Reduced Footprints of Monumental structures, landscapes and buildings

Energy efficient retrofitting in practice. Challenges and opportunities of three heritage buildings in Europe.

Climate KIC pathfinder project

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Contents

1 INTRODUCTION

1.1 Research background

The EU has been reactive to climate change concerns and has set goals for reducing greenhouse gases (GHG) emissions. The Europe 2020: A European strategy for smart, sustainable and inclusive growth report urges member states to reduce 20% of its GHG emissions comparatively to 1990 levels and increase the employment of renewable sources to achieve 20% of total energy production and level up energy efficiency by 20% (EC, 2014). To reach these climate targets, improvements have been made in the European regulation. One of the improvements comprises the revision of the EU Energy Performance of Buildings Directive, which subsequent to 2010 stimulates the development of energy performance of new and existing buildings through retrofitting (EPBD, 2010). Yet, heritage buildings are not included in the Directive (EPBD, 2010). While much research has been done to optimise the energy performance of new and existing buildings, this has not been the case for heritage buildings.

Over the last years, different European projects have focused on heritage buildings retrofitting, for example New4Old and 3ENCULT. ReFoMo has learned from these valuable experiences and at the same time wants to go further investigating how the retrofitting systems already in use can be applied in different European settings.

1.2 Problem definition

ReFoMo (Reduced Footprints of Monumental Structures, Landscapes and Buildings) is a project that has been responsive to the omission of heritage buildings in the EPBD. Our objective is to reduce the footprint of unique heritage buildings by bridging the gap between the energy performance of heritage buildings and the potential energy savings. After a theoretical study on the different techniques to be applied for the energy efficient retrofitting of heritage buildings (EERHB) (Rosales Carreón, 2015a). This report -the second written for the ReFoMo project-. discusses three case studies that show different technical approaches to retrofit a heritage building The aim of the study is twofold: i) Highlighting common practices among countries and ii) Understanding which energy efficient retrofitting practices can be applied for heritage buildings independent of their specific context. The report is organized as follows. After an introduction in section 1, section 2 explains the DMAIC approach, which was used as a method to reach the aims of the present study. Section 3 discusses the main findings. Finally, section 4 offers a discussion regarding the different approaches within ReFoMo in order to retrofit heritage buildings.

2 METHOD

By comparing different historic buildings in Europe, it is expected to find common facts to all cases or a solution that can be shared by all in order to make an energy efficient retrofitting and/or retrofitting of a heritage building. A comparative analysis was the selected method in this research as the cases within ReFoMo represent three geographical areas (North, Central and Southern Europe) in different climate zones and socio-cultural settings and distinctive building types. The three cases within ReFoMo are:

1. Historic fortresses (Utrecht);
2. Historic public buildings (Bologna);
3. Industrial heritage building (Budapest).

A comparative case study is defined as a tool of analysis that focuses into similarities and contrast among cases. It can contribute to the inductive discovery of problem solving and to theory building (Finifter, 1993). Using more than one case study enabled this research to explore differences between cases. A case study enables to gather data from a variety of sources and to converge the data to illuminate the case (Mills et al., 2006). The information gathered about the case studies was mainly obtained by reading the feasibility studies prepared by each partner of ReFoMo project. Moreover, some data was collected during informal and personal meetings with different team members.

Since the goal of comparative research is to replicate findings across cases, research needs equivalent definitions to measure constructs (Baxter & Jack, 2008). There is a procedure that needs to be followed to ensure coherency and consistency. Therefore, a comparative analysis through DMAIC approach was conducted. The DMAIC approach was selected to compare the three case studies because it focuses on improving existing processes that have not reached an optimal state (Desai & Shrivastava, 2008). It is an approach to improve a process consisting of the following five steps: i) Define, ii) Measure, iii) Analyse, iv) Improve and v) Control. The five steps of the DMAIC approach are explained in the following.

- Define

During this phase, the purpose and scope of the project are defined. Background information on the process is collected. The output of this phase is a clear statement of the intended improvement and a list of what is important to the costumer. In the case of this research, a general description of each case study was given during this step.

- Measure

This is the phase where a current baseline should be established. Namely, what parameters are to be measured and how they will be measured. The first findings of ReFoMo emphasize the need of starting any EERHB project with an energy audit (Rosales Carreon, 2015a). Therefore, the measure phase was based on the energy audit carried out for the different buildings within ReFoMO. An energy audit gives a baseline of the building since it shows the energy performance of the building

- Analyse

Analyze is the phase that develops theories of origin cause(s), confirm the theories with data and finally identify the root cause(s) of the problem. The verified cause(s) will form the basis to start searching for solutions. We studied how the different measurements done in the previous phase were used by the different ReFoMo cases.

- Improve

This phase refers to the identification, testing and implementation of possible solutions to the problem; in part or in a whole. In the case of this study, the different retrofitting strategies suggested by each of the ReFoMo partners were described.

- Control

This is the last phase of the DMAIC process. It is the phase where improvements are monitored to ensure the continuity of the solutions. During this step the creation of a monitoring plan, the updating of documents and business process is required. With respect to the ReFoMO case studies, we looked at how the different projects aimed at sustaining the retrofitting measures in the long term.

The strength of DMAIC approach is the way in which a specific case is structured and analysed. Its rigour and structured approach are the main differences between DMAIC approach and other process improvement techniques (Kumar et al., 2006). The core idea behind DMAIC approach is that if it is possible to measure how many defects there are in a process, it is possible to systematically figure out how to eliminate them and get as close to zero defects as possible (McKay & Shank, 2008). Considering energy inefficiency as a defect, DMAIC approach allows to search for both its causes and solutions. Through DMAIC approach, that clarity of thoughts is given allowing the proposition of measures that would eliminate the sources of energy inefficiency. The next section shows the results obtained from the DMAIC analysis for each of the ReFoMo cases.

3 RESULTS

This section presents our observations of how each case within ReFoMo was approached. It is organized under each of the DMAIC phases. ReFoMo focused on three key elements where energy efficient retrofitting can be implemented in heritage buildings. These are: i) Building envelope, ii) electrical appliances, heating and ventilation, lighting and integration of renewable energy and iii) Organisational measures. Therefore, the DMAIC analysis will be focused on these elements. For a more detailed discussion regarding the case studies, refer to the work of Gonçalves de Almeida (2014).

3.1 Define phase

3.1.1 Building Envelope

Starting by comparing the building envelope of the case studies, it is clear that the construction period differs. The fortresses are approximately a century older than the other two buildings. Between the two fortresses differences arise when comparing the barracks. The barracks of Fort aan de Klop went through a recent renovation. Therefore, these barracks present better energy performance and thermal comfort: wooden insulated walls, double glazed windows and exterior window shutters, insulated roof and solid heated floor. In contrast, the barracks from Fort de Gagel have walls of 1000 mm thick masonry. Older structures as fortifications present thicker walls than more recent buildings. When comparing the walls among all the buildings there is something to emphasize regarding the structure design. The fortresses only present walls while the Faculty of Engineering and the "Meter House" present a structure/frame (pillars) additionally to walls.

The fortresses have walls of 1500 mm thick masonry. The Faculty of Engineering has a structure of reinforced concrete and pillars with average thickness of 350 mm, covered with brick cladding on the ground floor and plaster on the upper floors. "Meter House" has brickwork cladding facade. Additionally, the Faculty of Engineering has opaque walls of masonry brick with thickness between 600 and 800 mm with an air gap. The external walls of "Meter House" are of clay bricks of varying thickness with plaster finish on the inner side. Even though the walls of more recent buildings are composed by more than one element (brick with air gap or clay brick with plaster finish), the walls of the fortresses are thicker. Another interesting aspect is the fact that Italian and Hungarian buildings both present an integrated layer of insulation: brick with air gap in the Faculty of Engineering and a plaster finish on the inner side of the clay bricks in "Meter House". These features show that at the time of the construction, the architects and engineers of both buildings thought about insulating them. In the future, the need for insulation will be reduced when compared to the fortresses. The majority of windows are single glazed so retrofitting might be suggested.

3.1.2 Electrical appliances, heating and ventilation, lighting and integration of renewable energy

Regarding the electrical appliances and heating systems, only the fortresses present standard appliances in use. Fort de Gagel has appliances used in offices. Fort aan de Klop has appliances used in restaurants. The heating system in use in Fort de Gagel consists of a gas boiler plus a water (electrical) boiler whereas in Fort aan de Klop is central heating on gas. Concerning the heating system in the Faculty of Engineering, either gas or electricity is consumed. The heating distribution system in Italy is made of non-insulated pipes and there is no temperature control in individual rooms. The industrial building in Budapest did not present energy consumption since it is currently functioning as a storage site for stones. Table 1 shows the relevant parameters that define each case study.

Table 1 – “Define” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope	- 1819 Guardhouse - Walls of 1500 mm thick masonry. - The roofs are integrated in defensive wall, i.e. covered by earth and vegetation. - Floor is of stone and partly of wooden beams with wooden floors. - Single glazed windows. Barracks - Walls of 1000 mm thick masonry. - Good artificial lighting due to orientation. Purpose of retrofitting: An information centre, offices (as current situation), café-restaurant and centre for outdoor activities.	- 1819. Guardhouse - Walls of 1500 mm thick masonry. - Flat roof. - Solid floors. - Single glazed windows. Barracks - Wooden walls. - Double glazed glass windows and exterior window shutters of historic design. - Floor is solid including floor heating system. Purpose of retrofitting: - Create an energy efficient and sustainable building while making the fortress even more attractive for visitors.	- 1935. - Structure of reinforced concrete and pillars with average thickness of 350mm, covered with brick cladding on the ground floor and plaster on the upper floors. - Floors are of mixed type and drilled in concrete, in most slabs with brick, sound-proof. - Opaque walls of masonry brick with thickness between 600 and 800 mm with an air gap. Purpose of retrofitting: - Improve difficult energy management due to different functions and rooms.	- 1914. - Brickwork cladding facade. - Dual-pitched roof, clad with red and yellow brickwork. - External walls of clay bricks of varying thickness with plaster finish on the inner side. - Open steel roof structure. - Single glazed windows. Purpose of retrofitting: - Establishing the Contemporary Cultural and Communication Centre, suitable for large masses and perform various functions is the aim of the retrofitting process
Electrical appliances and heating systems	Barracks - Appliances in use are of standard office use. - Heating boiler and water (electrical) boiler.	- Halogen and low energy light bulbs are used. Guardhouse - Standard restaurant appliances. - Central heating on gas. Barracks - Some of the barracks are heated through floor heating.	- Lighting and proper ventilation ensured throughout all day due to orientation. - The heating plant system consists in: central system with three gas boiler, a heating boiler and a heat pump.	- No energy use.

3.2 Measure phase

3.2.1 Building Envelope

Garai et al. (2014) performed an energy audit for the building in Bologna. They performed a thermography using an IR camera in order to obtain pictures to analyse local heat losses, assessing the effectiveness of insulation. This technique is included in the best practices of diagnostic and monitoring tools to evaluate energy performance of heritage buildings. A thermography offers the advantage of accurate and complete results to the “analysis” phase via a practical test to evaluate energy performance. Since it was part of an energy audit, by performing a thermography the auditors were able to observe and highlight thermal bridges of the building envelope. In the case of the Dutch fortresses, M. Bonnike (personal communication, October, 2014) resorted to a report with energy use values to simulate the fortresses structures on RETScreen software. The outcome of the simulation was a set of “U” values of the building envelope. However, there was not a formal energy audit performed at the fortresses. Alexa et al. (2014) explained that no energy audit was performed at the “Meter House”. Instead, they decided to perform energy calculations. These calculations included coefficient heat transmission of the building envelope structures and the total energy need of the building (heating, cooling, ventilation and lighting).

3.2.2 Electrical appliances, heating and ventilation, lighting and integration of renewable energy

There was not an explicit inclusion of this element within the different ReFoMo case studies. However, the team in Bologna has done a study on thermal environment conditions within the building under study. The team in Utrecht had commissioned an electricity and gas study in 2012 for fort aan de Klop (Jansen, 2012). This study showed that the appliances used in the kitchen and the cooling equipment were responsible for two thirds of the electricity consumption. Heating was responsible for 70% of the gas consumed by the fort. The team in Budapest did not have to do any accounting regarding this element because the building was being used as a storage facility.

3.2.3 Organisational Measures

The information, regarding the topic of organizational measures, was unavailable at the moment of writing this report. As part of the organizational measures, it was expected to know the energy management plan and the maintenance plan being carried out. For example, it would be important to know the daily operation of the appliances used in all buildings under study. In this way, it would be known if the buildings are on a time of use tariff paying a different price for their electricity during different time periods (peak or off peak time)[1]. Also, a lighting profile could be necessary to highlight unnecessary energy use. Table 2, shows the most important findings regarding the “Measure” phase.

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[1] Peak electricity is provided during set times of the day when demand for electricity is highest. At these times, the power system is stretched to its limits. Off-peak electricity is provided during set times of the day when homes and businesses use less electricity. To encourage people to use electricity during these times of the day, many providers offer cheaper electricity during these off-peak times.

Table 2 – “Measure” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope	RETScreen software simulation.		Thermography.	
Electrical appliances and heating systems	Tersteeg (2014)	Janssen (2012)		Energy calculations based on the HVAC systems required for the use described in a feasibility study (executed earlier by the owner of the site).
Organisational measures	No information focused on this topic was available. However, a number of measures can be audited in order to understand the energy use of the building. For example: the use of lights, appliances or natural lighting can be monitored by surveys, observation or smart monitoring (smart meters) when installed. These measurements may give an indication of how efficient the use of the different appliances is.			

3.3 Analysis phase

3.3.1 Building Envelope

Through the results of the energy audit it is possible to understand which elements require retrofitting and/or retrofitting processes to improve energy performance in each building under study.

On the topic of building envelope, walls and windows are comparable. All the walls of the buildings under study are insulated except for Fort de Gagel and the guardhouse at Fort aan the Klop. Analysing the "U" values of the walls, the insulated wooden walls of the barracks at Fort aan de Klop show lower thermal transmittance than the typical values of heritage buildings. Here, the insulation was effective and should be considered as an example of good practice EERHB. The "U" values of the windows are higher than the typical values. Nevertheless, the calculated "U" values of the fortresses and the Faculty of Engineering are approximately the same. Hence, all buildings should consider the retrofitting of windows. The main reason for these values to be higher than the typical ones is the preservation of original building envelope elements. The constraints forbid working freely on retrofitting and/or retrofitting the surfaces.

3.3.2 Electrical appliances, heating and ventilation, lighting and integration of renewable energy

On the topic of electrical appliances and heating systems, M. Bonnike provided energy use values. The energy use values of both fortresses showed the appliances/operations that consume more energy. The next section will discuss the possibilities for reducing those values.

3.3.3 Organisational Measures

The topic of organisational measures refers to human behaviour but also to energy use management and maintenance of heritage buildings. Garai et al. (2014) presented the constraints imposed at the Faculty of Engineering by architectural preservation when retrofitting and/or retrofitting processes are foreseen. These constraints are included as organisational measures due to the fact of being organisational/political impositions to the retrofitting. Regarding the other two buildings no information was available on this topic.

Table 3 – “Analysis” phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The “Meter House”, Budapest, Hungary
Building envelope	- Single glazing: 5.7 W/m^2K. - Double glazing: 3.3 W/m^2K. - Walls (barracks): 1.16 W/m^2K. - Roofs (barracks): 2.08 W/m^2K. - Floor: 0.47 W/m^2K.	- Single glazing: 5.7 W/m^2K. - Double glazing: 3.3 W/m^2K. - Walls (barracks): 0.82 W/m^2K. - Roofs (barracks): 1.08 W/m^2K. - Floor: 0.47 W/m^2K.	- 26% of all the thermal transmittances of walls are between 1.00 and 1.20 W/m^2K. - Single pane transmittance: 5.75 W/m^2K. - 14% is of double glazing. Thicknesses are 4/8/4 (8 mm air gap) and the thermal transmittance is 3.14 W/m^2K.	
Electrical appliances and heating systems	- Heating and lighting reflect the highest electricity uses.	- Kitchen and cooling equipment are the major parts using electricity.		
Organisational measures			- Architectural constraints have discouraged the replacement of the windows and frames.	

3.4 Improve phase

3.4.1 Building Envelope

Table 4 depicts the most important results for improve phase. Solutions were suggested for windows, walls and roofs (envelope). It was noted that window insulation is a recurrent solution in all the case studies. The solution Suggested for Fort aan de Klop is in line with the most widely adopted solution for window retrofitting, namely, secondary glazing. However, the replacement of windows could be done resorting to “smartwin historic”. A curtain wall windows works with the same purpose as secondary glazing on the inner surface. The thermal performance of cavity walls is normally improved by filling the cavity with insulation, which can reduce the heat loss through the walls by up to 40% (Roberts, 2008). Therefore, insulating walls is a priority aspect when retrofitting heritage buildings. Filling the cavity with insulation is the suggested solution at the Faculty of Engineering. At the “Meter House” internal insulation is proposed involving lining, the inside faces of the wall with plasterboard on a frame. At Fort aan de Klop, at some areas the walls were already insulated so there is no information about predicted plans on more insulation. Regarding roof retrofitting, insulation was a shared solution for the Faculty of Engineering and the “Meter House”. There are different methods to insulate roofs depending on if they are pitched or flat. In the case of the flat roof in Italy, the installation of thermal insulation on the roof allows 1% of energy savings. In the case of the Netherlands, there is no consideration regarding the insulation of roofs. The reason for that may be the fact that Fort de Gagel is covered by earth and vegetation and Fort aan de Klop presents an “U” value lower than the typical value of heritage buildings.

3.4.2 Electrical appliances, heating and ventilation, lighting and integration of renewable energy

Regarding electrical appliances, M. Bonnike (personal communication, October, 2014) suggested that all the energy generated has to be renewable (sun and wind). Within Fort aan de Klop, RES integration is feasible. These two solutions are applicable because the historical value of the building is preserved and there is a way of using land surrounding the fortress otherwise unusable. Garai et al. (2014) suggested the replacement of central heating boiler with a new condensing boiler as it is written in literature. Alexa et al. (2014) provided no information regarding the production of electricity. Regarding the heating of the building, a vertical heat exchanger using soil as source emerged as a solution according to Bonnike (personal communication, October, 2014). In contrast, Alexa et al. (2014) assumed that heating is provided by heat recovery from wastewater. This is another solution to produce heating without using fossil fuels. The three case studies show that it is possible to use RES in heritage buildings.

3.4.3 Organisational Measures

Energy efficiency improvements based on organisational measures were unavailable at the moment of writing this report. Organisational measures can be applied in every building to make people aware of a rational use of energy and resources. An interesting aspect worth mentioning is the fact that both Fort aan de Klop and the “Meter House” envision the cleaning and reuse of water. This reflects the awareness raised by the responsible entities towards a rational use of water.

Table 4 – "Improve" phase comparison

	Fort Gagel, Utrecht, The Netherlands	Fort aan de Klop, Utrecht, The Netherlands	Faculty of Engineering, Bologna, Italy	The "Meter House", Budapest, Hungary
Building envelope		- Possibility of secondary glazing at the guardhouse.	- Blown-in cellulose insulation in the air layer of walls. - External thermal insulation (on walls without architectural constraints). - Replacement of windows without architectural constraints. - Roof thermal insulation.	- Additional thermal insulating glass. - 100 mm thick layer of insulation (YTONG Multipor) on the inner surface of the wall. - Curtain wall windows with undivided glazing attached to the restructured inner surface of the walls. - Glazing with heat resistant coating.
Electrical appliances and heating systems		- Placement of solar panels and a windmill of 15 metres high. - Vertical heat exchanger (source is the soil). - Use LED lighting.	- Replacement of central heating boiler with new condensing boiler potential measures: central heating. - Zone control with thermostatic radiator valves.	- HVAC systems that require the least visible mechanical and architectural (chimneys etc.) elements. - The heat recovery from waste water is a cheap energy source continuously available in urban areas and production facilities.
Organisational measures		- Reuse of waste water. - Waste separation system and reuse of compostable waste for green surroundings.		- Implementation of outside interventions is unmanageable.

3.5 Control phase

3.5.1 Building envelope

The utilisation of thermostats and humidistats avoids deliberate fluctuations of temperature and RH in the valuable historic interior and thereby limits the risk of any damage. Electric radiators can be automatically switched on/off if connected to the thermostats saving unnecessary heating/cooling energy. (Saïd et al., 1997; Neuhaus & Schellen, 2007). This advice is applicable to any kind of historical building without temperature and RH control. If it is possible to set and maintain a temperature inside of a building, then the insulation of windows, doors and/or roofs was effective.

A specific advice for the Faculty of Engineering in Bologna is to perform another thermography after execution of retrofitting works. A new evaluation of the energy performance through new thermography would show if the thermal bridges revealed on the previous one performed were eliminated or, at least, diminished. For the other two case studies –in fact for any historical buildings- we encourage to perform an energy audit before and after the retrofitting processes. A blower door test and/or a thermography should be performed. The blower door test would inform about the heat losses through air infiltrations and a thermography would localize the thermal bridges and check where the materials change or are irregular.

3.5.2 Electrical appliances, heating and ventilation, lighting and integration of renewable energy

The owners/responsible entities of the buildings should analyse and compare energy bills before and after implementation of any retrofitting measure. The most important aspects to look at in the energy bill are: i) the billing period (the supply period); ii) whether the bill is based on an actual reading or an estimate; iii) the number of days the bill covers; iv) the total amount of electricity/gas used; v) the prices paid per kWh/m^3 in different periods, i.e. peak and off peak rate, and for the total billing period. This will allow better knowledge of the energy profile of the building. It is suggested that users build a chart where one can read the energy consumed during one year. The energy use during the night is another factor requiring monitoring. Some appliances such as computers and lighting are constantly turned on in heritage buildings. The occupants responsible for the buildings should be advised and reminded to turn off all the appliances that should not operate during the night before closing the buildings. The installation of smart monitoring as suggested for Fort aan de Klop is a feature that controls energy use values in real time (M. Bonnike, personal communication, October, 2014). The Company Navetas developed in 2012 a technology that – in addition to tracking the overall energy use – is able to distinguish the various power loads from one another (i.e. refrigerator, television, washing machine, etc.). Smart meters act as a two-way interface with the costumer's own appliances transmitting data, receiving commands, monitoring supply and communicating with appliances.

3.5.3 Organisational measures

The team responsible for the retrofitting of the building should meet regularly to discuss if any anomaly has been identified. In this way knowledge can be sustained. We recommend three times per year but the frequency needs to be decided by the team. In any case, the team should be able to have an open and fast communication at any time. In the case of ReFoMo two tools were used. The first one regards an online management tool. The second one was a website created for ReFoMo. Unfortunately, none of these tools was used for the different team members.

When users are informed about appliance efficiency labels, consumers adopt the most efficient technology and this is particularly true when there is an explicit link between energy efficiency savings and monetary savings (IEA, 2014). This information should be contained on the advertising/explanatory leaflets of the specific heritage building. The visitors/occupants of heritage buildings should be able to read information about the energy performance and retrofitting interventions at the sites (in the fortresses, in the Faculty of Engineering, in the “Meter House” and in all heritage buildings). The work involved in retrofitting historic buildings should be disclosed so visitors/occupants gain awareness of the relevance regarding maintenance and improved energy performance in these heritage properties.

4 Discussion and Conclusion

The present section discusses the findings of this research, namely the suggestions in order to perform an energy efficient retrofitting for heritage buildings. In 4.1, the idea of a multidisciplinary team to be responsible for the whole project is presented. In 4.2, the energy audit for heritage buildings is elaborated. The final section gives an overview of the best practices of techniques and retrofitting solutions discussed along the report.

4.1 Multidisciplinary team

The creation of a multidisciplinary team is essential during the retrofitting interventions of heritage buildings. This team should comprise architects, civil engineers, historians, energy experts, politicians, civil servants, financial institutions, owners, users, companies of specialized energy auditing and communication professionals that will provide the most complete data gathering. The goal of multidisciplinary is the contribution of each discipline to both understand the heritage value of the building and the renovation that the building needs to undergo.

The multidisciplinary team have as responsibilities:

1. Design the energy audit;
2. Supervise/conduct the energy audit (i.e. energy auditing expert);
3. Present the results in a report that shows relevant information for each of the team members;
4. Meet every year to monitor the benefits of the “improve” phase.

4.2 Energy Audit

An energy audit is compulsory as the first step of the retrofitting process. The significance of an energy audit lies in the possibility to identify the sources of over consumption and where it is possible to implement energy saving measures. There are three key topics where energy efficient retrofitting can be implemented in heritage buildings: building envelope; electrical appliances and heating systems and organisational measures.

Only the Italian case performed an energy audit. A thermography was performed and the system plant was described. The energy audit offered recommendations for both building envelope and the heating system. Nevertheless, it missed following the evaluation under the three topics suggested and consequently an accurate and detailed energy audit. Regarding the Dutch case studies it was suggested that in addition to the “U” values calculations at Fort de Gagel and Fort aan de Klop, either an air tightness measurement or a co-heating test should have been performed to acknowledge the permeability of the building fabric. An air tightness measurement would assess air permeability and location of air leakage paths. A co-heating test would measure heat losses resulting from both infiltration and thermal transmission through the building fabric. However, to perform a co-heating test the fortress would have to be unoccupied to eliminate human behaviour variables. With regard to the “Meter House” we suggested to consider performing a thermography or a heat flux measurement. The data resulting from either technique would provide the thermal conditions of the building. The thermography would analyse where the heat losses occur while the heat flux measurement would derive an in situ “U” value for the building elements.

4.3 The best practices on how to refurbish a heritage building

4.3.1 Building Envelope

Secondary glazing is the most widely adopted solution and the solution proposed to retrofit windows at Fort aan de Klop and the “Meter Hosue”. This is the most protective value solution of historic windows. However, it is suggested that the retrofitting team should confirm the possibility of replacing the existing windows for “smartwin”. This solution conserves the historic character of the building and achieves comfort standards of a modern window. Concerning draught-proofing, heavy-duty materials are particularly advisable. None of the case studies considered this solution but it is suggested that ReFoMo can benefit from these materials to better insulate windows and doors. The case studies did not refer to retrofitting floors. That circumstance suggests the floors are in good conditions and/or well insulated. At walls retrofitting, more solutions appeared in addition to the widely adopted. It was noted that the Faculty of Engineering suggested both interior and exterior insulation. The innovative solutions were not considered to retrofit the walls of the case studies. VIPs are fragile compared with conventional construction materials and edge effects are significant, requiring careful design and fabrication. Multi-foil insulation is made up of multi-layered reflective films only a few micrometres thick. This solution could also be applied into the case studies which chose other possible solutions. Only the Italian case study suggested roof insulation. Since they did not present how to thermally insulate the roof it is suggested options depending on the inclination of the roof (pitched or flat). Since no more information was available, it is suggested single glass type window for southern regions and casement type windows for northern regions. Table 5 summarizes the best practices on building envelope retrofitting of heritage buildings. These best practices include the most widely adopted solutions, the innovative solutions and the solutions proposed by the case studies.

Table 5 - Best practices on building envelope retrofitting of heritage buildings

Building envelope	**Windows** Secondary glazing (widely adopted solution + Fort aan de Klop + The "Meter House"). "Smartwin historic" (innovative solution). Glazing with heat resistant coating (The "Meter House").
	Draught-proofing Heavy-duty materials are particularly advisable.
	Floors From below the suspended floor with wood-fibre, compressed hemp, sheep's wool. From above the floor suspended with semi-rigid batts, boards or loose fill cellulose. Replacing solid floors carpets with wooden floors or tile.
	Walls Interior insulation: blown-in cellulose insulation in the air layer of walls (Faculty of Engineering). Layer of insulation (YTONG Multipor™) on the inner surface of the wall (The "Meter House"). Vaccum insulation panels (innovative solution). External thermal insulation (Faculty of Engineering). Useful materials include hemp-lime composites, sheep's wool and mineral wool. Multi-foil insulation (innovative solution).
	Roofs A variety of materials can be used from mineral fibre to natural materials such as wool of sheep for pitched roofs. Soft fibre rolls or unformed loose-fill materials for flat roofs. Green roofs (innovative solution).
	Shading devices Single glass type window (southern regions) and casement type windows (northern regions).

4.3.2 Electrical appliances, heating and ventilation, lighting and integration of renewable energy

Fort de Gagel has appliances used in offices and Fort aan de Klop has appliances used in restaurants. There is no additional information about this topic so it was advised the responsible entities of the building to note the energy label of equipment. On the topic of heating systems, the innovative system was not taken into consideration to retrofit the buildings under study. However, the active overflow prototype was installed in a heritage building and showed that it is an advantage compared to decentralised systems with two openings per room (in and outflow) to the outside (impacting on the building structure). Therefore it could also be applied in the case studies. These proposed vertical heat exchanger using the soil at Fort aan de Klop and heat recovery from waste water at the "Meter House". The solutions proposed for the case studies can be extrapolated for other cases if there is soil available to storage heat. The widely adopted solution to retrofit boilers is a condensing boiler. The only case study concerned with this element suggested in accordance to the widely adopted solution. At lighting level, the widely adopted solution was proposed for lighting retrofitting at Fort aan de Klop: led technology. The innovative solution, luminaire "wallwasher", provides on one hand optimized visual scenery and on the other hand it should slow down the deterioration process that any material undergoes. Therefore, "wallwasher" can be installed in the buildings under study if it is possible to replace the luminaires. The opportunities for passive heating and cooling were neglected by the case studies. Therefore it was recommended the use of transparent surfaces to gain heat so walls storage it as the best practice. Regarding RES integration, examples were found in literature of integration of solar roofs. This solution could also be applied on the flat roof of the Faculty of Engineering. At Fort aan de Klop it is recommended the installation of solar panels and a windmill to generate electricity. This RES integration is possible due to the existing wasteland nearby the fortress. Table 6 resumes the best practices on electrical appliances and heating systems retrofitting of heritage buildings.

Table 6 - Best practices on electrical appliances and heating systems retrofitting of heritage buildings

Electrical appliances and heating systems	**Electrical appliances** Energy labelled appliances.
	Heating systems Wet systems (widely adopted solution). Active overflow propotye (innovative solution). Vertical heat exchanger using the soil (Fort aan de Klop); heat recovery from waste water (The "Meter House").
	Boiler Condensing boiler (widely adopted solution + Faculty of Engineering)
	Lighting Led technology (widely adopted solution + Fort aan de Klop). Luminaire “wallwasher” (innovative solution).
	Passive heating and cooling Use of transparent surfaces to gain heat and wall to storage it.
	RES integration Integration of solar roofs - not visible from the streets. Solar panels and Windmill (Fort aan de Klop) - utilization of wasteland.

4.3.3 Organisational Measures

Table 7 depicts the best practices on organisational measures towards the improvement of energy performances of heritage buildings are presented. Our suggestions are twofold: change in human behaviour and use of energy efficient controls and equipment.

Table 7 - Best practices on organisational measures in heritage buildings

Organisational measures	**Changing behaviour** Reuse of waste water (Fort aan de Klop). Waste separation system and reuse of compostable waste for green surroundings (Fort aan de Klop). Inform users about appliance efficiency labels. Inform the visitors/occupants about the energy performance and retrofitting interventions at the sites.
	Using energy efficient controls and equipment Control temperatures and relative humidity (RH) inside the building with thermostats and humidistat, respectively. installation of smart monitoring.

4.4 Conclusion

Although it is acknowledged that each heritage building is unique and therefore it needs customized energy solutions, ReFoMo has been exploring technical solutions that can be put in place to advancing the implementation of EERHB in Europe. A complete list of energy efficient retrofitting measures that should be considered EERHB is given in Appendix A. The present report suggests that there are technical solutions that can be put in place to advancing the implementation of energy efficient retrofitting of heritage buildings in Europe. However, the aforementioned implementation is not occurring. Therefore, ReFoMo needs to identify the possible cause why EERHB is not taking place. Therefore, we also took a closer look at the barriers that hinder the EERHB and how to overcome these barriers (Rosales Carreón J, 2015b).

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APPENDICES

Appendix A

List of energy efficient retrofitting measures for heritage buildings

MANAGEMENT
Design - Flexibility and future proofness
Management and behavior

1	Avoid unnecessary cooling, heating and lighting of rooms
2	Set up energy management system
3	Set up/improve energy management system consistent with ISO 50001
4	Appoint energy management coordinator
5	Energy management course building managers
6	Carry out an Installation Performance Scan
7	Adjust room temperatures on basis of reconsidering comfort versus energy saving

ENERGY
Heating

8	Insulate heating and distribution pipes
9	Place heat shields behind radiators
10	Insulate central heating components
11	Use energy efficient pumps
12	Optimize fuel/air mixture
13	Apply a switch on heating pumps
14	Apply speed control on heating pumps
15	Avoid/replace oversized heating pumps
16	Decarbonate boilers
17	Adjust flows by re-tuning
18	Divide heating system in more central heating groups/boilers

Cooling

19	Apply radiation cooling
20	Use energy efficient pumps
21	Apply high temperature cooling
22	Apply pump switch/speed control on chilled water pumps
23	Apply (indirect) adiabatic cooling
24	Install a speed controlled compressor chiller
25	Insulate cooling pipes
26	Apply Phase Change Materials (PCM materials)