* strategy in HUD´s energy retrofitting has been proposed. The final goal is to generate a limited number of unique samples that reflect almost the entire stock of the HUD. In order to categorize the building stock in different typologies, it is necessary to choose carefully the parameters that will be easy to obtain and from which we can infer meaningful information for the clustering process. A literature review has been done to find the parameters that reflect the energy characteristics of the buildings and finally the use of the building, volume, number of facades and year of construction have been selected. But previous proposals to categorise the building stock from the energy perspective did not have taken into account the buildings of a HUDs as cultural entities. Therefore, additional parameters are proposed as the level of protection of the buildings. This parameter along with the already used year of construction and use will reflect the historic significance of the considered buildings.

→ The selection of the sample building that will represent the whole typology is a strategic decision for the decision maker, especially when the HS (or protection) of the elements of the building is not correlated with the general HS (or protection) of the whole building. The applicability of the results and the effectiveness of them will depend on the sample selected: the higher the constraints regarding the elements the higher the applicability (less impact on the HS but less impact also on the energy savings). Therefore if a sample building is selected which elements that are less protected than the building (and typology), the applicability will be smaller but the energy savings for this area bigger. This strategy could be reasonable to avoid the *loss of the opportunity* that happens when a retrofitting is done just with minor measures, but in a vulnerable context like a HUD has to be thought carefully. *Impact* *adjustment* coefficients have been proposed in order to correct the final impact due to the applicability of the strategies.

→ The diversity of HUDs in Europe demands a high flexibility in the design of the DM methodology. Four different LoDM have been proposed in order to cover the possibilities regarding the availability of information. These levels range from not having any information regarding the HUD to complete information data models. The higher the level of information the higher the accuracy of results. This research has focused in LoDM II, which is considered the core, as it is the level where optimum balance between the easiness of information acquisition and the meaningfulness of results is obtained. The previous two levels (LoDM 0 and LoDM I) can be considered as preparatory stages for a real urban energy rehabilitation strategy and the LoDM III can be understood as a second phase. This proposal of flexibility and continuity between different levels of information availability tries to overcome the limitations of previously proposed methodologies which did not take into account different scenarios regarding the information. This lack of flexibility forces time-consuming data acquisition when the available data are scarce, or to waste already existing information infrastructures when available data are rich.

→ The two main assessments that guide the DM process are the HS assessment and the EP assessment. For the HS, an adaptation of the method established in EFFESUS is proposed where the vulnerability/significance of the building elements is confronted with the impact of the measures in the HS. Based on the potentialities of the multiscale data model, this assessment can be done in element scale, and the not suitable measures could be discarded accurately. For the EP assessment the used method is the quasi-steady state monthly method explained in the EN ISO 13790:2008, Energy performance of buildings -- Calculation of energy use for space heating and cooling (ISO 2008). The use of this method is proposed due to its robustness and flexibility and the fact that it has been use previously for large scale energy assessment supported by multiscale data models.

→ A multicriteria DM methodology has been proposed based on the AHP method. The preferences of the decision maker regarding the criteria (thermal comfort, indoor air quality, energy savings, low budget solutions and low impact solutions) and the vulnerability assessment are translated to the DM for selection of the strategies. Those strategies are solutions that have been packed together due to their complementarity.

5.4 Conclusions about the multiscale information management

The third chapter proposes a solution which satisfies the requirements made in the two previous chapters regarding a mechanism to organise and structure the information regarding the HUD. A multiscale data model is designed to support the information necessities within the framework and in the DM methodology. Some conclusions:

- → As the heterogeneous information regarding the HUDs grows exponentially it gets more and more important to design ways to structure and update those information in order to exploit it at maximum for diagnosis, DM or management. It is important that cross-thematic information is structured in the same infrastructures so the necessary links and influences between different domains are identified and captured. The low cost generation of the model is another of the requirements identified.
- → The CityGML standard has been selected to build our data model. It has been chosen because it is the only format that fulfils all the identified requirements: 3D and georeferenced, based on a standard, extensible and multiscalar, it can structure semantic and geometric information in a coherent way and it is interoperable with other data models aimed at smaller scales (BIM) or bigger ones (GIS).
- → A unique model, based on real data has been proposed to structure all the geometric and crossthematic semantic information necessary to back the whole methodological framework described in Chapter 1 and to support the DM process described in the Chapter 2.
- → The 3D data model can storage information about the HUD at component level, especially important in historic cities where the building component has values that have to be documented and protected. This structure also allows making large scale assessments.
- → A strategic information management has been proposed as a broader concept than a specific data model. That means a strategic approach to the targeted data acquisition and usage and the seeking for the right balance between the minimum data and the accuracy of the results.
- → Using the extensibility of the data model, four different extensions have been proposed that address the detected thematic information requirements: an Energy Performance Domain Extension (Energy ADE) to organise the energy characteristics, a Cultural Heritage Domain Extension (Cultural Heritage ADE) to structure the HS and fabric compatibility information, an Indicators Domain Extension (Indicators ADE) to store the information regarding indicators and a Dynamic Domain Extension (Dynamic ADE) that deals with information that is not static.

5.5 Conclusions of the implementation of the methodology in a case study

The fourth chapter addresses the implementation of the DM methodology in the case study of Santiago de Compostela. Three typologies with a high representativity have been selected in order to test the validity of the proposal. The typologies have been selected in order to allow a pairwise comparison to see the effect of key parameters in the final results. The number of facades (determinant in the EP of the buildings) and the level of protection (key in their HS) have been chosen as key parameters. Some conclusions:

→ The DM methodology developed within this dissertation is feasible and affordable in order to build energy retrofitting strategies at urban level. Thanks to the multiscale data model and the sample building modelling strategy, it is possible to implement this DM methodology within a medium level information scenario. The majority of required data can be obtained quite easily from public sources and can be added to the data model almost automatically. The rest of the data have to be introduced by the user, but they are easy to obtain having a minimum knowledge of the chosen HUD.

→ The method for building stock categorization based on easily acquired parameters (use, number of facades, year of construction and level of protection)gives optimal balance regarding the number of typologies and the represented percentage of the building stock (in the case of Santiago the manageable amount of 10 typologies represent the 80,52% of the building stock)

→ The DM methodology, based on a tailored multiscale data model and implementing the sample buildings modelling strategy, improves the balance between the required information and the accuracy of the results. For example, quite accurate estimations regarding the energy demand of the buildings can be achieved with this method, as it has been proven by comparing the results obtained for the building Rua Nova 22 with the results obtained in (Liñares Mendez 2012) for the same building obtained with more complex methods and more complete information (the difference between the two results is lower than 4%).

→ An impact adjustment is necessary in order to adjust the theoretical applicability of the strategies. The influence can be seen clearly in the typology 1224 where the selected sample building windows have a lower HS than the typology in general. The results are higher energy savings per area (from 20 to 30 percentage points more for the same scenario), as the changing of old windows for high performance windows and glazing systems is an effective energy saving measure especially when the window/opaque ratio is high like in Santiago. But the overall impact is lower (from 30 to 35 percentage points less for the same scenario) as the applicability is lower and an impact adjustment coefficient has to be applied.

→ The user preferences regarding the criteria evidently determine the resulting strategies and the obtained improvements, but not linearly. Energy Savings obtained with strategies that prefer low impact solutions are only 5-8 percentage points lower than the ones that strongly preferred the energy savings; however those strategies have a 20-30 percentage points less impact in the HS of the HUDs.

→ Specific energy retrofitting strategies can be designed using the results obtained by the methodology. For the case of Santiago the following results can be highlighted:

- The EP of the buildings of the HUD is in general very poor, but high energy savings could be obtained per area (from 65% to 85% in thermal energy demand and more than 90% in Co2 emissions) with solutions that are respectful with the historic significance of the HUD.
- Low impact solutions related with the energy management have very good cost effectiveness and have to be preferred to other solutions as first step; however, more invasive solutions that improve the envelope of the buildings (airtightness and thermal characteristics) have a great impact in thermal comfort and energy savings and are suitable for HUDs if an impact assessment is carried out before.
- The energy savings obtained by insulation are not linearly proportional to its thickness; therefore thinner layers with less impact in the HS could suppose enough insulation for a mild climate as the one in Santiago.
- In the considered area, according to the PE data, only the 4.31% of the buildings have gas infrastructure. Changing the electrical heaters to gas boilers supposed a big saving in primary energy and therefore big reductions in CO_2 emissions (more than 90%). That is the kind of solution that is not addressed at building level but that is sound and attractive at district level once the whole impact is estimated, even for private investors.

6 FUTURE PERSPECTIVES

Calvin: It's a magical world, Hobbes,
ol' buddy…Let's go exploring!
Bill Watterson,
Calvin's last words (Calvin & Hobbes)

The natural continuation of this research is to extend the detailed development to other phases of the process and to higher levels of DM and Accuracy:

→ developing the management phase and detailing the generation of the Energy Retrofitting Program, especially the mechanisms of monitoring, maintenance and interconnection between scales using the multiscale data model
→ detailing the DM process at LoDM III, especially identifying the possibilities of using big data analysis with a model in a higher level of completeness
→ designing the feedback mechanism that will allow to refine the DM methodology
→ identifying the tools and databases, and their interoperability requirements, that could feed the model at level of Accuracy 3 and 5

Nevertheless, a strategic information management supported by an extensible multiscale data model has a huge potential in urban analysis and management not only in historic environments. A model, as the one proposed, can be the answer for smart city approaches and contemporary urban DM processes in need of models with integrated capabilities. In this line, some of the future research lines could be:

→ Extent the role of the fourth dimension: the use of the model for a monitoring in real time including the information provided by sensors or the extension of the model with more time-dependant information giving to the 4^{th} dimension more potential.
→ Improve the accuracy and scope of the energy analysis: the model can be used for more accurate energy calculations implementing own algorithms within the model or using the model to feed external tools. The energy behaviour associated with occupants can be modelled and included into the model.

- → Complement the energy analysis with other kind of analysis: the spatial and multiscale features of the model enables complementary analysis like life cycle analysis, risk assessment, economic and social studies, vulnerability assessments or landscape analysis
- → Ontology-based urban data models: the enhancement of the model with ontologies coming from the fields of urban planning, energy and cultural heritage, would improve the interoperability and the communication between the different stakeholders.
- → Extent the semantic capabilities of the model for its use for the multiscale documentation of the cultural heritage and its management at urban scale.
- → Extent the visualization capabilities in order to support more types of analysis and advanced visualization facilities to make the information more accessible to stakeholders and citizens.

As results of this thesis, various publications are foreseen:

- → A paper called "Multiscale information management: The role of urban data models in the sustainable DM of the historic district" is being prepared in collaboration with Dr Jose Luis Izkara and Mr Iñaki Prieto. It is expected to be submitted to "Journal of Urban Technology" before the end of 2015. The paper will be focused in the design and development of the multiscale data model (Chapter 3).
- → Another paper regarding the methodology of DM (Chapter 2) is planned for 2016 possibly with the collaboration of the Prof Tor Broström from Uppsala University (Sweden).
- → The Chapters 1 and 4, the methodological framework and the implementation in Santiago the Compostela, are expected to be the basis for two conference papers. An abstract called "Facilitating historic districts energy retrofitting through a comprehensive multiscale framework and its implementation in the EFFESUS Decision Support System" based on the Chapter 1 and written in collaboration with Dr Jose Luis Izkara have been already submitted to the "2nd International Conference on Energy Efficiency and Comfort of Historic Buildings (EECHB2016)".

7 BIBLIOGRAPHY

Let others pride themselves about
how many pages they have written;
I'd rather boast about the ones I've
read
Jorge Luis Borges,
Elogio de la sombra

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Annex I

Information					Decision making		Data Model	Repository	
Subcategory	Specific Indicator	Parameter	Unit of measure/scale	ELEMENT	Data available/measure with sensors or other	Priority for DM	Scale	tech. for the retrofitting	tech. supplying RE
Thermal comfort	**Temperature**	**Air temperature**	**°C**	**Room**	**Easy measure with sensors**	**Very high**	**Dwelling level**	**0-4 scale**	**Not applicable**
	Relative humidity	**Relative air humidity**	**%**	**Room**	**Easy measure with sensors**	**Very high**	**Dwelling level**		
	Predicted mean vote (PMV)	Air temperature	°C	Room	Easy measure with sensors	High	Dwelling level		
		Mean radiant temperature	°C	Room	Easy measure with sensors				
		Relative air humidity	%	Room	Easy measure with sensors				
		Air velocity	m/s	Room	Easy measure with sensors				
		Metabolic rate	met	Occupants	easy with tabulated values				
		Clothing insulation	clo	Occupants	easy with tabulated values				
		Calculated PMV	7 point scale (from -3 to +3)	Room and occupants	Calculated				
	Predicted percentage dissatisfied (PPD)	derived from PMV	%	Room and occupants	Easy if PMV is known	High	Dwelling level		
Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	average sound pressure level over 30 minutes	dB	Room	Easy with suitable sensors	Medium	Dwelling level	**0-4 scale**	
Visual comfort	Mean maintained illuminance	Average value of illuminance on a surface	lux	Room	Easy with suitable sensors or smartphone app	High	Dwelling level	**0-4 scale**	
	Illuminance uniformity	Ratio between minimum and average illuminance on a surface	number	Room	Calculated from illuminance values measured with suitable sensors	Medium	Dwelling level		
	Color rendering index (CRI) for lighting	Effect of light source on perceived colours of objects and surfaces	100 point scale	Room	Easy with suitable sensors	Low	Dwelling level		
	Daylight factor	Ratio between illuminance from skylight on horizontal surface within the room and illuminance	%	Room	Calculated from illuminance values measured with suitable sensors	High	Dwelling level		
Indoor air quality (IAQ)	**Pollutants**	**TVOC**	**mg/m^3**	**Room**	**Easy with suitable sensors**	**Very high**	**Dwelling level**	**0-4**	
		CO and CO_2	**mg/m^3**	**Room**			**Dwelling level**		
		NO_2	**µg/m^3**	**Room**			**Dwelling level**		
		$PM_{2,5}$,PM_{10}	**mg/m^3**	**Room**			**Dwelling level**		
	Microbial pollution	Persistent dampness and/or presence of condensation on surfaces or in	predefined scale	Room	Easy with suitable sensors	High	Dwelling level		
		Microbial growth, visible or odour perceived of mould	predefined scale	Room	Easy with visual inspection	High	Dwelling level		
		History of water damage, leakage or penetration	predefined scale	Room	Easy if documents are available	Medium	Dwelling level		
	Ventilation rate	**Ventilation for pollution from the occupancy**	**l/s/pers**	**Room and occupants**	**Easy with suitable sensors**	**Very high**	**Dwelling level**		
		Ventilation for pollution from the building itself	**l/s,m^2**	**Room**			**Dwelling level**		

Table 118: Indicators regarding indoor environmental conditions

Information					Decision making		Data Model	Repository	
Subcategory	**Specific Indicator**	**Parameter**	**Unit of measure/scale**	**ELEMENT**	**Data available/measure with sensors or other**	**Priority for DM**	**Scale**	**tech. for the retrofitting**	**tech. supplying RE**
Electrical energy use	**Total use/year**	**Energy use**	**KWh/ time period**	Building/ District	**Data available or easily measurable**	**Very high**	Building/ District	Determined the Energy Saving Potential	
		Floor area	**m^2**						
		Total use/year	**KWh/year**						
	Electricity use per m^2 building area	Energy use	kWh/m^2 time period		Data available or easily measurable	High			
		Floor area	m^2						
		Electricity use per m^2	kWh/m^2 time period						
Thermal energy use (heating and cooling)	**Total use/year**	**Energy use**	**KWh/ time period**		**Data available or easily measurable**	**Very high**			
		Floor area	**m^2**						
		Total use/year	**KWh/year**						
	Thermal energy use per m^2 building area	Energy use	kWh/m^2 time period		Data available or easily measurable	High			
		Floor area	m^2						
		Thermal energy use per m^2	kWh/m^2 time period						
CO_2 emissions	Total for a building or a district	Calculated from energy use	kg/time period		Easy with suitable sensors	High			
Peak power demand	Total for a building or a district	Hourly power demand	kW		Easy with suitable sensors	High			
% RES: Electric Thermal	Fraction of energy supply from renewable energy sources	Measure values and statistics	%		Data available or easily measurable	High			

Table 119: Indicators regarding Operational Energy

Information				Decision making		Data Model	Repository	
Subcategory	Specific Indicator	Unit of measure/scale	ELEMENT	Data available/measure with sensors or other	Priority for DM	Scale	tech. for the retrofitting	tech. supplying RE
Comprehensive (life cycle) energy consumption	Total Primary Energy consumption (over 100 years)	kWh/m² or MJ/m²	Building/district (and additionallly more detailed level as e.g. wall, window, heating system ...)	Easy (with dabase available)	High	building + district	To be assesed	To be assesed
	Total Primary Energy consumption (over 100 years) per year	kWh/m²a or MJ/m²a		Easy (with dabase available)	High	building + district		
	Total Carbon emissions (over 100 years)	Mt CO_2/m²		Easy (with dabase available)	High	building + district		
	Total Carbon emissions (over 100 years) per year	Mt CO_2/m²a		Easy (with dabase available)	High	building + district		
Comprehensive (life cycle) energy saving	Total Primary Energy saving (over 100 years)	kWh/m² or MJ/m²		Easy (with dabase available)	High	building + district		
	Total Primary Energy saving (over 100 years) per year	kWh/m²a or MJ/m²a		Easy (with dabase available)	High	building + district		
	Total Carbon saving (over 100 years)	Mt CO_2/m²		Easy (with dabase available)	High	building + district		
	Total Carbon saving (over 100 years) per year	Mt CO_2/m²a		Easy (with dabase available)	High	building + district		

Table 120: Indicators regarding Embodied Energy

Information					Decision making		Data Model	Repository	
Subcategory	Specific Indicator	Parameter	Unit of measure/scale	ELEMENT	Data available/measure with sensors or other	Priority for DM	Scale	tech. for the retrofitting	tech. supplying RE
Cost of Retrofit Measures	**Cost in euros**	**Cost**	**€**	**Retrofit Measure / Building / District**	**Easy (with database available)**	**High**	**Building**	Determined the "Relative Cost"	Determined the "Relative Cost"
Value of energy sa	Value in euros	Value	€	Retrofit Measure / Building / District	Easy (with database available)	Low	Building		
LCA (Life Cycle Analysis)	Combined Environmental Impact Indicator	Multiple	Relative scale	Retrofit Measure / Building / district	Complex assessment procedure	Low	Building		
NPV (Net Present Value)	Value over time	Measures the total amount an investment is expected to increase based on the present value of its potential cash flows and initial cost	€	Retrofit Measure / Building / District	Easy (with costs available)	Medium	Building		
ROI (Return on Investment)	Efficiency of investr	ROI = (gain from investment – cost of investment) / Cost of investment	%	Retrofit Measure / Building / District	Easy (with costs available)	Low	Building		
Public Domain Benefits	GDP	Value	€	Retrofit Measure / Building / District	Medium (if research assumptions accepted)	High	Building		
	Health care costs	Value	€	Retrofit Measure / Building / District	Medium (if research assumptions accepted)	High	Building		
	Health benefits	Value	€	Retrofit Measure / Building / District	Medium (if research assumptions accepted)	High	Building		
Overall Payback Period	**Payback time taking account of all benefits**	**Time**	**Years**	**Retrofit Measure / Building / District**	**Easy (with costs available)**	**High**	**Building**		
Energy Payback Period	Payback time only taking account of cost of energy	Time	Years	Retrofit Measure / Building / District	Easy (with costs available)	Low	Building		

Table 121: Indicators regarding Economic Return

Annex II

LEVELS OF DM						CRITERIA	CURRENT STATE					
LEVEL		ACCURACY		SCALE			DSS			EXTERNAL CALCULATIONS/DATA		
II	III	2	4	building		Habitability						
				building								
				building								
				building								
				building	district	Energy saving						
				building	district		Thermal energy use	Total use/year	EE ADE + EN ISO 13790:2008			
				building	district		Thermal energy use	Thermal energy use per m^2 building	DSS CALCULATION			
				building	district		Electrical energy use	Total use/year	DSS ESTIMATION			
				building	district		Electrical energy use	Electricity use per m^2 building area	DSS CALCULATION			
				building	district		CO_2 emissions	Total for a building or a district	EE ADE + EN ISO 13790:2008			
				building	district		% RES	Fraction of energy supply from RES	EE ADE + EN ISO 13790:2009			
				building	district	Economic feasibility						
				building	district							
				building	district							
		3	5	building		Habitability				Thermal comfort	Temperature	Simulation
				building						Thermal comfort	Relative humidity	Simulation
				building						Thermal comfort	PMV	Simulation
				building						Thermal comfort	PPD	with PMV
				building						Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	Simulation
				building						Visual comfort	Mean maintained illuminance	Sensors
				building						Visual comfort	Illuminance uniformity	Sensors
				building						Visual comfort	Color rendering index (CRI) for lighting	Sensors
				building						Visual comfort	Daylight factor	Sensors
				building						IAQ	Pollutants	Sensors
				building						IAQ	Microbial pollution	Sensors
				building						IAQ	Ventilation rate	Simulation
				building	district	Energy saving				Thermal energy use	Total use/year	More accurate simulations
				building	district					Thermal energy use	Thermal energy use per m^2 building area	More accurate
				building	district					Electrical energy use	Total use/year	Simulation
				building	district					Electrical energy use	Electricity use per m^2 building area	Simulation
				building	district					CO_2 emissions	Total for a building or a district	DSS calculation
				building	district					Peak power demand	Total for a building or a district	Simulations
				building	district					% RES	Fraction of energy supply from RES	Simulations
				building	district							
				building	district							
				building	district							
				building	district							
				building	district	Economic feasibility						
				building	district							
				building	district							
				building	district							
				building	district							
				building	district							
				building	district							

Table 122: Set of indicators at diagnosis phase

LEVELS OF DM						CRITERIA	DECISION MAKING					
LEVEL		ACCURACY		SCALE			DSS			EXTERNAL CALCULATIONS		
II		2	4	building		Habitability	Thermal comfort		REPOSITORY			
				building			Acoustic comfort		REPOSITORY			
				building			Visual comfort		REPOSITORY			
				building			IAQ		REPOSITORY			
				building	district	Energy saving	Energy Saving		REPOSITORY			
				building	district		Thermal energy use	Total use/year	EE ADE + EN ISO 13790:2008+ REPOSITORY			
				building	district		Thermal energy use	Thermal energy use per	DSS CALCULATION			
				building	district		Electrical energy use	Total use/year	REPOSITORY (ENERGY SAVING)			
				building	district		Electrical energy use	Electricity use per m^2 building area	DSS CALCULATION			
				building	district		CO_2 emissions	Total for a building or a district	DSS CALCULATION			
				building	district		% RES	Fraction of energy supply	DSS CALCULATION			
				building	district	Economic feasibility	Cost of Retrofit Measures	Cost in euros	REPOSITORY			
				building	district		Value of energy saved	Value in euros	DSS ESTIMATION			
				building	district		Energy Payback Period	Payback time only taking account of cost of energy	DSS ESTIMATION			
	III	3	5	building		Habitability				Thermal comfort	Temperature	Simulation
				building						Thermal comfort	Relative humidity	Simulation
				building						Thermal comfort	PMV	Simulation
				building						Thermal comfort	PPD	with PMV
				building						Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	Simulation
				building						Visual comfort	Mean maintained illuminance	Sensors
				building						Visual comfort	Illuminance uniformity	Sensors
				building						Visual comfort	Color rendering index (CRI) for lighting	Sensors
				building						Visual comfort	Daylight factor	Sensors
				building						IAQ	Pollutants	Sensors
				building						IAQ	Microbial pollution	Sensors
				building						IAQ	Ventilation rate	Simulation
				building	district	Energy saving				Thermal energy use	Total use/year	More accurate simulations
				building	district					Thermal energy use	Thermal energy use per m^2 building	More accurate simulations
				building	district					Electrical energy use	Total use/year	Simulation
				building	district					Electrical energy use	Electricity use per m^2 building area	Simulation
				building	district					CO_2 emissions	Total for a building or a district	DSS calculation
				building	district					Peak power demand	Total for a building or a district	Simulations
				building	district					% RES	Fraction of energy supply from RES	Simulations
				building	district					Comprehensive (life cycle) energy saving	Total Primary Energy saving (over 100 years)	Data base
				building	district					Comprehensive (life cycle) energy saving	Total Primary Energy saving (over 100 years) per year	Data base
				building	district					Comprehensive (life cycle) energy saving	Total Carbon saving (over 100 years)	Data base
				building	district					Comprehensive (life cycle) energy saving	Total Carbon saving (over 100 years) per year	Data base
				building	district	Economic feasibility				Cost of Retrofit Measures	Cost in euros	Data Base
				building	district					Value of energy saved	Value in euros	Data Base
				building	district					LCA (Life Cycle Analysis)	Combined Environmental Impact Indicator	Complex assessment procedure
				building	district					NPV (Net Present Value)	Value over time	External Calculation
				building	district					ROI	Efficiency of investment	External Calculation
				building	district					Overall Payback Period	Payback time taking account of all benefits	DSS calculation
				building	district					Energy Payback Period	Payback time only taking account of cost of energy	DSS calculation

Table 123: Set of indicators at DM phase

LEVELS OF DM						CRITERIA	MONITORING		
LEVEL		ACCURACY		SCALE					
II	III	2	4	building		Habitability	Thermal comfort		Sensors
				building			Acoustic comfort		Sensors
				building			Visual comfort		Sensors
				building			IAQ		Sensors
				building	district	Energy saving	Energy Saving		Billings
				building	district		Thermal energy use	Total use/year	Billings
				building	district		Electrical energy use	Total use/year	Billings
				building	district		Electrical energy use	Electricity use per m^2 building area	Billings
				building	district		CO_2 emissions	Total for a building or a district	DSS CALCULATION
				building	district		% RES	Fraction of energy supply from RES	DSS CALCULATION
				building	district		Thermal energy use	Thermal energy use	Billings
				building	district	Economic feasibility	Cost of Retrofit Measures	Cost in euros	Not applied
				building	district		Value of energy saved	Value in euros	Billings
				building	district		Energy Payback Period	Payback time only taking account of cost of energy	DSS ESTIMATION
		3	5	building		Habitability	Thermal comfort	Temperature	Sensors/ simulation
				building			Thermal comfort	Relative humidity	Sensors/ simulation
				building			Thermal comfort	PMV	Simulation
				building			Thermal comfort	PPD	with PMV
				building			Acoustic comfort	Indoor ambient noise levels in unoccupied spaces	Sensors/ simulation
				building			Visual comfort	Mean maintained illuminance	Sensors
				building			Visual comfort	Illuminance uniformity	Sensors
				building			Visual comfort	Color rendering index (CRI) for lighting	Sensors
				building			Visual comfort	Daylight factor	Sensors
				building			IAQ	Pollutants	Sensors
				building			IAQ	Microbial pollution	Sensors
				building			IAQ	Ventilation rate	Sensors
				building	district	Energy saving	Thermal energy use	Total use/year	Billings/sensors
				building	district		Thermal energy use	Thermal energy use	DSS CALCULATION
				building	district		Electrical energy use	Total use/year	Billings/sensors
				building	district		Electrical energy use	Electricity use per m^2	Billings/sensors
				building	district		CO_2 emissions	Total for a building or a district	Sensors
				building	district		Peak power demand	Total for a building or a district	Sensors
				building	district		% RES	Fraction of energy supply from RES	Sensors
				building	district				
				building	district				
				building	district				
				building	district				
				building	district	Economic feasibility			
				building	district		Value of energy saved	Value in euros	Billings
				building	district		LCA (Life Cycle Analysis)	Combined Environmental Impact Indicator	Complex assessment procedure
				building	district		NPV (Net Present Value)	Value over time	Billings
				building	district		ROI	Efficiency of investment	Billings
				building	district		Overall Payback Period	Payback time taking account of all benefits	Billings
				building	district		Energy Payback Period	Payback time only taking account of cost of energy	Billings

Table 124: Set of indicators at management phase

multiscale information management for historic districts´ energy retrofitting

a framework • a methodology • a model

Aitziber Egusquiza Ortega

PhD Thesis

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