Multi-scale urban data models for early-stage suitability assessment of energy conservation measures in historic urban areas

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Abstract

The demand for improving the energy performance of buildings located in the historic districts of cities is as high as the current demand in other city districts. The need to reduce energy consumption and improve the comfort of inhabitants is compounded by the need to preserve an environment of heritage value. The selection of rehabilitation strategies at urban scale offers significant benefits, but makes the process long and costly. Therefore, methods or tools are necessary to establish a rapid assessment that facilitates strategic decision making and a deeper analysis of a reduced number of alternatives.

This paper describes a method that supports decision making regarding the suitability of Energy Conservation Measures (ECMs) in historic districts at early stages. The method considers the improvement of the energy performance of buildings as a positive impact, balanced with the negative impacts that the implementation of ECMs could produce. A CityGML-based urban model allows the automation of a multi-scale assessment for different ECMs and provides possible global energy demand reductions. This method, combined with an economic evaluation, can be used by decision makers for large-scale energy retrofitting. The applicability of the method is demonstrated through implementation in the historic city of Santiago de Compostela.

Keywords: Urban conservation, Heritage impact assessment, CityGML, energy conservation, multiscalarity

1. Introduction

The interest in improving the energy efficiency and thermal comfort of historic built environments arises from a double demand: the sociocultural need to preserve historic cities and the environmental need to reduce the global energy demand of buildings. The cultural heritage of a city has proven to be an important feature for the wellbeing of citizens and historic buildings are highly appreciated [1][2], but city dwellers frequently choose more modern buildings since they are perceived as more comfortable than historic ones.

Buildings that are not used are rarely conserved, thus making the abandonment of historic cities a major urban conservation problem. The Council of Europe, in the Amsterdam Declaration of 1975, promoted the concept of integrated conservation establishing the improvement of the liveability and quality of life of their citizens as one of the main objectives of urban conservation [3]. Since then, the protection of the social context of historic urban environments has been seen as necessary as the preservation of the authenticity and integrity of their fabrics for urban conservation.

There is a close relation between liveability and energy efficiency. The objective of Energy Conservation Measures (ECM) is to provide suitable environmental conditions to the inhabitants and minimize the used energy [4]. The improvement of the energy efficiency of historic districts in general and their housing stock in particular reduces the energy demand required to reach comfort standards, enhancing the quality of life of their habitants in an affordable way.

Energy upgrading of historic buildings is not only a cultural issue but also important in terms of global environmental objectives in Europe since over 40% of the European housing stock was built before 1960 [5]. The Housing Statistics in the EU show that 24% of residential buildings of the European building stock are pre 1945 [6] and that a significant percentage have some kind of heritage significance [7], requiring specific solutions to conserve and promote these values.

Recent literature reviews regarding energy efficiency and thermal comfort in historic buildings highlight the importance of carefully balancing the improvement of energy efficiency measures and the integrity and authenticity inherent to historic buildings [8]. As recent research concludes, "there is a lack of a specific protocols aimed at providing well-balanced solutions for the energy efficiency improvement in historic and historical buildings" [9]. This lack is even more noticeable if we address the problem at the urban scale.

Studies at the urban scale can consume large amounts of energy and money due to the amount of information that is required, often as a result of field work. 3D models are an increasingly accepted solution for storing and displaying information at both the building and urban scales. They offer the same benefits as 2D GIS but provide further functionality through the third dimension [10]. This paper describes an early-stage suitability assessment (ESSA) method of ECM in urban historic areas supported by 3D models. The method balances the benefits of a given ECM with its negative impact on heritage significance. The applicability and economic feasibility of ECMs at the urban scale complement the assessments. The method is tested in Santiago de Compostela (Spain).

The rest of this paper is structured as follows: section 2 reviews the related work; section 3 describes the ESSA method and the multiscale data model that supports its automation; section 4 explains the implementation in the case of Santiago the Compostela; and, finally, the conclusions and future work section closes the paper.

2. Related work

The Heritage Impact Assessment (HIA), which originated in the framework of environmental impact assessments, is a tool to assess the acceptability of impacts caused by new interventions on cultural heritage assets. In this framework, the evaluation of the overall impact of an intervention is a function of the magnitude of the heritage value and the magnitude of the changes produced by the intervention. ICOMOS has developed guidance to implement the HIA specifically for World Heritage properties [11] . In this method, the positive and negative effects of new interventions are systematically assessed in contrast to the heritage significance values. This approach has been recently applied to urban development projects not only to reduce its negative potential impacts on cultural heritage but also to balance them with socio-cultural and economic benefits as beneficial impacts [12].

Industrialisation brought mechanical systems to modern architecture, decisively changing the relationship between our cities and the environment. Preindustrial architecture was built in a time when the comfort could not rely on mechanical systems. This traditional architecture takes into account the constraints that the climate and the local material impose [13] and consequently has an *instinctive care* to the whole life cycle of building materials [14]. Pre-industrial buildings are different from an energy behaviour perspective to modern ones, and they are not necessarily worse [15]. The way that historic buildings address environmental conditions to provide comfort conditions to their inhabitants must be considered part of their cultural value and technical heritage. Moreover, affordable comfort makes easier to keep the historic buildings inhabited thus facilitating their conservation. Therefore, improving energy performance can be considered to have a positive impact on the heritage significance of the historic buildings, as long as it is aligned with the conservation of the other components of this heritage significance.

Suitability of ECMs can be evaluated by balancing the positive impact to the preservation of cultural values (improvement of the energy efficiency and thermal comfort) with their negative values (impact on the authenticity and integrity of the building elements). From the cultural point of view, historic urban areas are information-rich environments, with multi-scale heritage values that envisage from urban landscape to building elements (such as windows, walls or chimneys) where a unitary and multi-level approach is required [16]. Although the district scale is the operative scale for the implementation of ECMs [17], the spatial decision processes for their implementation has to be addressed with a multi-scalar approach [18]. The implementation of ECMs in historic urban areas may thus benefit from information management strategies and tools, such as multi-scale and semantically enriched 3D city models [19].

Ross et al. defined a 3D city model as a georeferenced digital representation of objects, structures and phenomena that correspond to a real city [20]. The same authors identified CityGML as a very powerful interchange format for official 3D city models. CityGML is a multi-scale data model format that falls between the traditional 2D GIS and Building Information Modelling (BIM) scales [21]. Covering different levels of CityGML allows the reuse of the same data in different fields of application [22], and it was designed to store semantic and 3D multi-scale geometric information, considering urban and building scales [23]). In the comparison between different 3D exchange standards made by Vandysheva et al. [24], CityGML is the most complete standard, being the only one that supports different Levels of Detail (LoDs) and one of the most complete regarding the inclusion of both semantic and geometric information. The widespread use of CityGML across Europe is another advantage [25].

In energy modelling, the heating, cooling and ventilation demands of buildings, and therefore districts, are strongly dependent of the geometry of those buildings and their construction characteristics (semantic information). Consequently, the combination of spatial analysis with thematic data structuration offers an excellent way to calculate the energy demand at the urban level [26] [27] [28] [29] [30], to estimate the energetic rehabilitation state of the buildings in a city [31] or to represent the energy-related key indicators of buildings and neighbourhoods within 3D building models [32] [33]. The prediction of the energy demand of urban districts can be used as basis for simulating energy refurbishment scenarios, as in Eicker et al. [34], and thus for decision making regarding energy interventions [35].

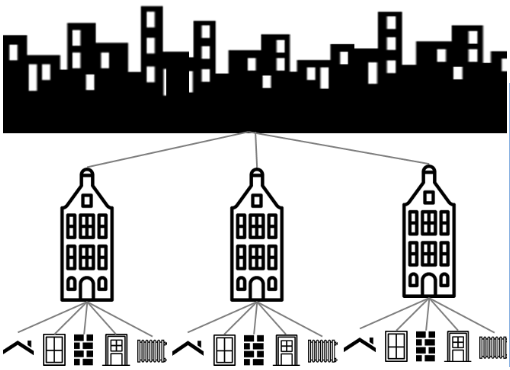
In the field of cultural heritage, the energy performance of heritage buildings has been mapped using 2D GIS [36], and 3D models have been widely used for the documentation of cultural heritage assets especially at object, building or archaeological site scales [37] [38]. However, as far as we are aware, 3D models have not been used for the suitability assessment of ECM in historic environments.

3. Method for suitability assessment of ECMs in historic urban areas

Our objective is to develop an early-stage suitability assessment (ESSA) method that facilitates the rapid feasibility and suitability assessment of ECM at the urban level in historic urban areas using open data or public sources. A multi-scale model based on CityGML is used to structure the information necessary for the assessment of negative and positive impacts at urban level of each ECM and their applicability.

The developed method adapts the ICOMOS guidance on HIA to be implemented with a multi-scale perspective. The urban interventions in valuable and vulnerable environments such as historic districts have to be carefully planned and managed to ensure that the new interventions are respectful with the heritage values in all the scales. It is possible to systematically link the impact of one ECM with the heritage value of the specific element that is affected (and not with the whole building) for an effective urban assessment. Then, interventions that were initially considered unacceptable at the building scale could be considered suitable at the component scale (e.g., window upgrading in highly protected buildings without their original windows). Therefore, the smaller the scale of the elements under assessment that is considered, the larger the obtained impact of the interventions.

The elements with heritage values (officially listed or not) in cities can be grouped into seven key elements types: historic urban area (HUA), building, windows, roofs, external wall, internal wall and installations. These key elements comprise the important heritage and energy values of the historic buildings, as shown in Table 1.

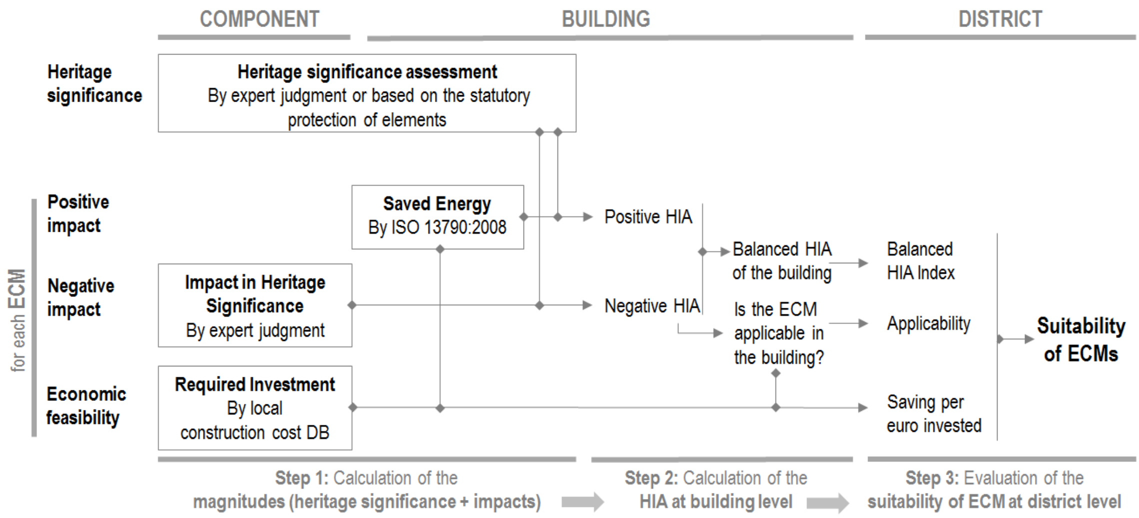


7 Key Elements	HERITAGE SIGNIFICANCE	ENERGY SIGNIFICANCE
Historic Urban Area	Urban landscape	Urban energy demand
Building	General heritage significance, statutory protection, shopfronts	Air infiltrations, occupation patterns, thermal mass
Windows	Windows, shadding devices, balconies, loggias	U value, G value
Roofs	Chimneys, other roof features	U value
External wall	Mansonry, finishes, sculptures	U value, orientation
Internal wall	Interior finishes	
Installations	Mechanical and electrical service installations	Efficiency, energy source

Table 1: Multi-scalarity of heritage and energy significances

Although the façade works as a unitary construction element from an energy perspective, it has been divided in two elements (internal and external wall) because they usually comprise different heritage values, and specific retrofitting solutions can be applied.

The ESSA method for ECMs in historic urban areas considers the improvement in the energy efficiency as a beneficial impact and compares it with the negative impacts caused by the application of the ECM that achieves this improvement. The symmetric approach to both assessments allows the creation of a Balanced HIA Index for ECMs applied in historic environments. The ESSA method, shown in Figure 1



, has three main steps: 1) the calculation of the magnitudes regarding heritage significance and positive and negative impacts at the component and building levels, 2) the calculation of the HIA for all the buildings in the area and 3) the final suitability assessment of each ECM where the Balanced HIA Index is compared to the applicability and economic feasibility. The next subsections explain in detail each of these steps.

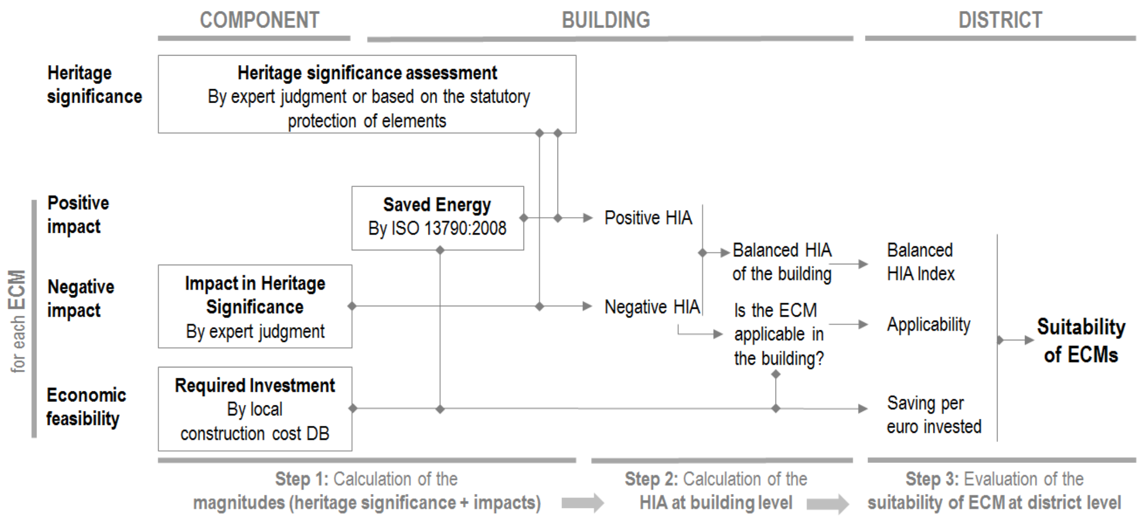


Figure 1: Multi-scalar process of ESSA method

3.1. Step 1: Calculation of the magnitudes of the heritage significance and positive and negative impact

The first step consists of calculating the magnitudes of the heritage significance and positive and negative impacts. The magnitudes regarding heritage significance are set for each key element according to expert judgement or based on the statutory protection of the elements. Positive impacts (saved energy) and negative impacts (impact in Heritage Significance) are calculated for each building and for each ECM and classified according to an ordinal scale ranging from 0 to 4, as shown in Table 2**.**

SCALE	HERITAGE SIGNIFICANCE ASSESMENT (EFFESUS)	MAGNITUDE OF THE IMPACTS		
			POSITIVE IMPACT (ESSA)	NEGATIVE IMPACT (ICOMOS 2010)
0	**Neutral or negative significance**	**No impact or negligible impact**	Savings <10 kWh/year	No appreciable change
1	**Minor significance**	**Minor impact**	Savings from 10 to 20 kWh/year	The historic building element has slight changes that hardly affect it
2	**Major significance**	**Moderate impact**	Savings from 20 to 40 kWh/year	The element is slightly different as a result of the intervention
3	**Outstanding significance**	**Major impact**	Savings from 40 to 60 kWh/year	The element is significantly modified
4	**Exceptionally outstanding significance**	**Extreme impact**	Savings >60 kWh/year	The element is totally altered

Table 2: Scale for heritage assessment and magnitude of the impacts for each ECM

Heritage Significance Assessment is calculated according to the EFFESUS method, which specifically assesses the multi-scale impact of ECMs in terms of the visual, physical and spatial values of historic environments [7].

The positive impact represents savings in energy demand by applying ECMs. The calculation procedure for assessing this improvement in energy efficiency has to provide enough accuracy and flexibility to model the building stock of any historic district, aiming to accomplish this calculation without relying heavily on a large amount of input data. For a rapid assessment, the quasi-steady state monthly method described in EN ISO 13790:2008 (Calculation of energy use for space heating and cooling) has been considered [39], which offers the right balance between needed input and provided accuracy. Methods for energy diagnosis based on this standard have been already tested over several districts (e.g. in Germany and the Netherlands [25] [40]) and have been used with a multi-scale approach [41]. From the perspective of historic environments, the proposed method allows us to take into account in the calculations two specific issues that are particularly important for preindustrial buildings: air infiltration and thermal inertia [42] [43]. With this method, the baseline energy demand and the saved energy for each ECM for each building in the considered area can be calculated and assigned to a 0-4 scale, as can be seen in Table 2.

Regarding the negative impact of ECMs, plenty of work has been done in recent years analysing and classifying ECMs for existing buildings [44] [45][46]. Some of them have even focused on structuring and making accessible retrofitting measures suitable for historic buildings [47], but there has not been an attempt to structure those measures according to their impact on heritage significance. To measure the impact of each ECM in terms of the physical, spatial and visual authenticity and integrity, the scale proposed by ICOMOS has been adapted (see Table 2**)**

The metrics that are necessary for the calculation of the required investment in a specific building include geometric and economic data. Geometric data can be directly obtained from the urban data model described in section 3.4. (e.g. the square metres of wall surface in need of insulation, the number of windows to be upgraded or substituted or the square metres of roof to be made airtight). The economic data can be obtained from local construction cost databases.

3.2. Step 2: Calculation of Heritage Impact Assessment at building level

According to the ICOMOS guidelines for the implementation of the HIA, the HIA is assessed considering the magnitude of impact (negative or positive) against the magnitude of the heritage significance of the element that is altered. In the ESSA method, both magnitudes are on a 0-4 scale, so a numerical approach is possible for the widespread HIA calculation at the urban level (unlike the approach from ICOMOS), as can be seen in Table 3. This output is positive for the positive impacts and negative for the negative ones and ranges from neutral impacts to extreme impacts. A distinctive colour code is used for visualization purposes.

		MAGNITUDE OF THE IMPACT (POSITIVE AND NEGATIVE)								
MAGNITUDE OF THE HERITAGE SIGNIFICANCE		**no impact/ negligible**	**minor impact**		**moderate impact**		**major impact**		**extreme impact**	
		0	**1**	**-1**	**2**	**-2**	**3**	**-3**	**4**	**-4**
exceptional significance	**4**	**neutral**	**minor**		**moderate**		**large**		**very large**	
		0	4	-4	8	-8	12	-12	16	-16
outstanding significance	**3**	**neutral**	**minor**		**moderate**		**large**		**large**	
		0	3	-3	6	-6	9	-9	12	-12
major significance	**2**	**neutral**	**slight**		**minor**		**moderate**		**moderate**	
		0	2	-2	4	-4	6	-6	8	-8
minor significance	**1**	**neutral**	**neutral/ slight**		**slight**		**minor**		**minor**	
		0	1	-1	2	-2	3	-3	4	-4
neutral significance	**0**	**neutral**	**neutral**		**neutral**		**neutral**		**neutral**	
		0	0	0	0	0	0	0	0	0

Table 3: Matrix of HIA calculation (based on ICOMOS 2010)

The symmetry of the approach makes possible the combination of both of them to obtain a comparable balanced HIA for each building (the negative HIA is subtracted to the positive HIA). A colour code again is used for a rapid visual assessment in the 3D model (Table 4).

Balanced HIA	**<-4**	**4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**>4**
Colour code											

Table 4: Balanced HIA

Additionally, the calculation of a negative HIA can be used as threshold of the applicability of the solution. It can be considered that an ECM that causes a moderate, large or very large negative impact (higher than a 4 HIA negative value) should not be applied to a building and therefore should be discarded for this specific building.

3.3. Step 3: Calculation of the suitability of each ECM at district level

For the evaluation of the suitability of each ECM for a historic urban area, the ESSA method requires the calculation at the urban level of three values: the balanced HIA index, the applicability and the economic feasibility, expressed in the energy saving for euro invested. The Balanced HIA Index of an ECM is the average of the Balanced HIA Index for that ECM for each building in the district. The applicability is the percentage of buildings where a given ECM could be applied because its impact would not have more than a minor impact (the threshold is a negative HIA value of 4).

$$Applicability = \frac{Number\ of\ buildings\ with\ a\ negative\ HIA \leq 4}{Number\ of\ buildings} * 100$$

Equation 1: Calculation of Applicability

The economic feasibility for each ECM is expressed as the obtained energy savings per euro invested (annual kWh/€), a metric commonly used to compare competing solutions for energy efficiency [48]. The required total investment for each ECM is calculated adding the cost of the implementation of each measure in all the buildings where the application is possible.

$$Economic\ Feasibility\ of\ the\ ECM_i = \frac{\sum_{Buildings\ wih\ negative\ HIA \leq 4} Energy\ Saving\ of\ the\ ECM_i\ for\ that\ building}{\sum_{Buildings\ with\ negative\ HIA \leq 4} Cost\ of\ the\ ECM_i\ for\ that\ building}$$

Equation 2: Calculation of Economic Feasibility

3.4. Multi-scale information model

The ESSA method described in this paper provides a rapid assessment of ECMs that requires no or little fieldwork and provides results at the urban scale, but at the same time the measures need to be applied at the building scale, considering the geometric characteristics of the buildings and their main elements (facade, roof, windows and installations) and the applicability of the measures according to the characteristics or preservation requirement. In these cases, a multi-scale information model that coherently combines geometric and semantic information is the most suitable option for the representation of the information. In our case, we used a urban model based on the CityGML standard. Within the framework of the EFFESUS project, a multi-scale urban model that works in different scales (e.g., urban, building, fabric, elements) and integrates energy and cultural heritage information has been developed [19]. This model aims to be the reference model for the diagnosis, decision making and management of the energy efficiency in historic urban areas; thus, its aim is broader than what is needed for the ESSA method.

A CityGML-compliant data model needs to be enriched with additional attributes for the applicability of the model to the assessment methodology. The implementation of the urban model requires:

1) The definition of the hierarchy of the key elements according to the elements defined in the CityGML schema. The structure of the elements of the city that is considered under the CityGML schema is generic due to its universality. As the concept of a district is not defined in CityGML, the HUA element has been defined using the grouping concept *cityObjectGroup*, which allows the aggregation of arbitrary city objects according to user-defined criteria. Each building can contain building installations in this case focused on the energy installations. Higher detail in the building description provides information about building boundary surfaces. Such elements represent walls and also the roof. Boundary surfaces can include openings, which can be of two types: doors and windows.

2) The extension of the semantic potential of the standard. Four specific CityGML Application Domain Extensions (ADEs) were designed in the EFFESUS project to structure all the semantic information necessary for the decision making and management of ECM in historic urban areas: a cultural heritage extension, energy extension, indicator extension and dynamic extension for monitoring purposes. For the rapid assessment described in this paper, only the first two extensions are used. They are described in sections 3.4.1 and 3.4.2.

3.4.1. Cultural heritage domain extension

The Cultural Heritage ADE includes information at the scale of the district, building, and building envelope. The model structures information regarding historic significance according to three main aspects (visual, physical and spatial) and for elements at different scales: the district scale (e.g., roof scape, street scape or public spaces), building scale (e.g., external walls, roof, windows, or balconies) and dwelling level (e.g., internal walls, doors or interior finishes). Information regarding the main construction materials as well as their properties is set at the level of the building envelope, and the general consideration of the integrity and state of preservation is established at the building level (e.g., historic type, integrity or physical state). Formal protection and law restrictions for heritage preservation are identified at both the building and envelope levels. All this information makes possible very detailed HIA assessments, but for the rapid assessment described in this paper, all this information is translated to the key elements (Table 1) and the one with the highest value of the three levels of heritage significance (visual, spatial and physical) is adopted. A detailed description of the Cultural Heritage ADE can be found in Chapter 3 of the thesis of A. Egusquiza [49]

3.4.2. Energy performance domain extension

The energy performance extension includes information at different scales: district, building, building envelope and building installation (demand and generation installations). Information related with climate is referenced at the district level. At the building level, information related with geometry (i.e., gross floor area and storey height), occupancy (i.e., internal gains, thermal mass and air infiltration) and use (i.e., comfort temperature and ventilation strategy) is set. The material properties (i.e., U values and g Value), type (i.e., façade or adjoining wall) and size of the windows and relation between opaque and opening areas are identified at the building envelope level. At the building installation level, the energy installations (e.g., type and efficiency) are referenced. A detailed description of the Energy Performance ADE can be found in Chapter 3 of the thesis of A. Egusquiza [49]

In Table 5, the data required for the energy assessment are presented. The required data represents the name of the required parameter for the energy assessment, the data model indicates the name of the parameter in the data model, the key element indicates the scale (HUA, building, façade, roof or wall), ECM indicates if this parameter value changes when applying an ECM, ADE shows if the parameter belongs to the core of the CityGML or it has been included in the extensions, and the input data indicate the source of the parameter.

REQUIRED DATA	DATA MODEL	KEY ELEMENT	ECM	ADE	INPUT DATA
Situation	Latitude, longitude	HUA	No	No	Cadaster
Total Area	area, storeysAboveGround	Building	No	Yes	Calculated
Thermal inertia	ThermalMass	Building	Yes	Yes	Manual
Air renovation (winter)	AirInfiltration	Building	Yes	Yes	Manual
Air renovation (summer)	VentilationStrategy	Building	Yes	Yes	Manual
Storeys height	StoreyHeightAboveGround	Building	No	No	Calculated
Set point cooling	summerConfortTemperature	Building	No	Yes	Manual
Set point heating	winterConfortTemperature	Building	No	Yes	Manual
Internal gains	Class, use	Building	No	No	Cadaster
Area	isAdjoiningWall, orientation, area	External wall, roof, internal walls	No	Yes	Calculated
% opening	openningPercentage	External wall, roof	No	Yes	Manual
U opaque	opaqueAverageU	External wall, roof, internal walls	Yes	Yes	Manual
U windows	openningAverageU	External wall, roof	Yes	Yes	Manual
G value	gValue	External wall, roof	Yes	Yes	Manual
Exposure	isAdjoiningWall	External wall, roof, internal walls	No	Yes	Calculated
Thermal Bridge	thermalBridge	External wall, roof	Yes	Yes	Manual
Shading strategy	hasShadowStrategy	External wall, roof	Yes	Yes	Manual

Table 5: Required data for energy calculation

4. The implementation in the case of Santiago de Compostela

Santiago de Compostela, universally known as the final destination of the St. James's Way pilgrimage route, is located in the north-west of Spain with approximately 100.000 inhabitants, whose historic district was declared a World Heritage Site by UNESCO in 1985. In 1997, the “Plan especial de protección e rehabilitación da cidade histórica” (Special Protection and Rehabilitation Plan for the Historic City Core of Santiago de Compostela-SPRP) was approved with the goal of addressing the preservation and restructuring of the old town. The area selected as the case study is the historic district of the city of Santiago de Compostela (See Figure 2).

Figure 2: Historic District de Santiago de Compostela

A detailed analysis of the original constructive type of the buildings of Santiago de Compostela and its evolution can be found in the work of Guallart Ramos et al. [50]. Two main urban layouts can be highlighted: *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 metres. The original structural concept was based on a light structure of wood (often reused wood) within the granitic walls. Table 6 summarizes the description of the different elements of the historic district of Santiago using the information of Guallart Ramos et al. [50] as seen in the work of Méndez [51] and the adopted values for calculations (i.e., thickness and U value).

ELEMENT	MATERIAL	DESCRIPTION	OBSERVATIONS	**Thickness** (m)	**U value** (W/m^2C)
Facade	Granite stone	Two layers of granite stone with a filling of earth or small pieces	Sometimes they have a protecting external finishing of lime mortar	0,6	2,3
Roof	Wooden structure	Wooden structure covered with tile		0,124	1,31
Windows	Singled glazing without framing	External aligned with the façade or internal window	High infiltrations but wooden shutters produces a buffering effect	0,1	5,6

ELEMENT	MATERIAL	DESCRIPTION	OBSERVATIONS	Thickness (m)	U value (W/m^{2}C)
	Singled glazing with wooden frame	Internal window	High infiltration lower buffering effect		

Table 6: Description of the elements of the Santiago de Compostela (source: Guallart Ramos et al. [50] as seen in Méndez [51])

According to the data from SPRP, only 35 buildings (0.04%) from the considered area have gas infrastructure.

4.1. Multi-scale information model for Santiago de Compostela

The EFFESUS data model has been completed for the case study of Santiago de Compostela with semantic information available from public data sources. Most of the parameters at the building level have been collected from the Spanish cadastre and 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. As a result, all buildings (819) of the historic district are represented in LoD2 by independent facades and the roof. The building height has been obtained from LiDAR data.

The magnitude of the heritage significance of the different key elements has been calculated taking as a basis the statutory protection of the different elements that they represent. The information for the heritage significance assessment has been obtained from the database of the SPRP, which was updated in 2009 and is accessible as open data. The database includes all the protected elements at the building and components levels. The 62 types have been grouped into the 7 previously defined key elements according to the logic shown in Table 1, and their heritage value have been translated to the proposed 0-4 scale, as can be seen in Table 7.

SOURCE VALUE (SPRP DATABASE)		ADOPTED VALUE		
HUA		**HUA**		
UNESCO World Heritage site		**4**	Exceptional significance	
BUILDING		**BUILDING**		
1	Monumental buildings of outstanding value	**4**	Exceptional significance	
2	Building of singular features and of major value	**3**	Outstanding significance	
3	Buildings with special features regarding architecture and environment	**2**	Major significance	
4	Interesting buildings in the urban context	**1**	Minor significance	
0	Not listed	**0**	Neutral significance	
PROTECTED ELEMENTS		**WINDOWS, ROOFS, EXTERNAL WALL, INTERNAL WALL AND INSTALLATIONS**		
E	Exceptional	**4**	Exceptional significance	If building HS = 4
		3	Outstanding significance	If building HS = 1-3
C	Common	**2**	Major significance	If building HS = 2-4
		1	Minor significance	If building HS = 1

N	Missing Value	**0**	Neutral significance	
D	Decontextualized Value	**0**	Neutral significance	

Table 7: Correlation between source values and adopted values for Heritage Significance

The heritage significance assessment has also been used to establish the scope of the assessment. Buildings with too high and too low values have been discarded, the first ones because their exceptional nature demands a specific evaluation and the second ones because they do not present any element with heritage significance. In total, 741 buildings from 819 (90%) have been considered. The majority (66.8%) of these buildings are of minor significance. 27.2% are of major significance, and only 5.9% are of outstanding significance. The 72% of buildings has some degree of heritage significance in their windows, 58% in their exterior walls or roofs and only 3% in their interior elements (walls and interior installations).

4.2. Energy Conservation Measures

Within the EFFESUS project, 77 ECMs were analysed to determine their impact on heritage significance. 11 of these ECMs have been selected to be tested in Santiago. To test the ESSA method, the main criterion for selection has been to choose solutions with a clear impact in energy behaviour and in the materiality of the buildings. Solutions that improve the airtightness of the building and the thermal characteristics of the envelope, impact different key elements and use different strategies or materials for the same purpose have been selected. The following table (See Table 8) shows the selected ECMs and the used values for the calculations. More details regarding ECMs analysed within the project can be found in the EFFESUS Energy efficiency solutions repository [52].

ECM			**KEY ELEMENT**	**IMPACT ON ENERGY EFFICIENCY**		**IMPACT ON HERITAGE SIGNIFICANCE***			**COST**	
				Modified Parameter	**New value**	**V**	**P**	**S**	**Euro**	**Unit**
1	Airtightness of the whole building	Sealing of all openings and joints	Building general	Air infiltration	n=0,75	0	2	0	6,16	l.m
2	Airtightness of windows	Sealing of all windows	Windows	Air infiltration	n=1	2	2	0	6,16	l.m
3	Airtightness of the roof	Airtightness membrane to underside roof	Roofs	Air infiltration	n=1	1	2	0	1,05	m2
4	Exterior insulation with a composite system	10 cm of a composite system	External wall	U value	0,3 (W/m ^{2}K)	3	4	3	81,9	m2
5	Exterior insulation plaster	5 cm of insulation plaster	External wall	U value	0,8 (W/m ^{2}K)	3	3	1	66,84	m2

6	Diffusion closed interior insulation	10 cm of mineral wool	Internal wall	U value	0,3 (W/m^2K)	3	4	2	9,50	m2
7	Diffusion-open, capillary-active interior insulation	5 cm of IQ-Therm	Internal wall	U value	0,50 (W/m^2K)	3	3	2	45,00	m2
8	Insulation of an existing cavity	5 cm of perlite	External wall	U value	0,65 (W/m^2K)	0	1	0	46,76	m2
9	New glazing systems	Install high performance window and glazing	Windows	U value Air infiltration	1,8 (W/m^2K) n=1	4	3	1	394	unit
10	Secondary double glazing	Secondary double glazing with wooden frame and shutters	Windows	U value Air infiltration	1,47 (W/m^2K) n=1	3	2	2	441	unit
11	Insulation of the roof	40 mm of EPS	Roofs	U value	0,7 (W/m^2K)	0	1	1	8,11	m2

*****Impact on heritage significance determined by experts in the EFFESUS project

Table 8: Evaluated ECMs in the case of Santiago with their impact in energy efficiency, heritage significance and cost (V= visual, P= Physical and Spatial)

4.3. Calculations

As previously mentioned, 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. Each building has been treated as a single zone, with residential use and data monthly typical day values for climate being used. Due to this residential use and the characteristic of the case study, low internal gains have been considered (2 W/m2). The Thermal Inertia has been considered medium high (400 kJ/m2·K), and the airtightness of the buildings has been considered low (1.5 air changes per hour). It has been taken into account that a traditional building needs to be ventilated at a higher rate than a modern building, usually approximately 0.8 to 1.0 air changes [43]; therefore, high levels of airtightness have not been pursued. The Thermal Bridge factor has been considered to have no impact; therefore, a value of 1 (f=1) has been used.

A specific tool has been developed for automatizing the calculations of the Heritage Impact Assessment at building level for all the buildings in the selected case study. The tool is based on the implementation of EN ISO 13790:2008 and an ad hoc implementation for the assessment of the application of ECMs on the Impact in Heritage Significance based on the ICOMOS guidelines.

For the positive impact, the energy saved per year with each ECM was calculated for each building comparing the baseline energy demand with the energy demand obtained with the parameters modified by the implementation of an ECM. The results have been translated to the scale explained in Table 2 and compared with the overall heritage significance of the building to obtain the positive HIA for each building and ECM, as explained in Table 3. The negative HIA has been calculated similarly: the negative impact has been evaluated comparing the most severe impact of ECMs (visual, physical or spatial) with the heritage significance of the element that is being altered. In both cases, a result from 0 to 16 is obtained as seen in Table 3: positive for energy efficiency improvement and negative for the impact on heritage significance. The combination of the two is the Balanced HIA index.

4.4. Results

The application of the ESSA method to the study area of Santiago de Compostela provides numerical results, which allow the comparison of different refurbishment strategies applicable to the historic urban area.

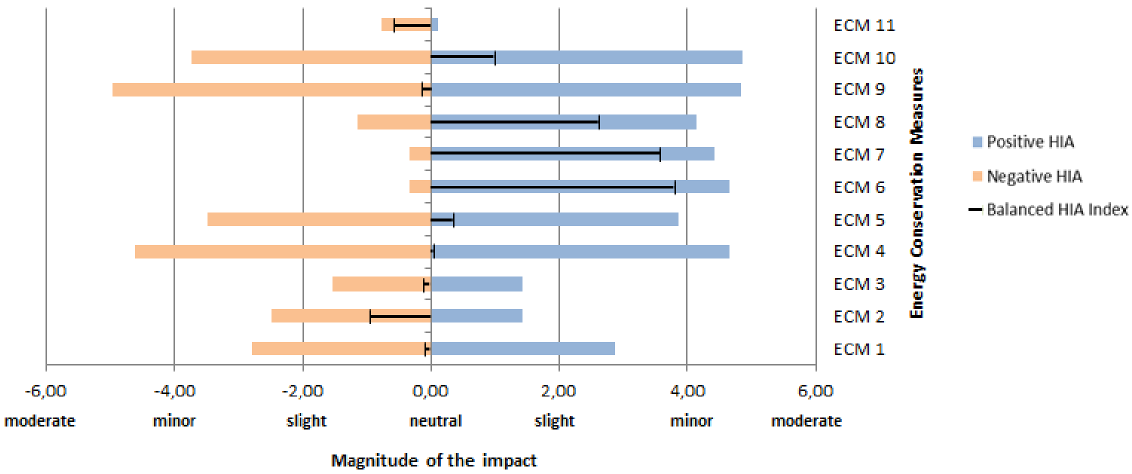


Figure 3: Results of the average Positive HIA, Negative HIA and Balanced HIA Index for each ECM

To have a global vision of the impact of each solution for the whole historic urban area, average values for each ECM have been calculated for the three HIA values (i.e., positive, negative and balanced). The ESSA method offers an easy way to see the balance between the positive and negative impacts, as can be seen in Figure 3. There is a group of solutions that offers a better balance between the negative and positive impacts: the solutions that improve the thermal characteristics of the envelope by insulating them from inside or using the internal cavity (ECM 6, 7 and 8).Their positive impacts are similar to insulation from the exterior (ECM 4 and 5), but their negative impacts are considerably lower, as they do not impact in exterior walls, which usually have heritage significance. Similarly, the improvement of the energy performance of the openings, by changing them (ECM 9) or adding a secondary glazing (ECM 10), has a high negative impact (windows and balconies are architectural features that frequently have high cultural value, and in the case of Santiago, 72% of the buildings have windows with some degree of heritage significance) that is not always compensated by their high positive impact, although in the case of secondary glazing, the impacts are positive, so it could be an ECM that is suitable after careful design. The ECMs that have an impact on the roof (ECM 3 and 11) have, on average, a slight or neutral beneficial impact.

The total energy savings and necessary investment have been calculated for an application threshold of 4 for the negative impacts (i.e., only the cases where the negative impact is minor, slight or neutral are considered). The results are summarized in Table 9. The results do not aim to offer a direct answer to the question of what are the best ECMs for a specific historic urban area. Their objective is to offer a basis for evidence-based decision making that has to be contrasted with the objectives and target of each city.

ECM	**Strategy**	**Element of impact**	**HIA$^-$**	**HIA$^+$**	**HIA**	**Total savings** (MWh/ year)	**Total invest.** (million €)	**Saving/ invest.** (MWh/€ year)	**App.** (%)
1	Improving the air tightness	Building general	-2,78	2,87	0,09	6476	1,85	3,50	94
2		Windows	-2,49	1,43	-1,06	4992	1,16	4,32	99
3		Roof	-1,54	1,43	-0,11	5073	48,20	0,11	99
4	Improving thermal performance of the envelope	External wall	-4,62	4,65	0,04	6156	14,23	0,43	44
5		External wall	-3,49	3,85	0,39	4647	11,62	0,40	44
6		Internal wall	-0,33	4,65	4,32	16079	4,32	3,72	96
7		Internal wall	-0,33	4,41	4,08	14527	20,47	0,71	96
8		External wall	-1,15	4,13	2,98	14274	22,74	0,63	100
9		Windows	-4,98	4,83	-0,15	7992	3,10	2,58	48
10		Windows	-3,74	4,86	1,12	8524	3,72	2,29	48
11		Roof	-0,77	0,11	-0,66	2124	0,85	2,50	100

Table 9: Results of each ECM for all the historic urban area (HIA$^-$ = Negative Heritage Impact Assessment; HIA$^+$= Positive Heritage Impact Assessment, HIA= Balanced Heritage Impact Assessment Index; Total invest. = total required investment; Saving/ invest. = Savings per euro invested, App. = Applicability)

The final suitability assessment of ECMs comes from a comparison of the Balanced HIA Index with economic feasibility (energy saved per euro invested) and applicability, as can be seen in the Figure 4.

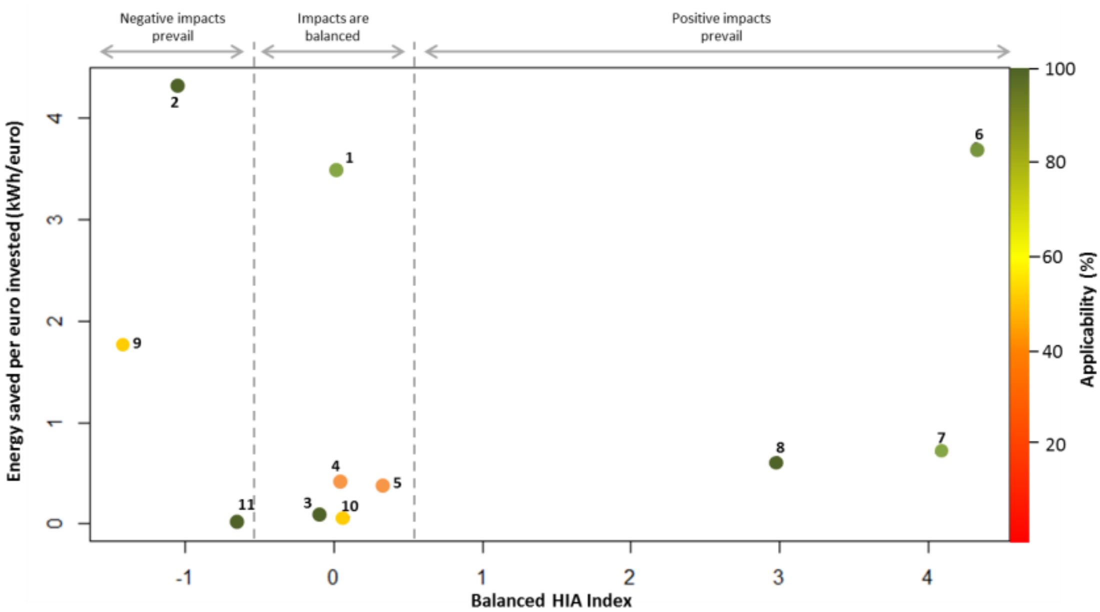


Figure 4: Suitability Assessment of the ECM

The cost effectiveness and applicability of the solutions give added criteria for selection within groups of ECMs with similar strategies and HIA values. As previously mentioned, the ECMs for internal insulation (ECM 6, 7 and 8) are clearly with the best balanced HIA but the insulation with diffusion closed material has clear economic advantages (although a more careful study regarding the hygrothermal consequences is necessary for its implementation). In the external insulations (ECM 4 and 5), the impacts are quite balanced, but their low applicability (44%) has to be considered. Improving the airtightness of the building (ECM 1 and 2) is clearly a cost-effective solution, but its suitability depends on the impact of the ECM in the heritage values of the windows.

The colour code (see Table 3 and Table 4) offers rapid visual access to the results of each ECM for each building, as can be seen in Figure 5.

Figure 5: Visualization of the results for the ECM6 (Diffusion closed interior insulation). From left to right: Negative HIA, positive HIA and balanced HIA index

5. Conclusions and Future work

This paper proposes a novel method for early-stage suitability assessment of ECMs at the historic urban level based on the multi-scale implementation of the concept of HIA. A multi-scale information model based on the CityGML standard has been designed and extended to account for the heritage and energy values of buildings in historic urban areas. The use of a Balanced HIA index and colour-coded maps as a rapid assessment mechanism is also proposed. This index, combined with the economic assessment and applicability of ECMs, can provide support to authorities and local bodies in decision-making processes regarding the sustainability of a historic district. Finally, an application of this method is demonstrated in a case study using the historic city of Santiago de Compostela, Spain, with 741 buildings and 11 ECMs.

This systematic method opens a path for more agile and operative methods of assessing energy efficiency strategies that can be used at the urban scale. The recently approved European Standard, EN 16883 (Guidelines for Improving the Energy Performance of Historic Buildings) aims to provide a normative working procedure for the planning and selection of measures based on the analysis of information on a historic buildings and the assessment of the impact of the measures in relation to the preservation of the cultural values of the building. The ESSA method is compatible with the standard and can be used to generate a long list of retrofit measures for a whole historic urban area. Recent research regarding methodologies for energy assessment and retrofitting of historic towns has highlighted the need to focus on specific local ECMs trying to avoid the application of solutions from different context [16]. The ESSA method can also be used with local specific ECMs as long as their thermal and heritage attributes are characterized.

As the data model structures wide-range data regarding the energy and architectonic characteristics of historic buildings, further assessments to be included in the HIA are possible. For a negative HIA, one of the most necessary is to include the compatibility assessment of ECMs. The design of the cultural heritage extension of the model already includes the characteristics of the buildings and components that can trigger a risk (chemical or physical) if combined with specific ECMs. The included risks are efflorescence and salt reaction, corrosion, risk related with moisture content and moisture movement, surface and interstitial condensation, structural movement, material contraction and expansion and reversibility issues. For a positive HIA, it would be necessary to broaden the perspective from energy demand in the operative phase to a whole life cycle assessment.

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