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PhD thesis

Title:

ENERGY EFFICIENCY IN BUILDINGS: WILLINGNESS TO PAY FOR BUILDINGS ENERGY RETROFIT

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Summary

INTRODUCTION

The Italian real estate asset is the oldest in Europe. It accounts for more than 12.2 million buildings, corresponding to 31.2 million dwellings, the 70% of which were built before the implementation of the first Law n. 373/1976 on building energy efficiency (ANCE, 2017, CRESME, 2018). The building sector is therefore responsible for almost 40% of the overall primary energy consumption. Data provided by the European Buildings Database accounts for a total amount of 44.22 Mtoe/year of energy consumption for both residential and non-residential buildings. In Italy in 2017 the National Energy Strategy (NES) set the target on the reduction of 10 Mtoe primary energy consumption by 2030 (ENEA, 2018) thus, the existing building stock is considered to have a high potential in terms of energy savings, sustainable development (Mangialardo et al., 2018, Jafari et al., 2019) and reduction of greenhouse gas (GHG) emissions (Mauri et al., 2019, Mutani et al., 2019, Ferrari and Beccali., 2017).

To reach EU targets on mitigation of climate change effects, in recent years the European Union has enacted directives, laws and regulations to boost investments in building energy retrofit projects (BERPs), among which the most well-known is Directive 2010/31/EU (Energy Performance of Buildings Directive, Recast EPBD) updated by the EU Directive 2018/844/EU. The aims of the above Directives are multiple: a) promote deep energy renovations of existing buildings; b) provide energy policies to boost investments in BERPs; c) set energy efficiency targets for new and existing buildings; and d) provide economic evaluation methods for BERPs.

The EU has fixed short and long-term targets (e.g., 2020 climate and energy package and 2030 climate and energy framework). Italy has just reached some of the 2020 targets by reducing up to 17.1% CO_2 emissions with respect 1990 levels (GSE, 2018). As regards the residential building sector, primary energy consumption dropped from 310 Mtoe in 2005 to 284 Mtoe in 2017 (COM, 2019). Medium-term targets and long-term targets are set in the 2030 Climate and Energy Framework and the 2050 Long Term Strategy, according to which EU member States are expected to reduce up to 80-95% GHG emissions with respect 1990 levels by 2050. To reach these targets, policy instruments, renewables and energy-efficient technologies (EETs) must be adopted (Knobloch F. et al., 2019). Concerning the building sector, the selection of EETs for energy retrofit of buildings (ERBs) is an optimization problem. Starting from a set of implementable EETs that defines a set of feasible BERPs, the goal is to determine the cost-optimal EET in a cost-effective perspective, by considering all related costs during the life cycle of the building, while respecting energy efficiency performance standards set by laws and regulations as well as ensuring acceptable thermal comfort levels (Ma. et al., 2012). The Italian Legislative Decree 192/2005 and the European Regulation 244/2012 provide the Life Cycle Cost method (LCC) for the economic valuation of BERPs. For each implementable BERP it is necessary to estimate its LCC that is the sum of the present value of investment costs paid to install EETs, running costs (energy, operational and maintenance costs), replacement costs as well as disposal costs if applicable. According to the Legislative Decree 192/2005 requirements, the BERP which minimizes the LCC is the "cost-optimal" project to be selected and implemented. LCC method is based on the principle of costs minimization, but some concerns emerged from literature. The LCC is the sum of different costs typology that vary in a different way depending on the obtained energy efficiency level through retrofit. Higher energy performance levels involve higher cost savings due to lower energy consumption, but higher investment, maintenance, operating and, replacement costs; where a slower energy performance levels involve lower savings costs as well as investment, maintenance, and replacement operating costs. The LCC method weights more economic performances rather than energy performances. In Italy, a minimum target for buildings energy efficiency with respect to the cost-optimal BERP is not provided and therefore it might not be possible to reach the 2030 and 2050 targets by adopting this methodology. In addition, it is argued in literature that the LCC method favours the point of view of policy makers and governments in order to minimize financial and fiscal incentives provided to boost investments in BERPs (Araujo et al, 2016) and does not focus on private investors interests. Several authors argue that buildings energy retrofit (BER) provides a wide range of co-benefits in addition to significant energy savings (Banfi et al, 2008; Capelletti et al, 2015; Ferreira and Almeida, 2017; D'Oca et al, 2018), therefore stakeholders might be willing to pay or to invest in most energy-efficient solutions rather than in the least cost as well as they might be most interested in environmental and energy-efficiency performances rather that in economic performances.

This in turn might lead to higher saving potentials in EU's residential buildings, optimize the use of energy resources (Bonifaci and Copiello, 2015; Araujo et al, 2016) and reach the 2030 and 2050 EU targets on mitigation of climate change effects. All the previous considerations highlight that the economic evaluation of BERPs is a complex process where different actors and a set of decision variables are involved: social, technical, economic and environmental aspects interact in BERPs investment decisions. To be exhaustive, the economic evaluation of BERPs have also to account for the trade-offs between retrofit costs and direct, indirect, tangible and intangible benefits of implementable BERPs (D'Alpaos and Bragolusi, 2018).

The aim of the research is to provide innovative valuation approaches of BERPs, investigate their relative cost-benefit trade-offs and address the multiple benefits of renovations and potential financial barriers to their taking up. In detail, the research focuses on the estimation of the monetary value of benefits and co-benefits related to buildings energy retrofit and examined whether they might encourage investments in BER.

In order to pursue these objectives, a systematic literature review was conducted as a preliminary step of the research, from which it emerged that several contributions focus on energy consumption modelling and the impacts of retrofit strategies on CO_2, as well as on valuation methodologies of different retrofit strategies (e.g., multicriteria analysis, life cycle costing and assessment, econometric models, etc.). Nonetheless, there is a lack in literature on the evaluation of individuals' willingness to pay (WTP) for BER. Stakeholders' preferences may play a crucial role in investments effective implementation, and their elicitation may contribute to fill the gap between scientific research and the actual undertaking of investments.

To estimate the WTP for BER and determine its market demand, we adopted the Stated-Preference (SP) method in the field of the Choice Experiments (CE) methodology, which was developed starting from the seminal works by Mitchell and Carson (1989) and Hanley et al. (2001). The CE is a survey-based methodology, which allows for eliciting preferences for goods. The lack in literature on the estimation of the WTP by the CE approach, specifically in Italy, added complexity in the experimental design and the identification of attributes and relative levels. Once the relevant benefits and co-benefits of BER are identified, it is possible to estimate the related willingness to pay (WTP) through a survey and an econometric model, which is meant to improve the economic evaluation of BERPs and provide some important implications for energy policy design. To address these issues first, a multiple criteria model, based on the Analytic Hierarchy Process (AHP), was developed to identify relevant key factors in BER and rank alternative energy retrofit measures; secondly, a novel approach to the valuation of BERPs which combines the LCC method and the cost-benefit analysis was implemented. From these preliminary steps, it emerged that: a) the higher the building energy performance, the higher the increase in property market value (i.e., price premium); b) the implicit marginal price of energy performance labels is high compared to others and contributes significantly to pay back investment costs; c) benefits related to BER, which are not usually considered in other conventional analyses (e.g., price premiums) play a key role in boosting investments. These results are of paramount importance in the development and implementation of the CE approach as they lead to the identification of: a) benefits and co-benefits, which are key drivers in BER investment decisions; and b) cost-benefit trade-offs of energy efficiency improvements.

The reminder of the thesis is organized as follows.

The first chapter provides a review of laws and regulations on ERBs at national and EU level, illustrates and discusses the LCC method. The second chapter reports the results of a systematic literature review conducted to define the state of the art on BER valuation approaches and analyses the most commonly used methodologies for the economic valuation of BERPs. In order to identify gaps in literature and identify possible improvements. The emerged gaps lead to a second literature review focused on the analysis of relevant benefits and co-benefits that retrofit involves, that might be key-drivers in BERPs investment decisions. The last part of the chapter illustrates the results of a further literature review, which focused on the estimation of WTP for BER specifically in the Italian context. The third chapter describes theoretical aspects and technicalities of the SP and CE methodologies and discusses econometric models, survey design and experimental design. The fourth chapter is focused on the CE application to estimate, following the methodological framework provided by Hanley et al. (2001), the WTP for BER and its market demand and in turn to provide a monetary value for most relevant benefits and co-benefits that retrofit involves. In the last chapter, results and relative policy implications are illustrated and discussed and conclusions are drawn.

1. BUILDINGS ENERGY RETROFIT: LOW AND REGULATIONS, THE COST-OPTIMAL APPROACH

1.1 Review of Laws and Regulations at EU and national level

During years, at European and national level several laws and regulations on BER were enacted. In this section, I carried out a review to describe and analyse the most important ones.

In Italy, the first important Law n. 373/1976 was enacted to establish some requirements for building thermal plants and for the thermal insulation of the building envelope in order to reduce the energy consumption of the buildings. The law provided some rules for the design, the maintenance, the operational procedures and the installation process of thermal plants. The law set the building indoor temperature limit at 20 degrees, this rule is nowadays still valid. A maximum temperature of 48 degrees was set for the domestic hot water production too. For new buildings and those subjected to renovation works, certain thermal insulation requirements of the building envelope had to be respect.

The second Italian innovative Law n. 10/1991 was enacted to reduce the building energy consumption, to improve the indoor comfort of building occupants and to improve the environmental compatibility conditions of the energy use; the law was in alignment with the energy policy provided by the European Union. Some technical requirements for the plant systems were introduced, in particular they had to respect a certain level of energy efficiency and the law promoted the energy production from renewable sources especially for the non-residential buildings. The thermal insulation of the building envelope for new buildings and those to be retrofitted had to ensure a minimum energy saving level of 20%. For building energy retrofit works, a technical report had to be presented to the municipality in order to demonstrate that it respected the law requirements.

The Dpr n. 412/1993 was enacted to implement the Law n. 10/1991. The Italian territory was subdivided into six thermal zones (from A to F) on the basis of the *degree days.* The *degree days* are defined as the sum (extended over the entire annual conventional heating period) of the positive daily differences between the indoor building temperature (conventionally set at 20 ° C) and the average daily external temperature derived from UNI 10349. The buildings were classified according to their use, eight categories were defined (from E.1 to E.8), this classification is still valid. The decree introduced the *FEN* index that specified the annual building energy demand utilized for the design of BERPs. This index was then replaced with the $EP_{gl,nren}$ index that is now in use (DM 26/06/2015) and it indicated the building annual energy consumption for heating.

In 2002 the EU enacted the Directive 2002/91/EC called *Energy Performance of Building Directive* (EPBD). The goal was to promote the energy retrofit of buildings taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. The Directive provided a general framework described in the *Annex I* for the calculation of the building energy performance, all the European Member States had to perform a calculation methodology at national or regional level on the basis of the proposed general framework. Minimum requirements of the building energy performances had to be defined for both new buildings and existing buildings. The building energy performance certificate was introduced in order to sold or rent the building and the Directive imposed regular inspections procedures of boilers and of air-conditioning systems.

The Italian Legislative Decree D.lgs n. 192 of 19/08/2005 implemented the European Directive 2002/91/EC. Then, the Italian Legislative Decree n. 311 of 29/12/2006 modified the Decree n. 192 of 19/08/2005 providing some adjustments.

The Italian Decree of the President of Republic Dpr n. 59/2009 defined the calculation methodologies, the criteria and the minimum requirements related to buildings and plants for cooling, heating, domestic hot water production and lighting. The decree identified the Italian technical standards for the calculation of the building energy performance too.

The Italian Ministerial Decree DM 26/6/2009 defined the guidelines for the building energy certification. It provided the methodologies to compute the building energy performance index and related technical standards to consider. The decree provided the format of the building energy certificate too.

In 2010 the European Parliament enacted the Directive 2010/31/EU on the energy performance of buildings. The Directive promotes the improvement of the energy performance of buildings taking into account outdoor climatic conditions, local conditions, indoor climate requirements and cost-effectiveness. An important general framework that described the methodology to calculate the energy performance of buildings was performed and it is reported in the ANNEX I of the decree.
Minimum requirements were specified for (source: Directive 2010/31/EU):

- "*existing buildings, building units and building elements that are subject to major renovation;*
- *building elements that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are retrofitted or replaced;*
- *technical building systems whenever they are installed, replaced or upgraded;*
- *national plans for increasing the number of nearly zero energy buildings;*
- *energy certification of buildings or building units;*
- *regular inspection of heating and air-conditioning systems in buildings;*
- *independent control systems for energy performance certificates and inspection reports*."

The Decree promoted the introduction of financial incentives to boost investments in BERPs and programmes focused on removing market barriers related to energy efficiency and energy from renewable sources; the decree underlined the importance of energy performance certificates too.
One of the most important aspects of this Decree was the definition of the *cost-optimal* levels of minimum energy performance requirements. This principle was provided to select the implementable ERMs for the BER. The cost-optimal level was defined as (source: EU Directive 2010/31/EU):

"'cost-optimal level' means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where:

(a) the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced), where applicable, and disposal costs, where applicable; and

(b) the estimated economic lifecycle is determined by each Member State. It refers to the remaining estimated economic lifecycle of a building where energy performance requirements are set for the building as a whole, or to the estimated economic lifecycle of a building element where energy performance requirements are set for building elements."

The *Global Cost* methodology for the economic evaluation of BERPs was defined in the subsequent EU Delegated Regulation 2012/244/EU which took up the cost-optimal principle of the EU Directive 2010/31/EU.

The EU Delegated Regulation 2012/244/EU it is one of the most important Decree on the economic evaluation of BERPs and it is described in Section 1.3. It provided a *comparative methodological framework* to determine cost-optimal levels of BERPs on the basis of EPBD principles. The Decree introduced the *Global Cost* method for the economic evaluation of BERPs better known in literature as *Life Cycle Cost* (LCC) method.

The Italian law n. 90 of 13/08/2013 modified the Legislative Decree n. 192 of 19/08/2005. It promoted the improvement of the building energy efficiency and the use of renewables for the energy production. The law provided a new tax rebate incentive policy and preferential loan schemes for the BER. The building energy certificate became mandatory also for the rented buildings and was renamed as *APE* (*"Attestato di Prestazione Energetica"*, Energy Performance Certificate).

In 2015 the Italian Inter-Ministerial Decree 26/06/2015 was enacted. It is the most important Italian Decree on BER. It defined the methodology to compute the building energy performance including the use of renewables, the minimum requirements of building energy performances, the format of the Energy Performance Certificate (APE) and the format of the technical report to attest that the retrofit works are in agreement with requirements of the Legislative Decree n. 192 of 19/08/2005.
As regards the building energy performance classification, it is determined computing the global annual primary energy consumption for heating, cooling, ventilation, domestic hot water production and for the non-residential buildings the energy consumption for elevators and escalators as well as lighting are added. The annual primary energy consumption it is indicated with the symbol EP_{gl} and it is expressed in kWh by square meters per year [kWh/m^2 year], it is the sum of:

- EP_H: annual energy consumption for heating;
- EP_W: annual energy consumption for domestic hot water production;
- EP_V: annual energy consumption for ventilation;
- EP_C: annual energy consumption for cooling;
- EP_L: annual energy consumption for lighting;

- EP_T: annual energy consumption for elevators and escalators.

The index may be express in term of total energy consumption $EP_{gl,tot}$ or considering the rate on non-renewable energy consumption $EP_{gl,nren}$. The last term it is utilized to define the EL of the building depending on the numeric value of the index and the $EP_{gl,nren,rif,standard\ (2019/21)}$ that define the non-renewable energy consumption of the reference building defined by the Section 3 (ANNEX I) of the decree. *Figure 1.2.1* reports the EL classification of the building depending on $EP_{gl,nren}$ and $EP_{gl,nren,rif,standard\ (2019/21)}$.

	Classe A4	$\leq$ 0,40 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,40 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe A3**	$\leq$ 0,60 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,60 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe A2**	$\leq$ 0,80 $EP_{gl,nren,rif,standard\ (2019/21)}$
0,80 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe A1**	$\leq$ 1,00 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,00 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe B**	$\leq$ 1,20 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,20 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe C**	$\leq$ 1,50 $EP_{gl,nren,rif,standard\ (2019/21)}$
1,50 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe D**	$\leq$ 2,00 $EP_{gl,nren,rif,standard\ (2019/21)}$
2,00 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe E**	$\leq$ 2,60 $EP_{gl,nren,rif,standard\ (2019/21)}$
2,60 $EP_{gl,nren,rif,standard\ (2019/21)}$ <	**Classe F**	$\leq$ 3,50 $EP_{gl,nren,rif,standard\ (2019/21)}$
	Classe G	> 3,50 $EP_{gl,nren,rif,standard\ (2019/21)}$

Figure 1.2.1 EL classification (source: DM 25/06/2015)

Table 1.2.1 summarizes the minimum requirements provided by the Decree.

Typology of retrofit work	Retrofit level	Requirements
New building	Construction of new buildings or demolition and rebuilding	Minimum requirements reported in the Section 2 and 3 of the Decree
Expansion of existing buildings	Expansion of an existing building if connected to an existing technical system.	• Requirements referred to Section 2 and 3.2; • Requirements relating to the overall heat transfer coefficient (H'_T), referred to Section 3.3; • Requirements relating to the $A_{sol,est}/A_{sup,utilt}$ of Section 3.3
	Expansion of an existing building if equipped with new technical systems.	Minimum requirements reported in the Section 2 and 3 of the Decree
First level retrofit	Interventions regarding building envelope affecting more than 50% of the gross dispersing surface and the heating and cooling systems.	Minimum requirements reported in the Section 2 and 3 of the Decree
Second level retrofit	Interventions concerning building envelope that affect between 25% and 50% of the gross dispersing surface and/or the heating and cooling systems	Minimum requirements reported in the Section 2, 4 and 5 of the Decree
Generic energy retrofit	Interventions concerning building envelope that affect less then 25% of	Minimum requirements reported in the Section 2, and 5 of the Decree

	the gross dispersing surface and/or the heating and cooling systems.	

Table 1.2.1 Minimum requirements provided by Inter-Ministerial Decree 26/06/2015

In 2018 European Parliament enacted the new Directive 2018/844/EU. The Directive provided some amendments of the Directive 2010/31/EU modifying the definition of "technical building system", "building automation and control system", "heating system", "heat generator" and "energy performance contracting". The main goal of the Directive was to promote long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings in order to reach the 2050 EU target. The Decree supported cost-effective transformation of existing buildings into nearly zero-energy buildings (NZEB).

The Decree retained the *cost-effectiveness* concept of BER interventions as the previous European Decree 2012/244/EU but it promoted the introduction of other benefits besides energy savings in the economic evaluation of BERPs. In the *Article 2a* at *g)* point the Decree stated:

"Each long-term renovation strategy shall be submitted in accordance with the applicable planning and reporting obligations and shall encompass:
……………….
g) an evidence-based estimate of expected energy savings and wider benefits, such as those related to health, safety and air quality." (source: 2018/844/EU)

The economic evaluation of BERPs have to consider other benefits as well as energy savings taking into consideration also other benefits related to health, safety and indoor air quality.

Table 1.2.2 reports the summary of laws and regulations on BER at national and European level.

EUROPEAN UNION	**ITALY**
Directive 2002/91/EC (EPBD) *"Directive 2002/91/EC of the European Parliment and of the council of 16 December 2002 on the energy performance of buildings"*	Law n. 373/1976 *"Norme per il contenimento del consumo energetico per usi termici negli edifici"*
	Law n. 10/1991 *"Norme in materia di uso razionale dell'energia, di risparmio energetico e di sviluppo delle fonte rinnovabili di energia"*
Directive 2010/31/EU *"Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings (recast)"*	Dpr n. 412/1993 *"Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della legge 9 gennaio 1991, n. 10"*
	D.lgs n. 192 of 19/08/2005 *"Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia"*
EU Delegated Regulation 2012/244/EU *"Commission delegated regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements"*	Dpr n. 59/2009 *"Regolamento di attuazione dell'articolo 4, comma 1, lettere a) e b), del decreto legislativo 19 agosto 2005, n. 192, concernente attuazione della direttiva 2002/91/CE sul rendimento energetico in edilizia"*
	DM 26/06/2009 *"Linee guida nazionali per la certificazione energetica degli edifici"*

Directive 2018/844/EU *"Directive (EU) 2018/844 of the European Parliament and of the council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency"*	Law n. 90 of 13/08/2013 *"Disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonché altre disposizioni in materia di coesione sociale"*
	Inter-Ministerial Decree 26/06/2015 *"Adeguamento linee guida nazionali per la certificazione energetica degli edifici"*

Table 1.2.2 Summary of Laws and Regulations on BER at national and European level

1.2 The Cost Optimal Approach

The European Directive 2010/31/EU, better known as Energy Performance of Buildings Directive-Recast (EPBD) provided the general framework for the economic evaluation of BERPs. The Directive stated that EU Member States had to fix minimum requirements for the energy performance of new buildings and existing buildings as well as building elements that are subject to major renovation. Thus, each EU Member State had to fix a minimum level of building energy efficiency on the basis of the *cost-optimal* level principle which considers investments involved in BERPs and the energy costs saved throughout the lifecycle of the building; in detail, the Article 2 of the Directive states: "*cost-optimal level means the energy performance level which leads to the lowest cost during the estimated economic lifecycle*". The Directive also gave the important definition of the "*energy performance of a building"* which was defined as the amount of energy to satisfy the building energy demand for heating, cooling, ventilation, domestic hot water production and lighting. This definition it is important because it indicates the building energy costs to consider in the economic evaluation of BERPs. The other costs involved for the economic evaluation of BERPs are also provided by the Directive such as the initial investment costs, maintenance costs, operating costs and disposal costs (the last two if applicable in the specific case analysed). The EPBD didn't provide a specific methodology for BERPs economic evaluation, it established some important concepts such as the definition of a minimum building energy performance level and the definition of the *cost-optimal* level. The methodology for the economic evaluation of BERPs was then formalized and specified by the Delegated Regulation 2012/244/EU which supplemented the EPBD. It provided a comparative methodological framework to determine cost-optimal levels of BERPs on the basis of EPBD principles. The framework is reported and explained in the ANNEX I of the Delegated Regulation and it consists in 6 steps:

1. *ESTABLISHMENT OF REFERENCE BUILDINGS;*
2. *IDENTIFICATION OF ENERGY EFFICIENCY MEASURES, MEASURES BASED ON RENEWABLE ENERGY SOURCES AND/OR PACKAGES AND VARIANTS OF SUCH MEASURES FOR EACH REFERENCE BUILDING;*
3. *CALCULATION OF THE PRIMARY ENERGY DEMAND RESULTING FROM THE APPLICATION OF SUCH MEASURES AND PACKAGES OF MEASURES TO A REFERENCE BUILDING;*
4. *CALCULATION OF THE GLOBAL COST IN TERMS OF NET PRESENT VALUE FOR EACH REFERENCE BUILDING;*
5. *UNDERTAKING A SENSITIVITY ANALYSIS FOR COST INPUT DATA INCLUDING ENERGY PRICES;*
6. *DERIVATION OF A COST-OPTIMAL LEVEL OF ENERGY PERFORMANCE FOR EACH REFERENCE BUILDING.*

STEP 1: ESTABLISHMENT OF REFERENCE BUILDINGS

EU Member States have to define three typologies of *Reference Buildings* (RBs) categories such as single-family buildings, apartment blocks and multifamily buildings and office buildings. The ANNEX III of the Delegated Regulation specifies how to define the RB typologies. RBs have specific characteristics in terms of geometry (shape, volumes, walkable area, surfaces of construction elements and components), orientation, location, use and location, thermal characteristics, outdoor climatic conditions (climate zones) and energy parameters. RBs must reflect the characteristics of the real estate asset of EU Member States and they are defined in order to estimate the building energy consumption to perform the economic analysis.

STEP 2: IDENTIFICATION OF ENERGY EFFICIENCY MEASURES, MEASURES BASED ON RENEWABLE ENERGY SOURCES AND/OR PACKAGES AND VARIANTS OF SUCH MEASURES FOR EACH REFERENCE BUILDING

Once RBs are defined, the *Energy Efficiency Measures* (EEMs) are selected, in this thesis they are also defined as "energy retrofit measures" (ERMs). EEMs are implementable technologies that have a direct or indirect impact on the energy performance of the building, the utilization of renewable energy sources it is considered too. The BER consists in the installation of a single EEM or a set of EEMs called by the Delegated Regulation as "*packages*" of EEMs. Different packages of EEMs define implementable BERPs. The most important EEMs consist on:

- Thermal insulation of walls, floors and roofs;
- Low-emissivity doors and windows replacement,
- Solar and photovoltaic panels (PV) to produce electricity and domestic hot water;
- Mechanical ventilation systems;
- High efficient heating, cooling and air ventilation systems (HAVC).

STEP 3: CALCULATION OF THE PRIMARY ENERGY DEMAND RESULTING FROM THE APPLICATION OF SUCH MEASURES AND PACKAGES OF MEASURES TO A REFERENCE BUILDING

After the definition of the RB, for each implementable BERP the annual primary energy consumption of the building must be estimated. The annual primary energy consumption (defined with the acronym EP) is related to the energy demand for heating, cooling, ventilation, domestic hot water production and lighting (lighting is taken into consideration only for non-residential buildings). EP it is computed taking into account all the indications reported in ANNEX I of the EPBD utilizing specific software and tools. The thermal characteristics of the building must be considered such as the thermal capacity, the insulation, the passive heating, the cooling elements and the thermal bridges. The other following characteristics are taken into account:

- heating installation and hot water supply, including their insulation characteristics;
- air-conditioning installations;
- natural and mechanical ventilation which may include air-tightness;
- built-in lighting installation (mainly in the non-residential sector);
- the design, positioning and orientation of the building, including outdoor climate;
- passive solar systems and solar protection;

- indoor climatic conditions, including the designed indoor climate;
- internal loads.

In Italy, the annual primary energy consumption it is defined with the symbol $EP_{gl,nren}$ as indicated by the Italian Ministerial Decree DM 26/06/2015. It is expressed in terms of annual energy consumption by square meters per year [kWh/m^2 year]. It indicates the building annual energy consumption for cooling, heating, mechanical ventilation and domestic hot water production considering only the amount of non-renewable energy consumption. As regards non-residential buildings the energy consumption for lighting and transport of persons (e.g. elevators and mobile ladders) must be considered too.

STEP 4: CALCULATION OF THE GLOBAL COST IN TERMS OF NET PRESENT VALUE FOR EACH REFERENCE BUILDING

For each implementable BERP the *global cost* during the lifecycle of the buildings is estimated. The *global cost* is the sum of the present value of the *initial investment* costs, *running* costs, and *replacement* costs (referred to the starting year), as well as *disposal* costs if applicable. It is possible to consider an additional cost category related to greenhouse gas emissions for the calculation at macroeconomic level. The *global cost* is also defined in literature as Life Cycle Cost (LCC). The lifecycle of the building for the *global cost* estimation it is 30 years for residential buildings and 20 years for non-residential buildings. The Regulation Decree specifies in detail all the costs that must considered (source: Article 2 of Delegated Regulation 2012/244/EU):

"- <u>Initial investment costs</u> mean all costs incurred up to the point when the building or the building element is delivered to the customer, ready to use. These costs include design, purchase of building elements, connection to suppliers, installation and commissioning processes;

- <u>Energy costs</u> mean annual costs and fixed and peak charges for energy including national taxes;

- <u>Operational costs</u> mean all costs linked to the operation of the building including annual costs for insurance, utility charges and other standing charges and taxes;

- <u>Maintenance costs</u> mean annual costs for measures for preserving and restoring the desired quality of the building or building element. This includes annual costs for inspection, cleaning, adjustments, repair and consumable items;

- <u>Running costs</u> mean annual maintenance costs, operational costs and energy costs;

- <u>Disposal costs</u> mean the costs for deconstruction at the end of-life of a building or building element and include deconstruction, removal of building elements that have not yet come to the end of their lifetime, transport and recycling;

- <u>Annual cost</u> means the sum of running costs and periodic costs or replacement costs paid in a certain year;

- <u>Replacement cost</u> means a substitute investment for a building element, according to the estimated economic lifecycle during the calculation period;

- *<u>Cost of greenhouse gas emissions</u> means the monetary value of environmental damage caused by CO_2 emissions related to the energy consumption in buildings."*

The methodology to estimate the *global costs* was provided by the European technical regulation EN 15459. For each BERP the *global cost* is computed as follows:

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \cdot R_d(i) - V_{f,i}(j)\right)\right]$$ (EQ 1.3.1)

where:

τ: it is the calculation period (30 or 20 years fixed by law);

C_I: it is the initial investment cost for EEMs installation;

$C_{a,i}(j)$: represents the sum of all annual costs (listed above) during the year i for the EEM or set of EEMs j;

$V_{f,i}(j)$: represents the residual value of the measure or set of measures j at the end of the calculation period;

$R_d(i)$: represents the discount factor for the year i based on the discount rate r to be calculated.

The discount factor $R_d(i)$ is computed as:

$$R_d(i) = \left(\frac{1}{1+{}^{r}/_{100}}\right)^i$$ (EQ 1.3.2)

where i means the number of years from the starting period and r means the real discount rate.

It is worth note that usually C_g is referred in literature as *LCC*.

STEP 5: UNDERTAKING A SENSITIVITY ANALYSIS FOR COST INPUT DATA INCLUDING ENERGY PRICES

A sensitivity analysis must be carried out varying energy price development scenarios and the discount rate. A minimum of two discount rates must be considered both for the macroeconomic analysis and the financial analysis. One of the discount rates to be used for the sensitivity analysis shall be equal to 3 % expressed in real terms. It is recommended to extend the sensitivity analysis also to other crucial input data if they are affected by uncertainty factors.

STEP 6: DERIVATION OF A COST-OPTIMAL LEVEL OF ENERGY PERFORMANCE FOR EACH REFERENCE BUILDING

In the final step, the cost-optimal BERP or a set of cost-optimal BERPs are selected. In the previous steps, for each implementable BERP, the global cost C_g and the primary annual energy consumption $EP_{gl,nren}$ were estimated. It is possible to represent in a ($EP_{gl,nren}, C_g$) graph all the implementable BERPs, a cloud of points is obtained as showed in *Figure 1.3.1*.

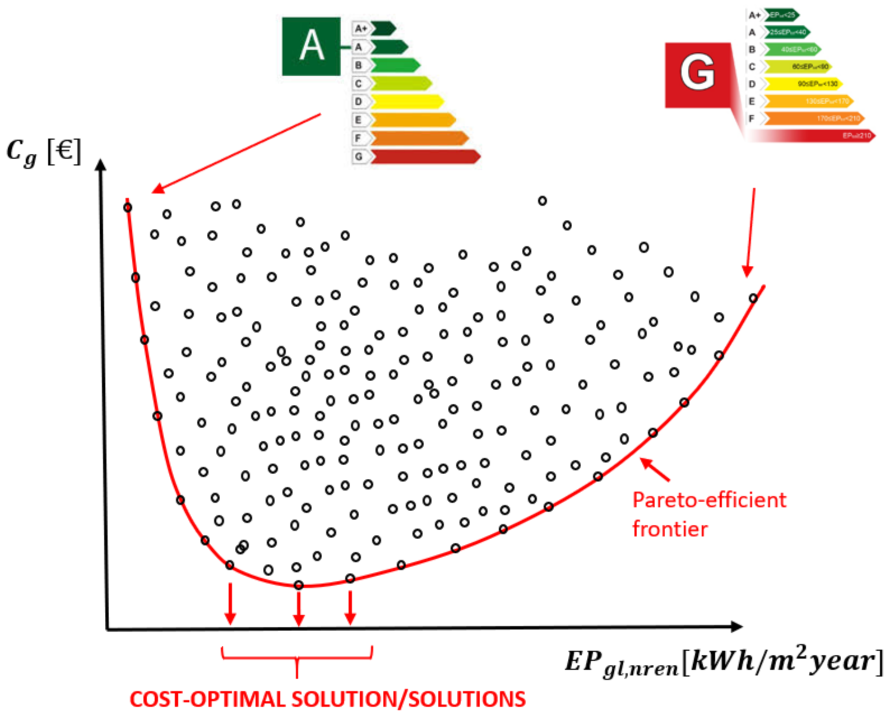

Figure 1.3.1 Pareto efficient frontier

The external frontier of the cloud of points defines a curve which is defined "*Pareto*" frontier, each point of the *Pareto* frontier it is a possible best solution. From *Figure 1.3.2*, if a set of points (that represents a set of implementable BERPs) are characterized by the same amount of primary annual energy consumption $EP_{gl,nren}$, the extreme point positioned in the *Pareto* frontier is a possible best solution because its global cost C_g it is the lower.

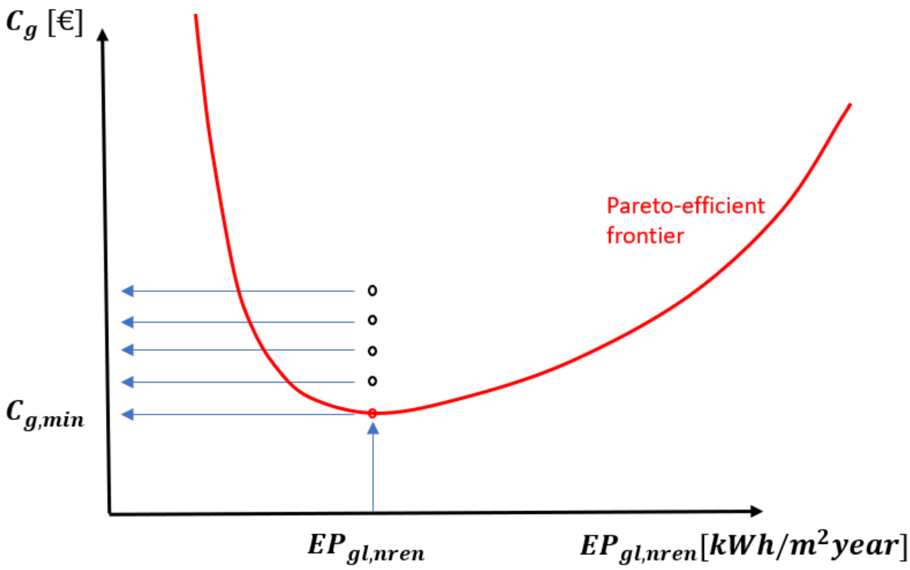

Figure 1.3.2 Best solution of a set of points characterized by the same $EP_{gl,nren}$

From *Fig 1.3.1*, the cost-optimal BERP solution or a set of cost-optimal BERPs solutions is/are the one/ones located in the Pareto efficient frontier and characterized by the lower value/values of the global cost C_g. Some EU Member States fix a minimum level to reach of $EP_{gl,nren}$, in Italy a minimum level it is not provided but the Italian DM 26/06/2015 establishes some energy efficiency requirements for EEMs. The best solutions located on the left of the graph (*Fig 1.3.1*) are the most energy efficient solutions (EL A or B) characterized by a very low primary annual energy consumption. These solutions have high initial investment costs to install EEMs, high maintenance and operational costs while energy costs are low. On the contrary, the best solutions located at the right of the graph are the less efficient solutions (EL F or G) characterized by high energy costs and low operational and maintenance costs.

2. LITERATURE REVIEW AND STATE OF ART

2.1 Buildings energy retrofit valuation approaches

BER is a complex process where multiple actors (e.g., homeowner, construction industry, Governments, etc.), decision variables, issues related to technical and technologic aspects as well as environmental, social and cultural aspects are involved (Roberts, 2008). In BER processes, each actor may have different objectives and stakes and actors interact with each other. Stakeholders and homeowners undertake BER investment decisions and aim at maximizing the profitability of their investments, through exploitation of Government incentives and adoption of optimal alternatives design by professionals (e.g., architects, engineers, etc). Governments provide different policy instruments to boost investments in BERPs, whose goals are multiple: energy policies may be cost-effective taking into consideration social costs and benefits, EU targets and environmental concerns (D'Alpaos and Bragolusi, 2018); social acceptability of energy policies must be considered too. Construction industry executes BER works to maximize profits and needs interact with homeowners and designers. In addition, BER may generate business opportunities for the construction industry and thus contribute to solve the current crisis of the Italian construction sector.

Due to their relevance, the analysis of BERPs and relative valuation approaches deserved great attention in literature as this topic is still widely debated among academicians and practitioners. From a recent systematic literature review by D'Alpaos and Bragolusi (2018), it emerged in fact that there are several contributions on energy consumption modelling and on the impacts of retrofit strategies on CO_2 emission reduction, as well as on valuation approaches of alternative retrofit strategies (e.g., multi-criteria analysis, life cycle costing and assessment, econometric models, etc.). According to literature, economic, environmental, technical and social aspects are of paramount importance in BER processes. Zuo and Zhao (2014) conducted an extensive literature review and investigated environmental, social and economic issue related to BERPs. According to their findings, with respect to environmental sustainability, GHG emissions reduction, energy efficiency, water use efficiency and resource preservation efficiency are the most relevant; whereas the most investigated aspects from a social perspective concern the quality of living, occupational health and safety, future professional development opportunities and human aspects such as thermal comfort, indoor environmental quality, health and productivity (Zuo and Zhao, 2014). Zuo and Zhao (2014) identified as key economic aspects energy cost savings, employment opportunities and increase in the market price of buildings due retrofit; whereas with respect to technical features, renewable energy technologies utilization and the use of construction and demolition (C&D) waste for BER works resulted to be the most important ones.

In addition, the literature review on the state of art of existing buildings retrofit by Ma et al (2012), revealed that the key factors influencing BER are six: policies and regulations, retrofit technologies, human factors, uncertainty factors, building specific information and client resources.

All the previous considerations highlight that the economic evaluation of BERPs must consider several aspects and different perspectives and pursue multiple objectives.

As mentioned in the introduction of the thesis, laws and regulations at national and EU levels provide the LCC method for the economic evaluation of BERPs. This methodology, based on the cost-minimization principle, is widely adopted and it weights more BERPs economic performances rather than energy efficiency performances. The LCC approach meets the goal of policy makers and Governments to minimize costs related to financial and fiscal incentives (Araujo, 2016), nonetheless, it does not account for other important environmental, social and technological aspects, which emerged from literature. Therefore by purely implementing the LCC method, it might not be possible to reach the 2050 European long-term targets, which requires the building sector to reach higher energy-efficiency levels, by adopting more energy-efficient BERPs. An in-depth analysis on building energy retrofit valuation approaches is then required to improve current valuation methodologies.

There are several BER valuation methodologies, which can be grouped in two main categories: single criteria approaches and multiple-criteria or multiple-objective approaches (D'Alpaos and Bragolusi, 2018). Ma et al (2012) listed the most important single criteria ones: the LCC method, the Net Present Value (NPV), the Internal Rate of Return (IRR), the Discounted Payback Period (DPP), the Simple Payback Period (SPP) and Benefit-Cost Ratio (BCR). These methodologies are commonly used in the valuation of private and public investment projects and are also implementable to the economic evaluation of BERPs, as they allow for selecting the best performing BERP from an economic perspectives, but usually do not account for social and environmental factors which may affect the investment decision.

Multiple-criteria or multiple-objective approaches may be sub-divided into Multi-Attribute Decision-Making (MADM) methods and Multi-Objective Optimisation (MOO) models. MADM methods develop a proper theoretical and methodological framework to face BERPs investment decisions taking into account economic, technical, social and environmental aspects (D'Alpaos and Bragolusi, 2019). Several authors developed MADM models to address BERPs investment decisions (Ginevičius et al., 2008; Zavadskas et al., 2009; Hong et al., 2012; Ruzgys et al., 2014; Wang, 2015; Carli et al., 2017; Seddiki et al., 2016; Silva et al., 2016; Delgarm et al., 2016; Wang et al., 2017; Carli et al., 2018; Ighravwe and Oke, 2019); among MCDM models, the Analytic Hierarchy Process (AHP) developed by Saaty (1980) is one of the most used (Mohsen and Akash, 1997; Alanne, 2004; Zhao, 2009; Shao, 2014; Garbuzova and Madlener, 2016; Si, 2016; Lizana et al., 2016; Cecconi, 2017; Roberti et al., 2017; D'Alpaos and Bragolusi, 2019).

MOO models are based on the Optimization theory and objective and constraint functions are defined in terms of economic, environmental, technical and social goals, as well as design variables can be expressed either as discrete values or by boundary values (Evins, 2013). Design variables reflect BER design parameters, which in turn are the variables of objective functions and constraint functions; by means of optimization algorithms, optimum values of design variables are determined. In literature there is a relevant number of contributions that develop MOO models in BER contexts (Gustafsson, 2000; Asadi et al., 2012(a); Asadi et al., 2012(b); Diakaki et al., 2013; Malatji et al., 2013; Rysanek and Choudhary, 2013; Asadi et al., 2014; Shao et al., 2014; Wu et al., 2015; Fan and Xia, 2017; Ascione et al., 2017; Jafari and Valentin, 2017; Schütz et al., 2017). Different typologies of optimization algorithms are adopted, which can be classified according to Evins (2013) into "direct search" algorithms (e.g., pattern search, linear and non linear programming methods), "Evolutionary" algorithms (e.g., Genetic Algorithms -GA, Evolutionary and Genetic programming, Covariance Matrix Adaptation Evolutionary Strategy - CMA-ES, Differential Evolution (DE) method) and "Meta-

Heuristic" algorithms (e.g., Harmony Search - HS, Particle Swarm Optimisation - PSO, Ant Colony Optimisation - ACO, Simulated Annealing - SA). Concerning objective functions, the most used are expressed in terms of LCC, initial investment cost, CO_2 emissions level, Net Present Value of BERPs, thermal comfort level, energy saving level and payback period of BERPs (Jafari and Valentin, 2017).

MADM and MOO methods are very efficient to reach the best compromise in BER decisions, as they simultaneously consider economic environmental, social and technical factors. These methodologies are very complex to apply cause of experts are needed and the processes are time consuming.

Recently, D'Alpaos and Bragolusi (2018) developed a systematic literature review on BER valuation approaches following the systematic literature review (SLR) protocol provided by Brown (2007), which they improved by implementing an additional research "dynamic protocol", which allowed for changing research criteria, parameters and settings during the search to optimize the review process. After a preliminary literature review to map the research field, they identified research strings and relative key and they conducted a Meta-Analysis on most relevant contributions. Their Meta-Analysis revealed that the most cited key words in the period 2000-2017 are "Life Cycle", "Cost" and "Energy Performance". This finding is strictly related to the LCC method that is the most frequently investigated and adopted in the economic evaluation of BERPs (D'Alpaos and Bragolusi, 2018). The analysis of documents by country and research field area revealed that, starting from 2010 (when the EPBD recast entered into force), the academic community's research interest for the LCC method raised up, due to the fact that the EPBD recast established that Member States set minimum requirements for the energy performance of buildings and building elements in order to achieve the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building (D'Alpaos and Bragolusi, 2018). From the meta analysis it emerged that the key word "Optimization" is ranked in the fifth position and it is cross referred to MOO methodologies, which are largely employed in economic evaluation of BERPs, whereas MADM methods are less implemented and among the most cited key words, there are not any directly referred to these methodologies.
As the LCC method proved to be the most investigated and applied in literature, D'Alpaos and Bragolusi (2018) provided an in-depth analysis on LCC.

2.1.1 The LCC approach

In the refinement phase of the systematic literature review on BERPs valuation approaches, D'Alpaos and Bragolusi (2018) analysed in detail eighteen relevant contributions, selected among the most cited contributions that explicitly adopt the LCC method as valuation method. The results of this focus revealed that many authors (Tadeu et al., 2015; Mangan e Oral, 2016; Krarti e Ihm, 2016) consider the building climatic zone as an important key factor in the estimation of the building energy consumption, which in turn affects the determination of the cost-optimal BERP. In fact, as different building locations are characterized by different climatic zones and related different temperature trends, which involve different building heat flows, buildings energy consumption changes. Buildings energy costs are computed according to building energy consumption levels and energy prices, which significantly affect the LCC value the determination of the cost-optimal BERP.

In addition, D'Alpaos and Bragolusi (2018) found that a large number of authors (Kneifel, 2010; Corrado et al., 2014; Ferrara et al., 2014; Pikas et al., 2014; Tadeu et al., 2015; Krarti and Ihm, 2016; Di Giuseppe et al., 2017a; Fregonara et al., 2017; Jones et al., 2017; Zangheri et al., 2017) argue that the most adopted ERMs concern the building envelope, and more specifically thermal insulation of roof, walls and floors as well as the installation of low-emittance windows and doors. These ERMs involve very low maintenance and substitution costs (nearly zero), ensure technical performances over time and allows for reducing energy consumption by 50% or more (Kaynakli, 2012; Kolaitis et al., 2013; Fregonara et al., 2017; D'Alpaos and Bragolusi, 2018). The implementation of these ERMs is fundamental in reaching the cost-optimal targets, due to low maintenance and substitution costs, as well as significant energy consumption reductions, which decrease both the LCC and the building energy consumption. Other ERMs commonly used consists in substitution/installation of heating, ventilation, air conditioning (HVAC) systems, lighting systems, solar panels and photovoltaic panels (Harvey, 2009).

Another important key factor that affects the LCC methodology and emerged from the literature review is uncertainty. Uncertainty in fact affects future energy prices, energy demand, discount rates, investment costs, maintenance costs and the technical efficiency of ERMs over time. To tackle the issue of uncertainty, Monte Carlo simulations, sensitivity analyses and the adoption of stochastic variables probability distribution can be implemented (Risanek et al., 2013; Di Giuseppe et al., 2017; Copiello et al., 2017; D'Alpaos and Bragolusi, 2018). Copiello et al. (2017) provided an interesting study on uncertainty effects. They combined Monte Carlo simulations with the LCC method to determine cost-optimal BERPs and they found that discount rates affect results four times as much as energy prices; thus, a proper adoption of a risk-adjusted discount rate is fundamental in order to obtain good estimates of ERMs' LCC.

2.1.2 The Cost-Benefit Analysis

In their SLR, D'Alpaos and Bragolusi (2018) identified some gaps: there are very few studies which consider direct, indirect, tangible and intangible benefits generated by BERPs.
The above described valuation approaches of BERPs consider mainly cost-efficiency, energy efficiency and CO_2 emissions reduction and the selection of the optimal BERP is focused on energy performance and economic performance (D'Alpaos and Bragolusi, 2018); nonetheless, some investors may be more concerned with environmental performance rather than economic performance (Araújo et al., 2016; Jafari and Valentin, 2018; Alberini et al., 2018; D'Alpaos and Bragolusi, 2018).
There is evidence in literature that BER involves other benefits and co-benefits besides energy savings. Among others, Banfi et al. (2008), Capelletti (2015), Ferreira (2017) and D'Oca (2018) highlighted that investors appreciated additional benefits and co-benefits, such as increased comfort of the building, indoor air quality, better aesthetic appearance of the building and a better protection against external noise. These benefits and co-benefits may affect investment decisions and boost investments towards more energy-efficient solutions; nonetheless they are not considered in the LCC method. See Section 2.3 for an investigation and discussion on the estimation of their economic value.

BER may generate another relevant monetary benefit as it increase the market value of a retrofitted building, which is proved to be greater than the market value of a low performing one (D'Alpaos and Bragolusi, 2018). There exists a relevant strand of literature (Achtnicht, 2011; Popescu et al.,2012; Banfi *et al.,* 2008; Zalejska J.A., 2014; Bonifaci e Copiello, 2015; Bottero et al., 2018), which investigates this issue by implementing the Hedonic Price method or the CE method. The market price premium due to BER may exceed the present value of energy saving costs and contribute to payback the initial investment costs. The LCC method does not account for this important net benefit, and in literature few authors consider it in the economic valuation of BERPs. The most relevant contribution on this issue is by Popescu et al. (2012), who adopted the NPV rule for the economic valuation of BERPs and took into account both the building market price premium and the present value of annual energy savings; their results reveal that these last two factors are key drivers to payback initial investment costs.

In the light of the above considerations, we argue that BERPs economic evaluation procedures need to be improved, by considering the cost-effectiveness of ERMs and relative energy performance levels as well as the trade-offs between costs and direct, indirect, tangible and intangible benefits that BER generates (D'Alpaos and Bragolusi, 2018).

In this respect, the Italian Legislative Decree 192/2005 establishes to implement the LCC method in the economic valuation of BERPs, but it also suggests to perform a Cost-Benefit Analysis (CBA). In detail, art. 2 states that the cost-optimal level is among those whose cost-benefit analysis calculated over the economic life cycle is positive.

According to the CBA approach (which is a commonly used methodology in investment decisions), the BERP which maximizes the difference between the sum of benefits and sum of costs is to be chosen. Among the contributions in literature, those by Liu et al. (2014) and Araujo et al. (2016) deserve a mention.

Liu et al. (2014) implemented a CBA to evaluate energy efficiency technology application on green buildings in China. Their aim was to compare two alternative BERPs, characterized by different energy retrofit levels, where the first was designed to reach the baseline performance level set by the Government (BBEES henceforth) and the second involved a deep green building energy efficiency scheme (GBEES henceforth). They computed the incremental costs and benefits of the two BERPs, then they calculated the investments internal rate of return (IRR) and payback period (PP) to assess the profitability and the feasibility of GBEES compared to BBEES.

Araújo et al. (2016) compared investments in alternative BERPs to the status quo of the building to be retrofitted and determined the cost-optimal solution is by considering both the economic and energy performances of the building. They calculated both the primary energy consumption quota and the costs generated over the building life cycle by each BERP and their variation with respect the status quo:

$$\Delta En = En_{Ref} - En_j \qquad \text{(EQ 2.1.2)}$$

$$\Delta Cost = Cost_j - Cost_{Ref} \qquad \text{(EQ 2.1.3)}$$

where:

En_j is the primary energy consumption quota of the j-th BERP;
En_{Ref} is the primary energy consumption quota of the status quo;
$Cost_j$ is the j-th BERP LCC*;*
$Cost_{Ref}$ is the status quo LCC.

According to the requirements of the Portuguese Decree Law 79/2006, in order to identify the cost-optimal solution, they determined the alternatives cost-benefit ratio, which represents stakeholders' propensity to invest in ERMs:

$$\frac{\Delta Cost(j)}{\Delta En(j)} = A \cdot \sum_{i=1}^{PB} Ecost(i) \cdot R_d(i) \quad \text{(EQ 2.1.4)}$$

where:

$\Delta En(j)$ is the primary energy consumption variation (kWh/m^2 year);
$\Delta Cost(j)$ is the costs variation (€);
A is the building area (m^2);
PB is the payback period (set equal to 8 years by Decree Law 79/2006);
$Ecost(i)$ is the cost of energy (€/kWh);
$R_d(i)$ is the discount rate for year *i*.

The cost-optimal solution may be obtained in a graphical form. It is possible to represent each implementable BERP in a (ΔEn, $\Delta Cost$) graph as a point, from the EQ4 it is possible to define a reference line (the red one in *Figure 2.1.1*) that passes through the origin; moving from the right and the bottom of the graph the most energy-efficient and cheaper solutions are identified:

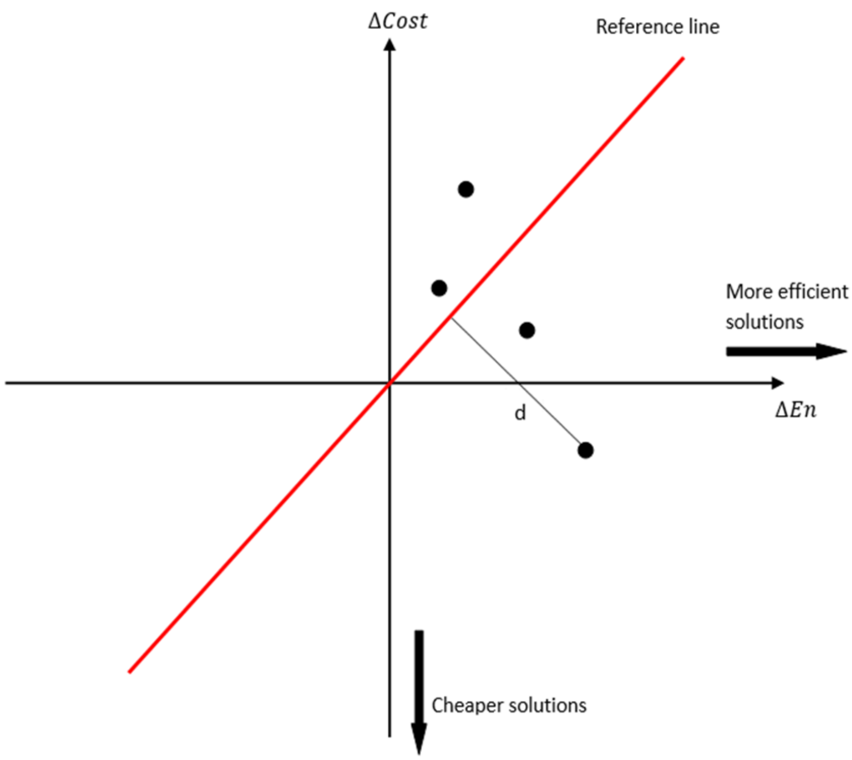

Figure 2.1.1: Araújo et al. (2016) methodology graphical solution (Source: our processing from Araújo et al. (2016))

The cost-optimal BERP it is represented in *Figure 2.1.1* as the point characterized by having the greatest negative or smallest positive distance (d) from the reference line (i.e., the red line). By implementing this approach (AAA), Araújo et al. (2016) provide the cost-optimal BERP by considering simultaneously economic performances and energy performances compared to a reference solution. Nonetheless, they do not account for others of the benefits generated by BERPs.

To fill this gap, starting from Liu et al (2014) and Araujo et al. (2016), Bragolusi and D'Alpaos (2019) proposed a valuation approach based on the comparisons of the net benefits generated by the set of alternative BERPs with those generated by the non-retrofitted building (i.e., the *Reference Building)*. In this framework, the optimal BERP is therefore the BERP which maximizes the *differential net benefit* (DNB):

$$DNB_j = \sum_i \left[\left(B_{ji} - B_{Ref} \right) - \left(C_{ji} - C_{Ref} \right) \right] \quad \text{(EQ 2.1.1)}$$

where:

B_{ji} is the i -th benefit generated by the j-th BERP;
B_{Ref} are the total benefits generated by the *Reference Building*;
C_{ji} is the i -th cost generated by the j-th BERP;
C_{Ref} are the total costs generated by the *Reference Building*.

All costs related to the life cycle of the building may be considered as indicated by the Italian Ministerial Decree 25/06/2015 such as investment costs, operating costs, energy costs and disposal costs. From the EQ1, if the i-th C_{ji} is lower than C_{Ref}, the costs difference is negative and it turns out to be a benefit, thus contributing to increase DNB_j. This effect is generated e.g. by energy savings.

D'Alpaos and Bragolusi (2019b) applied the above algorithm as well as the LCC, NPV and AAA approaches to a case study and evaluated investments in alternative ERMs in public housing. The case study focused on a four-storey condominium located in the North of Italy, which comprises fifteen residential units. The building, built in 1984, is a public-housing asset currently managed by a regional agency. Internal and external walls and floors are not thermally insulated, HVAC systems are obsolete and are low-efficiency systems. The alternative ERMs under investigation consisted of heating system substitution, replacement of existing doors and windows with low emittance ones, construction of building envelope thermal insulation and combinations of them for a total amount of 7 alternatives. A sensitivity analysis varying energy prices and discount rates was carried out to test the robustness of results.

In their analysis, D'Alpaos and Bragolusi (2019b) considered the monetary benefit related to the market price premium of the retrofitted building and the effect of fiscal incentives (i.e., tax rebates) on the decision to invest.

They estimated the building market price premium utilizing the Sales Comparison Approach (SCA) and results obtained by the Hedonic Price Regression performed by Bonifaci and Copiello (2015) which estimated the market price premium of the building due to the EL in the same market area of the case study (see ANNEX III for detail).

Table 2.1.1 reports the EL price premium estimated by Bonifaci and Copiello (2015) while *Table 2.1.2* reports, for each retrofit scenario, the market price premium of the building.

Energy Label	% of market price increment
G	0
F	2.3
E	9.5
D	17.1
C	17.4
B	20.2
A	21.9

Table 2.1.1 EL price premium estimated by Bonifaci and Copiello (2015)

Scenario	Market Price Premium [€]
S1	0
S2	28269
S3	42096
S4	19584
S5	47479
S6	74774
S7	76015

Table 2.1.2 Market price premium of the building for each retrofit scenario

The sensitivity analysis showed that the results by D'Alpaos and Bragolusi (2019b) are more stable compared to those provided by LCC, NPV and AAA approaches. In addition, they proved that the market price premium contributes significantly to pay-back investment costs and it might play a key role in boosting investments in BERPs.

In order to properly investigate the feasibility and profitability of investments in BERPs, it is therefore fundamental to assess the monetary value of the entire set of benefits and co-benefits generated by these investments (See APPENDIX III).

2.2 Willingness to pay for buildings energy retrofit: benefits and co-benefits

This Section provides a synthetic literature review on direct, indirect, tangible and intangible benefits provided by BER. The most important direct benefit is related to the reduction of energy consumption and the improvement in energy performance labels (Verbeeck, 2005; Harvey, 2009; Castleton et al., 2010; Price et al., 2011; Asadi et al., 2012; Dall'O et al., 2012; Ballarini et al., 2014; Hoyt et al., 2014; Penna et al., 2015; Sözer, 2019; Rathore et al., 2019; D'Amico et al., 2019; Zheng et al., 2019; Berseneva et al., 2020; Shao et al., 2020). Energy savings (ES) are computed as the difference between the building energy consumption before and after the installation of ERMs and their measurement and verification are key activities in BERP design (Ma et al, 2012) as the optimal trade-off between energy savings and costs drives BER investment decisions (Ballarini et al., 2014). As previously mentioned, to calculate BERPs LCC and identify the cost-optimal BERP in compliance with the EU Regulation 244/2012, buildings energy consumption and LCC are the two fundamental parameters to be accounted for.

In addition, energy savings are usually targeted by policy makers in the design of incentive policies for the mitigation of climate change effects (Price et al., 2011; Wang and Ren, 2014; Liang et al., 2019; Zhang et al., 2019). Energy savings are in fact strongly related to CO_2 emissions reduction. In compliance with the Kyoto protocol, which entered into force in 2005, the EU set the so-called 20-20-20, 2030 and 2050 EU-wide targets (See Section 1.1), as established to reduce GHG greenhouse gas emissions by 20%, 40% and 80-95%, when compared to 1990 levels, respectively.

CO_2 emissions reduction is a global issue, caused by consumption of carbon-based energy worldwide (Song, 2006), as they contribute to global warming, worsening of climate change effects and negative impacts on the environment and human life (Mata et al., 2010). The reduction in CO_2 emissions may de facto favour investments in BERPs due to environmental awareness of investors (stakeholders and homeowners). Many contributions in literature (Goett et al., 2000; Wiser, 2003; MacKerron et al., 2009; Longo et al., 2012; Diederich and Goeschl, 2014; Alberini et al., 2018) argue that people are willing to pay for CO_2 emission reduction, and they reports that the related WTP ranges from "a few to a few thousand dollars (or euros) per ton" (Alberini et al., 2018, p. 171). The role of CO_2 emissions produced in relation to buildings energy consumption is acknowledged by the Commission Delegated Regulation 244/2012, which recommend to consider CO_2 emissions costs in a macroeconomic approach to the valuation of BERPs.

As mentioned before, energy savings involve monetary cost savings that represent the largest benefits generated by BER (Banfi et al., 2008; Ma et al., 2012; Malatji et al., 2013; Subbarao et al., 2014; Adan et al., 2015; Medal and Kim, 2017; Wang and Lee, 2017; He et al., 2019) and significantly contribute to pay back operating, disposal and BERP investment costs. In the LCC method, these costs are internalised in energy costs as avoided costs, thus contributing to reduce BERPs LCC. Whereas, when the NPV, PP and IRR rules are adopted in BERPs valuation (Kumbaroglu et al., 2012; Valdiserri and Biserni 2016; Wu et al., 2016; Preciado-Pérez and Fotios, 2017; Guardigli et al., 2018), these monetary savings are explicitly accounted for and may increase investments profitability.

In addition to CO_2 emissions reductions and energy cost savings, specific ERMs (e.g. insulation of the building envelope, HVAC systems) guarantee an improvement in buildings thermal comfort, i.e. a thermally comfortable level of indoor climate and minimum variations of indoor temperature during all seasons of the year (Nicol and Humphreys, 2002; De Dear and Brager, 2002; Balaras et al., 2016; Ascione et al., 2017; Escandón et al., 2019; Papadopoulos et al., 2019; Che et al., 2019).

The thermal comfort it is one of the most important parameters (See Section 1.2), as well as energy savings and investment costs, in MOO models for BERPs valuation (Asadi et al., 2012; Asadi et al., 2014; Yu et al., 2015; Fan and Xia, 2015; Garcia et al., 2016; Wang et al., 2017). Many contributions in literature (Banfi et al., 2008; Carroll et al., 2016; Galassi and Madlener, 2017; Marmolejo-Duarte and Bravi, 2017; Tan et al., 2017; Gupta et al., 2018; Wang et al., 2018) investigate the WTP for buildings thermal comfort due to BER and their results show that people are willing to pay for thermal comfort (see Section 2.3 for detail).

Another important indirect benefit generated by BER involves the aesthetic appearance of the building. In particular, some ERMs meant to improve thermal insulation of the building envelope (e.g., insulation of external walls, replacement of windows contribute as well to the improvement of the aesthetic appearance of the building façade. Thermal insulation of the building involves external wall painting, whereas doors and windows replacement modernize fixtures and thus the overall quality of finishing increases. There is a strand of literature that investigated homeowners' WTP for a better aesthetic appearance of the building façade (Carroll et al., 2016; Galassi and Madlener, 2017; Marmolejo-Duarte and Bravi, 2017), which in turn may increase the property market value (Martinaitis et al., 2007).

Insulation against external noise is a benefit that people usually appreciate. This benefit is provided by the installation of specific thermal insulation technologies, which combine thermal and acoustic insulation. Nonetheless in literature there are few contributions on the WTP for insulation against external noise (Banfi et al., 2008; Syahid et al., 2016; Carroll et al., 2016; Claudi et al., 2019).

In addition, the installation of the *Controlled Mechanical Ventilation* (CMV) systems contribute to the improvement of indoor air quality, thus generating an additional benefit (Bluyssen, 2000; Hall et al., 2013; Turner et al., 2013; Frey et al., 2015; Almeida and Freitas, 2014; Hamilton et al., 2015; Diaz Lozano Patino and Siegel, 2018). CMV systems guarantee a clean and dry air exchange inside the building, operate all day long and avoid manual opening of windows for air daily change. In addition, through filtration, recycling and control of indoor air humidity, CMV systems avoid the formation of potential mold, spores, carbon dioxide, minimize the presence of volatile organic compounds, filter pollen, dust, spores and other harmful substances from the external environment and eliminate the annoying air currents which can arise with air manual exchange through the opening of doors and windows. Basically, CMV systems reduce thermal energy losses caused by windows opening when there is a relevant difference in temperature between indoor and outdoor environment and they are characterized by high energy efficiency (low electricity consumption). In literature, there is a growing number of studies on benefits provided by the installation of CMV systems (Banfi et al., 2008; Kwaak et al., 2010; Syahid et al., 2016; Carroll et al., 2016; Galassi and Madlener, 2017; Marmolejo-Duarte and Bravi, 2017). The benefit related to the improvement of occupant's health turned to be as one the most important (Syahid et al., 2016; Carroll et al., 2016).

Finally, investments in BER may favour job creation (Kibert et al., 2011), which does not directly impact private investors' investment decisions and thus are beyond the aim of this thesis. There is in fact no literature on the WTP for job creation due to the BER. *Table 2.2.1* list the most relevant benefits generated by BER found in literature.

DIRECT BENEFITS	INDIRECT BENEFITS
Energy savings CO_2 emissions reduction Monetary savings Thermal comfort Indoor air quality Aesthetical appearance Protection against external noise	Job creation Preservation of natural sources

Table 2.2.1 Most relevant benefits generated by BER

2.3 Valuation of benefits and co-benefits: the Stated Preference approach

The SP method was firstly employed to estimate the economic value of environmental goods (Hanley et al., 2001) and over the years, the methodology was applied in other fields such as medicine, social sciences, agricultural and biological sciences. The first fundamental principle of the methodology derives from the consumer's behaviour theory by Lancaster (1966). This theory stated that the consumers' utility for a good can be derived from the composing characteristics of the good: "….*The chief technical novelty lies in breaking away from the traditional approach that goods are the direct objects of utility and, instead, supposing that it is the properties or characteristics of the goods from which utility is derived*….." (Lancaster, 1966, page 133). Consequently, an utility function which models consumers' behaviour in a market, can be expressed as a sum of the characteristics of the good. The second principle of the methodology derived from the *Random Utility* theory, from which in turn *Random Utility Models* (RUMs) were obtained (Marschack, 1959; Manski, 1977; Walker and Ben-Akiva, 2002). From a set of choice alternatives, RUMs express the probability that the decision-maker chooes an alternative on the basis of his/her utility level. RUMs base on hypothesis that decision makers assume a rational behaviour (i.e., they choose the alternative which maximizes their utility). Among the variety of RUMs, great attention in literature has been paid to *Discrete Choice* (DC) models (Hensher et al., 2005; Train, 2009). These models will be presented in detail in Section 3.2. *Figure 2.1.3* summarizes the fundamental principles of the SP methodology.

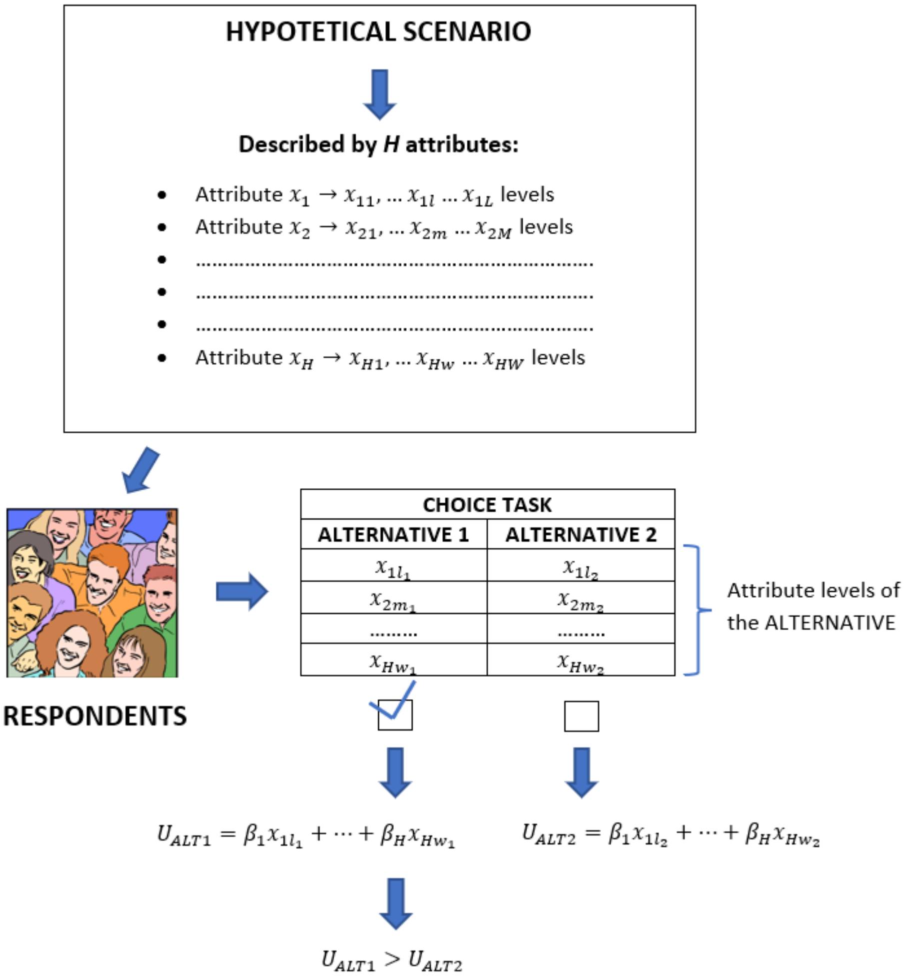

Figure 2.3.1 SP method principles

The SP method is a survey-based methodology, in which respondents express in a hypothetical scenario (or contingent market) their preferences among a set of choice tasks which contains the choice alternatives. The hypothetical scenario is characterized and described by a set of $(x_1, \dots \dots, x_H)$ attributes which assumes different levels. With respect to the valuation of benefits and co-benefits generated by BERPs, according to the above mentioned literature review, only seven contributions were found: Banfi et al. (2006), Kwak et al., (2010), Syahid et al. (2016), Carroll et al. (2016), Galassi and Madlener (2017), Marmolejo-Duarte and Bravi (2017), Matosovic and Tomšic (2018).

Banfi et al. (2008) estimate consumers' WTP for potentially implementable ERMs in residential buildings in Switzerland. The survey involved 163 apartment tenants and 142 house owners. *Table 2.3.1* illustrates attributes and relative attribute levels investigated in their study.

Attribute	Categories/Levels
Window	1. Enhanced insulation (triple glazing, double coated pane, rubber seal) (a)
	2. Standard insulation (coated, rubber seal)
	3. Medium old (low insulation, not coated, no rubber seal) (b)
	4. Very old (single glazing, not coated, no rubber seal) (b)
Facade	1. Enhanced insulation (a)
	2. Standard insulation
	3. No insulation, but newly repainted (b)
	4. Old (not repainted) (b)
Ventilation system	1. With air renewal system (housing ventilation)
	2. Without air renewal system
Price	In 5 levels: approximately −100, −50, 0, 50 and 100 CHF per month for rented apartments and −90,000, −45,000, 0 +45,000, +90,000 CHF per house, in addition to the actual price
(a) is related to the study for rented apartments; (b) is related to the study for single houses	

Table 2.3.1 Attribute and attribute levels in Banfi et al. (2006) [Source: Banfi et al. (2006)]

Banfi et al. (2008) considered three ERMs (*Table 2.3.1*): installation of a ventilation system (dummy variable), windows replacement, retrofit of façades; the price attribute was included to estimate the WTP for BER. The benefits considered in the study are thermal comfort, indoor air quality, protection against external noise and aesthetic appearance of the building. With respect to the hypothetical scenario, respondents chose between their status-quo building and different retrofit alternatives, characterized by different retrofit levels and costs. Banfi et al. (2006) implemented a Multinomial Logit Model (MNL) and, according to their findings, all the attributes levels were statistically significant and the WTP values varied between 1% and 13% of the rental price for flats and of the purchase price for single family houses. The highest WTP amount was stated for the replacement of new windows, whereas the lowest was for the enhanced insulated window.

Kwak et al., (2010) conducted a similar analysis and investigated the WTP for the installation of the following three ERMs: windows replacement, installation of a thermal insulation in the outer wall and installation of a ventilation system. They also considered a cost attribute to estimate the WTP for the potentially implementable ERMs. The attributes and attributes levels considered by Kwak et al. (2010) are reported in *Table 2.3.2*.

Attribute	Categories/Levels
Window	18 mm double glazing
	24 mm system glazing
	Double-sash system
Facade	Present level
	5 mm thicker than now
	10 mm thicker than now
Ventilation system	YES
	NO
Price	KRW 80,000, KRW 150,000, KRW 250,000, KRW 400,000

Table 2.3.2 Attribute and attribute levels in Kwak et al., (2010) [Source: Kwak et al.(2010)]

In their SP study, respondents chose between their status-quo building and different retrofit alternatives, characterized by different retrofit levels and costs. Kwak et al., (2010) implemented a MNL and a Nested Logit (NL) model, ad regards the experimental design they adopted the *Fractional Orthogonal* design method. They conducted a survey collecting 509 observations and found that the NL model estimates are more statically significant than the MNL ones. According to their findings, respondents expressed the highest WTP (i.e., USD 18.2) for windows replacement and specifically for the 18 mm double glazing typology; whereas the WTP for ventilation system was ranked as second (i.e., USD 12.4) and the WTP for the façade insulation resulted as the less important (i.e., USD 1.2).

Syahid et al. (2016) provided a SP study to estimate the WTP for sustainable housing in Malaysia. They considered as attributes the percentage of energy saving (although relative attribute levels are not reported), the enhancement of interior soundproofing, the installation of a mechanical ventilation system, the percentage of development area set aside for landscaping and recreational uses (although relative levels are not reported), the energy production by renewable sources and a cost variable (although relative levels are not reported). Syahid et al. (2016) investigated the WTP for different benefits such as energy savings, improvement in indoor air quality, protection against external noise and awareness for using renewable energy sources. They presented to respondents two hypothetical scenarios, which involved different hypothetical retrofit levels (identified on the basis of the attribute levels selected by the authors). The survey sample consisted of 50 respondents, and it was adopted as experimental design method, the *Orthogonal Design*, whereas the DC model implemented was the MNL. The WTPs estimated by Syahid et al. (2016) are reported in *Table 2.3.3*.

	MWTP	2.50%	97.50%
No Renewables	-27.802	-234.293	155.671
Enhanced Soundproofing	20.909	-94.779	166.089
Enhanced Ventilation	14.352	-93.299	154.339
Energy	1.829	-9.82	14.629
Landscaping	1.152	-6.594	11.176

method = Krinsky and Robb

Table 2.3.3 WTP estimates by Syahid et al., (2016) [Source: Syahid et al. (2016)]

By a direct analysis of WTP estimates, it emerges that the enhancement of interior soundproofing is characterized by the highest WTP, whereas the installation of a ventilation system is ranked as second. Energy savings are ranked as third and they are characterized by a low WTP value (MYR 6007.17). This result is counterintuitive because people are usually more interested on energy savings than other attributes.

Carroll et al. (2016) investigated the WTP for BER of single-bedroom apartments and the survey involved 865 university renters at the Trinity College in Dublin. The attributes and the attribute levels selected by Carroll et al. (2016) are reported in *Table 2.3.4*.

ATTRIBUTE	ATTRIBUTE LEVELS
Distance to work/college	Three levels: 10, 30 or 60 minutes
Age of the apartment	Three levels: 10 years old, 5 years, new building
Energy label	Seven levels: A, B, C, D, E, F and G
Area safety [Number of crimes]	Three levels: 40, 70 and 110
Rent [€/month]	800, 1000, 1200 and 1400
Size of the apartment [m^2]	30, 40 and 50

Table 2.3.4 Attribute and attribute levels by Caroll et al. (2016) [Source: Caroll et al. (2016)]

In this survey, respondents had to choose between two hypothetical apartments, characterized by different retrofit levels, where the "NONE" alternative (i.e., status quo with no retrofit interventions) was included. Caroll et al. (2016) implemented the MNL and the Mixed Logit (MMNL) models, as regards the experimental design they utilized the fractional D-efficient design method. Caroll et al. (2016) found that respondents were willing to pay for building energy efficiency (i.e., EL) but the highest WTP value was for the lower energy performance level (i.e., the G EL), which corresponded to a monthly amount of 82.237 €. The WTP for the highest energy performance levels (i.e., A and B) resulted negative (-3.636 €/month for the B-EL and -25.104 €/month for A-EL), whereas the WTP for intermediate ELs (i.e., C, D, E) resulted to be positive. According to their findings, respondents were also willing to pay for safety (about 90 €/month for the attribute level characterized by the lower number of crimes) and for optimal maintenance and conservation condition of the apartment (about 32 €/month).

Galassi and Madlener (2017) provided an SP study to investigate environmental concern and comfort expectation for BER of dwellings in Germany. *Table 2.3.5* reports attributes and attribute levels selected by the authors.

Attributes and their levels.

Attribute	Level
A1. Room air quality (AIRQ)	1.1 As before[a]
	1.2 Better than before
	1.3 Worse than before
A2. Room temperature (TEMP)	2.1 As before[a]
	2.2 Slightly warmer than before
A3. Monthly payment for the system/monthly increase in rent (COST)	3.1 Low, customized
	3.2 Intermediate, customized[a]
	3.3 High, customized
A4. Control over windows and heating system (CONTR)	4.1 High
	4.2 Intermediate[a]
	4.3 Low
A5. Noise reduction (NOISE)	5.1 Reduction of noise from inside and outside the building
	5.2 Reduction of noise from outside the building
	5.3 Reduction of noise from inside the building[a]
	5.4 No reduction of noise from outside or inside the building
A6. Aesthetics of the flat (AESTH)	6.1 Improved inside and outside appearance
	6.2 Improved inside appearance
	6.3 Improved outside appearance
	6.4 Improved outside appearance but worsened inside appearance
	6.5 Improved inside appearance but worsened outside appearance[a]
A7. Potential savings in energy costs (SAV)	7.1 20%
	7.2 40%[a]
	7.3 80%

[a] Reference levels in the regression analysis.

Table 2.3.5 Attributes and attribute levels in Galassi and Madlener. [Source: Galassi and Madlener, 2017]

The benefits considered are: indoor air quality (attribute A1), thermal comfort (attribute A2), system automation to control indoor temperature (attribute A3), noise reduction (attribute A5), aesthetic appearance of the building (attribute A6), energy savings (attribute A7) and a cost attribute (attribute A4). The survey involved 3161 owner-occupiers and tenants in Germany in Germany, who had to imagine living in their houses and chose among a set of two hypothetical retrofit level scenarios, characterized by the benefits and cost levels reported in *Table 2.3.5*. In this study the *status quo* alternative (i.e., no retrofit interventions) was included as well. Galassi and Madlener (2017) implemented a MMNL model and a fractional D-efficient experimental design. They provided four different models by coding the cost variable in four different ways in order to analyse the best way to code the variable. Galassi and Madlener (2017) found interesting results: respondents preferred low retrofit levels and low investment costs. According to these findings, respondents do not manifest environmental concern in investing in BER. High level of thermal comfort is not appreciated due to the *rebound effect* of BER (for detail on the rebound effect see Sunikka-Blank and Galvin, 2012) and to the fact that Germany is not a fuel-poverty country, where efficient subsidy energy policies are implemented. In addition, Galassi and Madlener (2017) found that benefits related to improvement in indoor air quality and energy savings are more appreciated than those related to aesthetical appearance of the building.

More recently, Marmolejo-Duarte and Bravi (2017) investigated the WTP for buildings energy performance labels in Spain. *Table 2.3.6* reports attributes and the attribute levels respectively.

ATTRIBUTES	ATTRIBUTE LEVELS
Condominium amenities	Two levels: storage room or storage room plus swimming pool
Additional private spaces	Two levels: terrace and powder room or balcony plus complete bathroom.
Quality of finishes	Three levels: basic, standard, and high quality
Active conditioning	Two levels: (radiant) heating and heating plus air conditioning (heating pump)
Energy label	Three levels: A, C and E
Price charging (monthly payment)	Four levels: 75, 100, 120, 130 [€]

Table 2.3.6 Attributes and attribute levels by Marmolejo-Duarte and Bravi. [Source: Marmolejo-Duarte and Bravi (2017)]

Marmolejo-Duarte and Bravi (2017) considered benefits produced by BER in terms of energy savings (measured by different energy label levels), aesthetical appearance of the building, improvement in thermal comfort by implementing two different heating and cooling systems (radiant and radiant plus air conditioning system) and include a cost attribute expressed a in terms of a monthly payment or equivalent mortgage instalment. They also considered two additional attributes related to both condominium amenities (i.e., storage room or storage room plus swimming pool) and additional private spaces (i.e., terrace and powder room or balcony plus complete bathroom). Marmolejo-Duarte and Bravi (2017) implemented a Conditional Logit (CL) model and a *Fractional Factorial* experimental design method. In their survey, respondents had to choose between three hypothetical building alternatives characterized by different retrofit levels and they found that income and educational level have a positive impact on BER investment decisions; specifically higher educational levels involved greater awareness on energy performances of the building. The results suggest that ELs do matter and are statistically significant in relation to other residential attributes and the marginal WTP for an A-EL instead of an E-EL is significantly higher than the stated savings in energy costs. In detail, the WTP for the transition from a C-EL to a A-EL is equal to 15.41€/month, whereas the WTP to shifting from C-EL to a worse (i.e., E-EL) is equal to -27.70 €/month. The quality of finishes is indeed the most important driver of choices and it emerged a positive WTP for conditioning systems.

Finally, Matosovic and Tomšic (2018) conducted a very interesting study and estimated investment costs and the related WTP for BER in Croatia. BER investment costs were determined processing data from a dataset of 4610 BERPs of private dwellings (obtained by Croatian Government data), whereas the WTP was estimated through the SP method. In detail they provided estimations of WTP for energy efficiency refurbishment in private family houses in relation to income class the owners belong to. By comparing BERPs investment costs and theoretical WTP, Matosovic and Tomšic (2018) analysed *free-riders* effect, and obtained useful information for energy policy optimal design. Based on the Government dataset, they analysed 4 ERMs (*Table 2.3.7)* and implemented a MNL model and a Nested Logit Model, but they do not specify the experimental design they employed.

Measure's short name	Measure's description
M1	Integral thermal refurbishment
M2.1	Windows replacement
M2.2	Walls and roof refurbishment
M4	Heating system replacement

Table 2.3.7 ERMs considered in the study. [Source: Matosovic and Tomšic, (2018)]

Table 2.3.8 shows the WTP estimates.

Marginal willingness to pay.

Measure	MWTP EUR / kWh
Integral thermal refurbishment	0.0130
Windows replacement	1.0761
Walls and roof refurbishment	0.0797
Heating system replacement	0.0133

Table 2.3.7 WTP estimates for ERMs by Matosovic and Tomšic (2018). [Source: Matosovic and Tomšic, (2018)]

The *free-rider* effect value was estimated for each implementable ERM as follows(Grösche et al., 2009, Matosovic and Tomšic, 2018):

$$WTP_e + WTP_{ne} + FR = iC - sub + hc \rightarrow FR = iC - sub + hc - WTP_e - WTP_{ne}$$
(EQ 2.3.1)

where WTP_e is the WTP for energy related benefits, WTP_{ne} is the WTP for non-energy related benefits, iC is the total investment cost, sub is the subsidy amount and FR is the experienced value of free-riding. In detail, according to their definition, if the WTP of the household for the specific energy-saving measure is greater than the sum of observed and hidden cost, the household is a free-rider since it would implement that measure even in the absence of the incentive scheme. The terms WTP_e and WTP_{ne} were estimated implementing the SP method, iC was derived by Croatian Government BERPs data, hc was set to 0 and sub was estimated according to national laws and regulations on subsidy incentive policies. Matosovic and Tomšic (2018) found that subsidies for windows replacement were overestimated, whereas no *free-rider* effectr was observed for investments in thermal refurbishment and heating system replacement. The authors analysed as well interaction effects between some socio-economic variables and ERMs attributes and they concluded that homeowners' social status and income should be taken into consideration in energy efficiency policy design in the future.

Table 2.3.9 reports the most relevant aspects of the core seven SP studies analysed and synthetize key utility function attributes and benefit and co-benefit investigated.

AUTHOR	UTILITY FUNCTION ATTRIBUTES	BENEFITS AND CO-BENEFITS
Banfi et al. (2008)	Window, façade, ventilation system, price	thermal comfort, air quality and noise protection, aesthetic of the building
Kwak et al., (2010)	Window, façade, ventilation system, price	thermal comfort, air quality, noise protection, aesthetic of the building
Syahid et al., (2016)	Energy savings, interior soundproofing, ventilation system, development area set aside for landscaping and recreational users, renewable energy sources, cost	Energy savings, air quality, noise protection, environmental awareness

Carroll et al. (2016)	Distance to work/college, age of the apartment, energy label, area safety, rent, size of the apartment	Energy savings, aesthetic of the building, safety, building location, size of the apartment
Galassi and Madlener (2017)	Indoor air quality, thermal comfort, automation of some systems, noise reduction, aesthetic appearance of the building, energy savings, cost	Energy savings, air quality, noise protection, thermal comfort, aesthetic of the building, automation of some systems
Marmolejo-Duarte and Bravi (2017)	Condominium amenities, additional private spaces, quality of finishes, active conditioning, energy label, price	Energy savings, thermal comfort, aesthetic of the building, amenities
Matosovic and Tomšic (2018)	NOT DECLARED	thermal comfort, aesthetic of the building

Table 2.3.3 Synoptic table of core articles on SP: utility function attributes, benefits and co-benefits

3. METHODOLOGY: THEORETICAL ASPECTS

3.1 The Conjoint Analysis

The Conjoint Valuation (CV) Analysis is utilized to elicit people's preferences for public goods or non-market goods adopting survey methodologies, through this method it is possible to estimate the willingness to pay for specified improvements of people’s preferences (Mitchell and Carson, 1989).
The methodology was firstly developed by Ciriacy and Wantrup (1947) that studied economic benefits derived from a project of soil-conservation practices, the project involved environmental benefits that were not estimable using traditional economic evaluation methodologies. They sustained that the economic value of environmental benefits could be determined through a survey methodology able to estimate the willingness to pay (WTP) amount for the benefits related to all members of a social group. Ciriacy and Wantrup (1947) provided general indications and principles to develop the CV analysis methodologies which were then developed in later years.
Since the seventies, starting from the research of Luce and Tukey (1964) that formulate the theoretical work on conjoint measurement, several authors (Falmagne 1971; Green and Rao 1971, Frenwick 1978, Green and Srinivasan 1978, Saito et al 1978; Olshavsky and Acito 1980; Greenhalg and Neslin 1981; Zufryden 1983) began to develop CV Analysis methodologies and applications; the seminal work of Mitchell and Carson (1989) formalized the CV analysis and analyzed the methodologies that may be adopted.
The CV analysis was firstly developed to determine the WTP for public goods in particular to estimate the non-use value and the option value of the goods, the total economic value of a good *Figure 3.1.1* may be subdivided into use e non-use values.

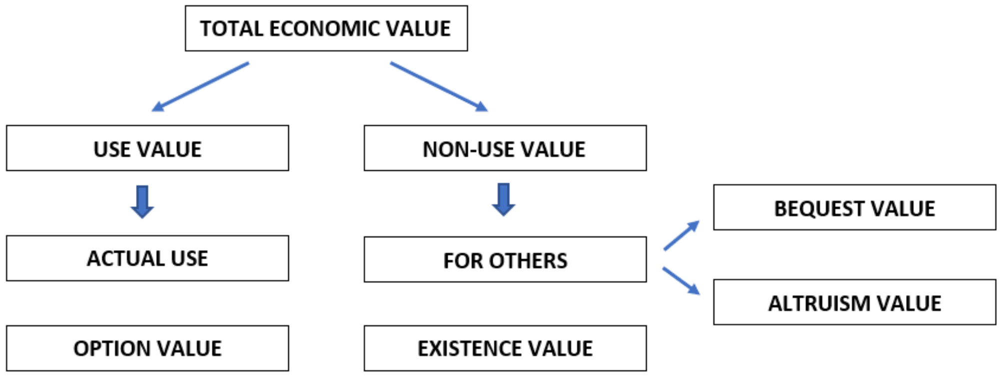

Figure 3.1.1: Total economic value

Use values are referred to the actual use of a good or the option value that is the willingness to pay (WTP) of the people to maintain a good in existence or to preserve its use in the future. Non-use values may be classified into existence value, altruistic value and bequest value: the existence value may be express as the WTP to maintain a good in existence, the altruistic and bequest values are related to maintain the good available for the current generation and the next generations (Pearce at al., 2006); the conjoint analysis technique is able to estimate these values. Adopting a survey methodology, the CV analysis simulates a contingent market (hypothetical market) on which consumers express their preferences, the goal is to estimate the willingness to pay (WTP) for benefits or the willingness to accept (WTA) compensation for

losses; the basic assumption of the CV analysis is that a set of different independent attributes, characterized by a limited number of levels, determine the preference of a stimulus (Poortinga et al, 2003). As introduced before, people preferences are collected using survey methodologies, data collected may be classified into Reveal Preference (RP) data or Stated Preference (SP) data.
RP data are related to real choices observed in a real market, the aggregate market behaviour is predicted on the basis on objectively measured variables, SP data are referred to behavioral intentions in hypothetical market situations (Ben-Akiva et al., 1994; Pearce at al., 2006).
Some researchers sustain that the terms “RP” and “SP” are referred to some specific elicitation techniques or economic approaches, Carson and Louviere (2011) developed a work to clarify the nomenclature for stated preference approaches concluding that the terms “RP” and “SP” should be only used to signal the nature of the collected data.
In the CV field several methodologies are adopted, the most utilized are summarized in *Table 3.1.1*:

CONJOINT VALUATION METHODOLOGIES	
METHODS	OPEN-ENDED FORMAT (OE)
	PAYMENT CARD (PC)
	DICHOTOMOUS CHOICE SINGLE BOUNDED (CV-CVM)
	DICHOTOMOUS CHOICE DOUBLE BOUNDED (CV-CVM)

Table 3.1.1 Main CV methodologies

The simplest one is the *Open-Ended* (OE) format, it consists in asking directly to respondents their willingness to pay for a good or a benefit in order to estimate its economic value. The advantage of this method is that the influence of the interviewer in the response is minimized but It may involve bad estimations; WTP estimates are good if the respondent knows a priori an estimate of the price or if he knows the price of a good that may replace the good analysed. The WTP is estimated starting from data collected using descriptive statistic indexes, the arithmetic mean or the median may be computed, if the data are characterized by some statistical distributions, the inferential statistic may be utilized.
In the *Payment Card* (PC) approach (Mitchell and Carson, 1981) each respondent chooses an amount from the same pre-specified and ordered list (payment card) or an interval of amounts. In both cases, the estimated WTP falls within the range of amounts chosen by respondents. If p_k is the price chosen by the respondent *k* considering respondents *k = 1,…..,n*, it is possible to provide a price list in ascending order $p_0; \dots ; p_{k-1} ; p_k; \; p_{k+1} \dots ; p_n$. For each interval, the mean value is computed, the global mean WTP results as the mean or the median of the mean values computed related to intervals.
Another utilized methodology is the *Dichotomous Choice Contingent Valuation* Method (DC-CVM) (Hanemann, 1984; Hanemann, 1989) that may be both in the single and the double bound formulation. In the simplest single form, a fixed sum of money for a good or a service is proposed to respondents that express if they are willing or not to accept the sum of money proposed (Herriges J.A., Shogren J.F. 1996). Hanemann (1984) model assumes that the probability to accept or not the proposed sum of money depends on the differential in utility between two conditions in which the good or a service are available or not. Let Y a variable that indicates the income of an individual, $\bar{s}$ a vector of socio-economic variables, d a dummy

variable that is equal to 1 if the good or the service is provided (0 otherwise), the indirect utility function u of an individual is:

$$u_1 = u(d = 1; Y; \bar{s}) \qquad \text{(EQ 3.1.1)}$$

$$u_0 = u(d = 0; Y; \bar{s}) \qquad \text{(EQ 3.1.2)}$$

where u_1 is the utility function related to the condition that the good or the service is provided while u_0 is the utility function related to the condition that the good or the service is not provided. The utility function is considered as a stochastic variable characterized by an error term e_d, it is possible to define the individual utility function observed by the researcher v (in the two conditions) as:

$$u_d = v(d; Y; \bar{s}) + e_d; \quad d = 0; 1 \qquad \text{(EQ 3.1.3)}$$

If the good or the service is provided, an amount of money A (that reduces the income) is required, the individual accepts it if the utility in the $d = 1$ condition it is higher then the utility in $d = 0$ condition:

$$v_1(d = 1; Y - A; \bar{s}) + e_1 \geq v_0(d = 0; Y; \bar{s}) + e_0 \qquad \text{(EQ 3.1.4)}$$

Let $\Delta v = v_1 - v_2$ the differential utility and $\mu = e_0 - e_1$ the differential error term, the equation may be rewritten as:

$$\Delta v \geq \mu \qquad \text{(EQ 3.1.5)}$$

From the last equation, it results that the individual is willing to pay for the good or the service if the differential in the utility is greater than the differential in the error term e_d. Considering a cumulative distribution function F_μ for the error term e_d, the probability P_1 that the individual accepts the providing of the good or service is:

$$P_1 = P_r(\mu \leq \Delta v) \qquad \text{(EQ 3.1.6)}$$

If it is assumed that the error terms e_d are identically and independently distributed (iid) characterized by the *Logistic* distribution, the last equation results in the well-known *Logit* model:

$$P_1 = F_\mu(\Delta v) = \frac{1}{1+e^{-\Delta v}} \qquad \text{(EQ 3.1.7)}$$

If it is assumed that F_μ is a normal distribution function, the *EQ 3.1.6* results in the *Probit* model.

Considering a generic cumulative distribution F_μ, the goal is to estimate the utility function v. This is done maximizing the logarithm of the likelihood function L, starting from sample data and hypnotizing that observations are independent, the likelihood function L relates the observed probabilities (in the data sample) and the theoretical probabilities (assuming for example the *Logit* or *Probit* model). Maximizing the logarithm of the function L, the maximum probability to obtain sample data is estimated:

$$\log L = \sum_{i=1}^{n} I_i \log\left[F_\mu(\Delta v_i)\right] + (1 - I_i) \log\left[1 - F_\mu(\Delta v_i)\right] \qquad \text{(EQ 3.1.8)}$$

where n is the number of respondents of the sample, I_i is a dichotomous variable that is equal to 1 if the individual is willing to pay the proposed and 0 otherwise. Maximizing the *EQ 3.1.8* it is possible to estimate the utility function v parameters. The average WTP is defined as the integral (Hanemann, 1984):

$$Average\ WTP = E(A) = \int_0^{A^{max}} [1 - G(A)]dA \qquad \text{(EQ 3.1.9)}$$

where $G(A)$ is the WTP distribution, A is an amount of money, A^{max} is the maximum amount of money accepted by individuals. $G(A)$ parameters depend on the formulation of v and F_μ and are estimated using *EQ 3.1.8*. If $\pi(A)$ is the probability that an individual accepts an offer to buy for A, the relation between $\pi(A)$ and $G(A)$ is (Hanemann, 1984):

$$\pi(A) = 1 - G(A) = F_\mu(\Delta v)$$

As regard the double bounded DC-CVM, an initial price A_i is proposed, other two follow-up prices A_i^a (greater that A_i) and A_i^b (less than A_i) are offered depending on A_i price, *Figure 3.1.3* represent the double bounded DC-CVM scheme:

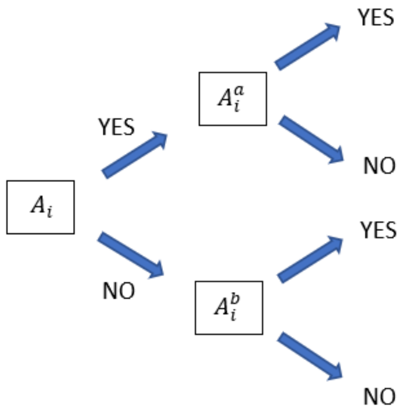

Figure 3.1.3 Double bounded CV-DCM scheme

In this case, if *E* is the unknown WTP of the individual, there are four possibilities that represent the probabilities for the YES or NO choices related to the proposed prices A_i, A_i^a and A_i^b:

$$\Pr(YES, YES) = \Pr(E \geq A_i^a \geq A_i) = 1 + F(A_i^a)$$

$$\Pr(YES, NO) = \Pr(A_i \leq E \leq A_i^a) = F(A_i^a) + F(A_i) \qquad \text{(EQ 3.1.10)}$$

$$\Pr(NO, YES) = \Pr\left(A_i^b \leq E \leq A_i\right) = F(A_i) + F(A_i^b)$$

$$\Pr(NO, NO) = \Pr\left(E \leq A_i^b \leq A_i\right) = F(A_i^b)$$

The log-likelihood function for this model is:

$$\log L = \sum_{i=1}^{n} I_i I_i^a \log[F(A_i^a)] + I_i(1 - I_i^a)\log[F(A_i^a) - F(A_i)] + I_i^b(1 - I_i)\log\left[F(A_i) - F\left(A_i^b\right)\right]$$

$$+(1 - I_i)(1 - I_i^b)\log\left[F\left(A_i^b\right)\right] \qquad \text{(EQ 3.1.11)}$$

where I_i, I_i^a and I_i^b are dichotomous variables that assumes the value 1 or 0 depending on the first proposed price A_i and subsequent follow-up prices A_i^a and A_i^b.

3.2 Discrete choice models

Discrete choice (DC) models are a preference elicitation approaches able to describe and predict choice(s) between a discrete number of alternatives (Carson and Louviere, 2011). An agent that is in general term defined as "decision maker" (DM) faces a choice or a set of choices among a series of options. Through economic, statistic and mathematical principles DC models are able to predict the behavioural decisional process of the decision maker. The behavioural decisional process is studied by the researcher, he is able to capture some factors that determine DM choices but exist some factors that are not observable (unobservable). Let y a generic outcome decision, it is possible to define a *behavioural process* function h as:

$$y = h(x, \varepsilon) \qquad \text{(EQ 3.2.1)}$$

where x is a vector of observable factors (deterministic factors) while ε denotes unobservable factors. Since ε are not-deterministic factors, they are treated as random variables characterized by a density function $f(\varepsilon)$. Considering a set of outcomes, the probability that the DM chooses the outcome y considering x observable factors it is defined as:

$$P(y|x) = Prob(\varepsilon \; s.t. \, h(x, \varepsilon) = y) \qquad \text{(EQ 3.2.2)}$$

It is possible to define an *indicator function* $I[\cdot]$ that is equal to 1 if the result $h(x, \varepsilon) = y$ is true and 0 otherwise. The probability that the DM chooses the outcome y becomes:

$$P(y|x) = Prob(I[h(x, \varepsilon) = y] = 1) = \int I[h(x, \varepsilon) = y] f(\varepsilon) d\varepsilon \qquad \text{(EQ 3.2.3)}$$

The probability that the DM chooses the outcome y results as an integral of the outcome indicator over all possible values of not-deterministic factors. The basic hypothesis to derive DC models is the utility-maximizing behaviour of decision maker (Marschack, 1959), these models are defined *Random Utility Models* (RUMs).
Let consider a decision maker *n* that chooses among *J* alternatives, each alternative it is characterized by a certain utility level, the utility related to the generic alternative j considering $j = 1, \ldots J$ alternatives it is defined as U_{nj}. The DM n chooses the alternative i if and only if:

$$U_{ni} > U_{nj}; \; \forall \, j \neq i \qquad \text{(EQ 3.2.4)}$$

EQ 3.1.4 expresses the behavioural model. The utility U is the DM's theoretical utility, the researcher doesn't know it, he considers some attributes x_{nj} of the alternatives j and some attributes s_n of the decision maker *n*, the utility function $V_{nj} = V(x_{nj}, s_n)$ is defined *representative* utility. The utility U may be decomposed as:

$$U_{nj} = V_{nj} + \varepsilon_{nj} \qquad \text{(EQ 3.2.5)}$$

where ε_{nj} is an error term cause of the representative utility V_{nj} does not consider some factors of U_{nj} (also defined "unobserved component"), the term ε_{nj} is treat in a random way characterized by a density function. The DM n chooses the alternative i if:

$$P_{ni} = Prob\big(U_{ni} > U_{nj}, \; \forall \, j \neq i\big) = Prob\big(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj}, \; \forall \, j \neq i\big) =$$
$$= Prob(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj}, \; \forall \, j \neq i) \qquad \text{(EQ 3.2.5)}$$

This probability is a cumulative distribution and considering the density function $f(\varepsilon)$, the cumulative probability is:

$$Prob\left(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj}, \quad \forall\, j \neq i\right) =$$

$$= \int_{\varepsilon} I\left(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj},\ \forall\, j \neq i\right) f(\varepsilon) d\varepsilon \qquad \text{(EQ 3.2.6)}$$

where I is the indicator function that is equal to 1 if the expression in the parentheses is true, 0 otherwise. The different specification of $f(\varepsilon)$ determines different discrete choice models. In the next paragraphs properties of discrete choice models and the Logit model utilized for the purpose of this thesis will be presented.

3.2.1 Properties of Discrete Choice models

Discrete choice models are characterized by three fundamental characteristics, firstly the DM chooses among a finite number of alternatives defined as *choice set*, the number of alternatives must be finite. The second characteristic is that alternatives must be mutually exclusive, from the choice set of alternatives the DM chooses only the alternative that maximizes his utility and he excludes the others. The third characteristic is that the choice set must be exhaustive containing all the possible alternatives.
Moving from the three fundamental characteristics that characterized discrete choice models, the behavioural model described in *Section 3.1* it is characterized by two important properties. The probability that the DM chooses the alternative i from a set of j possible alternatives was defined as $P_{ni} = Prob\left(U_{ni} - U_{nj} > 0,\ \forall\, j \neq i\right)$, from this equation the probability to choose the alternative i depends only on the difference between utilities, the absolute value of utilities is not relevant; this property it is also valid for the representative utility V, this can be seen from the *EQ 3.1.5*, the probability that the DM chooses the alternative i from a set of j possible alternatives was $P_{ni} = Prob(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj},\ \forall\, j \neq i)$. From this property, that estimated parameters of the utility function V are related to the differences across alternatives. Another consideration derives from this property and affects utility function constant, it is usual to express the utility function linear in parameters with an alternative constant k_j:

$$U_{nj} = \beta x'_{nj} + k_j + \varepsilon_{nj}, \forall j \qquad \text{(EQ 3.2.1.1)}$$

where β is a vector of estimated coefficients related to x'_{nj}, the constant k_j captures the effect of all factors that are not included in the model as classic regression models, the error term ε_{nj} it is characterized by having zero mean for construction $E\left(\varepsilon_{nj}\right) = 0$, without inserting the k_j constant, the utility function becomes:

$$U_{nj} = \beta x'_{nj} + \varepsilon^*_{nj}, \forall j \qquad \text{(EQ 3.2.1.2)}$$

the expected value of the error term in this case has not zero mean $E\left(\varepsilon^*_{nj}\right) = k_i \neq 0$ thus constants may be included in utility function formulation, however alternative constants are not relevant cause of only utility differences are important as seen before; so the researcher must set the overall level of the constants. Having J alternatives, a commonly used methodology is to set one constant normalized to zero (the constant related to the specific alternative it is not considered in the model), the other $J - 1$ alternative-specific constants enter in the model and they are thus related to the alternative normalized to zero.
The second important property is that the overall scale of utility it is not relevant, if a constant $\lambda > 0$ is added to the utility alternatives, the two models:

$$U^0_{nj} = \lambda V_{nj} + \lambda \varepsilon_{nj}, \forall j \qquad \text{(EQ 3.2.1.3)}$$

$$U^1_{nj} = V_{nj} + \varepsilon_{nj}, \forall j \qquad \text{(EQ 3.2.1.4)}$$

are equivalent cause of the alternative with the highest utility it is the same for each value of λ. The researcher thus normalized the scale of the utility, a common way is to normalize the variance of the error term. Multiplying by λ the utility the variance of each ε_{nj} changes:

$$Var(\lambda\varepsilon_{nj}) = \lambda^2 Var(\varepsilon_{nj}) \quad \text{(EQ 3.2.1.5)}$$

Thus, normalizing the scale of the utility it is equivalent to normalizing the variance of the error term. If the error terms are assumed independent and identically distributed (i.i.d.) all the errors are characterized by having the same variance, normalizing the variance of one error means normalizing all other error variances. Let we consider a simple utility linear model:

$$U_{nj}^0 = \beta x_{nj}' + \varepsilon_{nj}^0,\ Var\left(\varepsilon_{nj}^0\right) = \sigma^2 \quad \text{(EQ 3.2.1.6)}$$

normalizing for example the variance to 1, the model it is equivalent to the second model:

$$U_{nj}^1 = \left(\frac{\beta}{\sigma}\right) x_{nj}' + \varepsilon_{nj}^1,\ Var\left(\varepsilon_{nj}^1\right) = 1 \quad \text{(EQ 3.2.1.7)}$$

The new coefficients $\beta\,/\sigma$ represent the effect of the observed variables related to the standard deviation of unobserved variable.

3.2.2 The Logit model

Luce (1959), Marschack (1959) and McFadden (1974) are the researcher that contributed to derive the most important discrete choice model that is the Logit model. As seen before in the EQ 3.1.5 the utility of a DM n related to the j alternative may express as:

$$U_{nj} = V_{nj} + \varepsilon_{nj} \quad \text{(EQ 3.2.2.1)}$$

where V_{nj} is the utility know by the researcher and ε_{nj} is the error term. To derive the Logit model, the hypothesis is that the error term ε_{nj} is independent and identically distributed (i.i.d.) characterized by Gumbel type I extreme value. The related density function is:

$$f\left(\varepsilon_{nj}\right) = e^{-\varepsilon_{nj}} e^{-e^{-\varepsilon_{nj}}} \quad \text{(EQ 3.2.2.2)}$$

the related cumulative distribution is:

$$F\left(\varepsilon_{nj}\right) = e^{-e^{-\varepsilon_{nj}}} \quad \text{(EQ 3.2.2.3)}$$

From the EQ 3.1.6, the probability that the DM n chooses the alternative i is:

$$P_{ni} = Prob\left(\varepsilon_{nj} < V_{ni} - V_{nj} + \varepsilon_{ni},\ \forall\, j \neq i\right) \quad \text{(EQ 3.2.2.4)}$$

According to EQ 3.1.2.2 the cumulative distribution of each ε_{nj} is:

$$F\left(\varepsilon_{nj}\right) = e^{-e^{-\varepsilon_{nj}}} \quad \text{(EQ 3.2.2.5)}$$

the i.i.d. hypothesis of error terms involves that the cumulative distribution over all $j \neq i$ of the errors taking into account EQ 3.1.2.4 and EQ 3.1.2.5 may be express as:

$$P_{ni}|\varepsilon_{ni} = \prod_{j\neq i} e^{-e^{-(\varepsilon_{ni}+V_{ni}-V_{nj})}} \quad \text{(EQ 3.2.2.6)}$$

the integral of $P_{ni}|\varepsilon_{ni}$ over all values of ε_{ni} is:

$$P_{ni} = \int \left(\prod_{j\neq i} e^{-e^{-(\varepsilon_{ni}+V_{ni}-V_{nj})}}\right) e^{-\varepsilon_{ni}} e^{-e^{-\varepsilon_{ni}}} d\varepsilon_{ni} \quad \text{(EQ 3.2.2.7)}$$

it is possible to solve the integral in the closed form, let the substitution $s = \varepsilon_{ni}$, the probability that the DM n chooses the alternative i is:

$$P_{ni} = \int_{-\infty}^{+\infty} \left(\prod_{j \neq i} e^{-e^{-(s+V_{ni}-V_{nj})}}\right) e^{-s} e^{-e^{-s}} ds = \int_{-\infty}^{+\infty} \left(\prod_{j} e^{-e^{-(s+V_{ni}-V_{nj})}}\right) e^{-s} e^{-e^{-s}} ds =$$
$$= \int_{-\infty}^{+\infty} exp\left(-\sum_j e^{-(s+V_{ni}-V_{nj})}\right) e^{-s} ds = \int_{-\infty}^{+\infty} exp\left(-e^{-s} \sum_j e^{-(V_{ni}-V_{nj})}\right) e^{-s} ds \qquad \text{(EQ 3.2.2.8)}$$

let $t = \exp(-s)$ and consequently $dt = -\exp(-s)ds$, if s approaches to infinity the variable t approaches to zero and if if s approaches to negative infinity the variable t approaches infinity, the EQ 3.1.2.8 becomes:

$$P_{ni} = \int_{\infty}^{0} exp\left(-t \sum_j e^{-(V_{ni}-V_{nj})}\right)(-dt) = \int_{0}^{\infty} exp\left(-t \sum_j e^{-(V_{ni}-V_{nj})}\right) dt =$$
$$= \left[\frac{-t \sum_j e^{-(V_{ni}-V_{nj})}}{-\sum_j e^{-(V_{ni}-V_{nj})}}\right]_0^{\infty} = \frac{1}{\sum_j e^{-(V_{ni}-V_{nj})}} = \frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}} \qquad \text{(EQ 3.1.2.9)}$$

The well-known Logit model results:

$$P_{ni} = \frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}} \qquad \text{(EQ 3.1.2.10)}$$

3.2.3 Logit model properties

The Logit model is characterized by having several properties. The probability P_{ni} has a range of values from 0 to 1, if V_{ni} rises, maintaining constant all V_{nj} $\forall\, j \neq i$, the P_{ni} tends to one, vice versa if V_{ni} decrease then P_{ni} approaches to 0; the *Figure 3.1.2.1* shows the graph of the Logit curve:

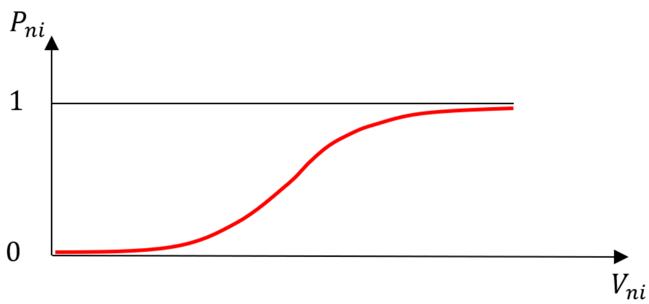

Figure 3.1.2.1 Graph of Logit curve

The Logit curve it is S-shaped, if the representative utility V_{ni} related to the alternative i is lower than others representative utilities V_{nj} related to other alternatives $j \neq i$, a low utility increment of V_{ni} has a little effect on its probability to be chosen. This occurs until the probability P_{ni} is closer to 0.5, starting from this point, a small increase of the representative utility V_{ni} related to the alternative i results in a significant increment of its probability P_{ni}. Thus, utilizing the Logit model, if an alternative has a probability of being chosen closer to 0.5, a little increment of its related representative utility has an important effect in people' choices; vice versa if an alternative has a probability of being chosen less then 0.5, a little increment of its related representative utility doesn't significantly affect people' choices. Analyzing EQ 3.1.2.9, the Logit probability P_{ni} is never equal to zero and it is never equal to one unless only one alternative is considered in the choice set. The sum of the probabilities of all alternatives it is equal to one:

$$\sum_{i=1}^{J} P_{ni} = \sum_{i} \exp(V_{ni}) / \sum_{j} \exp(V_{nj}) = 1 \qquad \text{(EQ 3.2.3.1)}$$

As mentioned in the Section 3.1.1, discrete choice models are affected by a scale parameter depending on the random error term distribution assumption. In the Logit model, the hypothesis is that the error term ε_{nj} is independent and identically distributed (i.i.d.) characterized by Gumbel type I extreme value. Considering the generic model:

$$U_{nj}^{*} = V_{nj} + \varepsilon_{nj}^{*} \qquad \text{(EQ 3.2.3.2)}$$

utilizing the Logit model, the error term has the variance equal to:

$$Var(\varepsilon_{nj}^{*}) = \sigma^2 \frac{\pi^2}{6} \qquad \text{(EQ 3.2.3.3)}$$

scaling U_{nj}^{*} by σ, the model of EQ 3.1.3.2 becomes:

$$U_{nj} = \frac{V_{nj}}{\sigma} + \varepsilon_{nj};\ \varepsilon_{nj} = \frac{\varepsilon_{nj}^{*}}{\sigma};\ Var(\varepsilon_{nj}) = \frac{\pi^2}{6} \qquad \text{(EQ 3.2.3.4)}$$

The σ is defined “scale parameter”, if the representative utility function it is assumed as linear in x_{nj} parameters:

$$V_{nj} = \beta' x_{nj} \qquad \text{(EQ 3.2.3.5)}$$

the Logit model of EQ 3.1.3.4 becomes:

$$P_{ni} = \frac{e^{(\beta^*/\sigma)' x_{ni}}}{\sum_j e^{(\beta^*/\sigma)' x_{nj}}} \qquad \text{(EQ 3.2.3.6)}$$

each β parameter it is scaled by σ, once the model is estimated, the ratio (β^*/σ) is computed, it is not possible to separately estimate β^* and σ thus, entire ratio is estimated. The model is thus expressed in the scaled form, defining $\beta = \beta^*/\sigma$, the standard Logit expression is:

$$P_{ni} = \frac{e^{\beta' x_{ni}}}{\sum_j e^{\beta' x_{nj}}};\ \beta' = (\beta^*/\sigma)' \qquad \text{(EQ 3.2.3.7)}$$

The scale factor σ that is related to the variance of the error term it is embedded, estimating the Logit model each sample of respondents it is characterized by a specific value of σ; the variance of the error term it is thus relative to estimated coefficients of the utility function. This fact becomes important when different coefficients' estimates related to different samples of respondents are compared (Swait and Louviere, 1993).

The Logit model takes into consideration taste variation over respondents but only within limits. Taste variation it is not only related to demographic characteristics, people make different choices because they have individual preferences and different tastes. In Logit model, taste variation into the observed part of the utility function may be captured manipulating socio-economic variables. Instead for the unobserved factors, taste variation it is assumed randomly distributed, this may be sometimes not true and therefore the Logit model is not suitable; in this case other more complex models must be adopted.

Another important aspect of the Logit model it is the proportional substitution across alternatives. Let i and k two possible choice alternatives of the decision maker n, the ratio of the related probabilities is:

$$\frac{P_{ni}}{P_{nk}} = \frac{e^{V_{ni}}/\sum_j e^{V_{nj}}}{e^{V_{nk}}/\sum_j e^{V_{nj}}} = \frac{e^{V_{ni}}}{e^{V_{nk}}} = e^{V_{ni}-V_{nk}} \qquad \text{(EQ 3.2.3.8)}$$

From the EQ 3.1.3.9, the ratio between the probabilities to choose two alternatives it is independent from other alternatives in the choice set, the Logit model it is thus characterized by the independence from irrelevant alternatives; this property may be unrealistic in some choice situations, in these cases the Logit model cannot be adopted.

In some market studies, the cross-elasticities between alternatives' probabilities is investigated, changing an attribute of an alternative, it is interesting to study the change in probabilities of other alternatives. Let z_{nj} the attribute of the alternative j faced by the decision maker n, the elasticity of the probability P_{ni} related to the change of the z_{nj} attribute of the alternative j:

$$E_{iz_{nj}} = \frac{\partial P_{ni}}{\partial z_{nj}}\frac{z_{nj}}{P_{ni}} = \frac{\partial(e^{V_{ni}}/\sum_k e^{V_{nk}})}{\partial z_{ni}}\frac{z_{nj}}{P_{ni}} = -\frac{e^{V_{ni}}}{\left(\sum_k e^{V_{nk}}\right)^2} e^{V_{nj}}\frac{\partial V_{nj}}{\partial z_{nj}}\frac{z_{nj}}{P_{ni}} = -\frac{\partial V_{nj}}{\partial z_{nj}} P_{ni}P_{nj}\frac{z_{nj}}{P_{ni}} =$$
$$= -\frac{\partial V_{nj}}{\partial z_{nj}} z_{nj}P_{nj} \qquad \text{(EQ 3.2.3.9)}$$

if the utility function it is explicated in the linear form $V_{nj} = \beta' x_{nj}$ the EQ 3.1.3.9 becomes:

$$E_{iz_{nj}} = -\beta_z z_{nj} P_{nj} \qquad \text{(EQ 3.2.3.10)}$$

From the EQ 3.2.3.10, the cross-elasticity doesn't depend on the generic i, this means that varying an attribute of an alternative, the changing in probabilities of all other alternatives it is characterized by the same percentage variation; this property it is called *proportionate shifting*. This property may be thus unrealistic in some cases, the Logit model thus imply a specific pattern of substitution. The elasticity related to a change of the z_{ni} attribute related to the P_{ni} probability may be derived as:

$$E_{iz_{ni}} = \frac{\partial P_{ni}}{\partial z_{ni}}\frac{z_{ni}}{P_{ni}} = \frac{\partial(e^{V_{ni}}/\sum_j e^{V_{nj}})}{\partial z_{ni}}\frac{z_{ni}}{P_{ni}} = \left(\frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}}\frac{\partial V_{ni}}{\partial z_{ni}} - \frac{e^{V_{ni}}}{\left(\sum_j e^{V_{nj}}\right)^2} e^{V_{ni}}\frac{\partial V_{ni}}{\partial z_{ni}}\right)\frac{z_{ni}}{P_{ni}} =$$

$$= \left[\frac{\partial V_{ni}}{\partial z_{ni}}(P_{ni} - P_{ni}^2)\right]\frac{z_{ni}}{P_{ni}} = \frac{\partial V_{ni}}{\partial z_{ni}} z_{ni}(1 - P_{ni}) \qquad \text{(EQ 3.2.3.11)}$$

if the utility function it is explicated in the linear form $V_{ni} = \beta' x_{ni}$ the EQ 3.2.3.11 becomes:

$$E_{iz_{ni}} = \beta_z z_{ni}(1 - P_{ni}) \qquad \text{(EQ 3.2.3.12)}$$

As the cross elasticity, from the EQ 3.2.3.12 results that $E_{iz_{ni}}$ is a function of z_{ni}, β_z and P_{ni}, it doesn't depend on other alternatives' characteristics $j \neq i$.

3.2.4 Model estimation

The estimation process leads to the determination of the representative utility function V to be determined. It is usual to express the utility function linear in parameters x_{nj} (explanatory variables):

$$V_{nj} = \beta' x_{nj} + k_j \quad \text{(EQ 3.2.4.1)}$$

where k_j is the constant of the model and β' is a vector of the coefficients related to explanatory variables x_{nj} which must be estimated. As the simplest, the linear form of the utility function V it is the most utilized but other typologies may be adopted, for the purpose of this thesis the linear form is adopted. Considering a sample of *N* decision makers that face choices, the hypothesis is that the sample is randomly stratified and the explanatory variable of the utility function V are independent of the unobserved component of the utility function U. The probability of a decision maker n chooses the observed alternative may be defined as:

$$\prod_i (P_{ni})^{y_{ni}} \quad \text{(EQ 3.2.4.2)}$$

where y_{ni} it is equal to 1 if the alternative i is chosen and 0 otherwise. Assuming that the choice of each decision maker it is independent from the choices of others, the probability that all the decision makers N of the sample choose the observed alternative it is computed as:

$$L(\beta) = \prod_{n=1}^{N} \prod_i (P_{ni})^{y_{ni}} \quad \text{(EQ 3.2.4.3)}$$

where β is the vector of the coefficients related to explanatory variables of the model to estimate and $L(\beta)$ is the likelihood function. Due to computational reasons, the logarithm of the likelihood function ($LL(\beta)$) is utilized:

$$LL(\beta) = \sum_{n=1}^{N} \sum_i y_{ni} \ln P_{ni} \quad \text{(EQ 3.2.4.4)}$$

considering the Logit model (EQ 3.1.2.9) and a linear utility function, the log-likelihood function becomes:

$$LL(\beta) = \sum_{n=1}^{N} \sum_i y_{ni} \ln P_{ni} = \sum_{n=1}^{N} \sum_i y_{ni} \ln \left(\frac{e^{\beta' x_{ni}}}{\sum_j e^{\beta' x_{nj}}} \right) = \sum_{n=1}^{N} \sum_i y_{ni} (\beta' x_{ni}) -$$

$$- \sum_{n=1}^{N} \sum_i y_{ni} \ln\left(\sum_j e^{\beta' x_{nj}}\right) \quad \text{(EQ 3.2.4.5)}$$

in order to estimate β', the log-likelihood function must be maximized, in this way, the values of β' that express the best observed choices of decision makers in the sample are computed. It was demonstrated (McFadden, 1974) that considering a linear utility function, the log-likelihood function results concave then the maximum of the function may be determined; to find the maximum the first order condition must be set:

$$\frac{dLL(\beta)}{d\beta} = 0 \quad \text{(EQ 3.2.4.6)}$$

from EQ 3.2.4.5 and EQ 3.2.4.6:

$$\frac{dLL(\beta)}{d\beta} = \frac{\sum_{n=1}^{N} \sum_i y_{ni} (\beta' x_{ni})}{d\beta} - \frac{\sum_{n=1}^{N} \sum_i y_{ni} \ln\left(\sum_j e^{\beta' x_{nj}}\right)}{d\beta} = \sum_{n=1}^{N} \sum_i y_{ni} x_{ni} -$$

$$-\sum_{n=1}^{N}\sum_{i} y_{ni}\sum_{j} P_{nj}x_{nj} = \sum_{n=1}^{N}\sum_{i} y_{ni}x_{ni} - \sum_{n=1}^{N}\left(\sum_{j} P_{nj}x_{nj}\right)\sum_{i} y_{ni} =$$

$$= \sum_{n=1}^{N}\sum_{i} y_{ni}x_{ni} - \sum_{n=1}^{N}\left(\sum_{j} P_{nj}x_{nj}\right) = \sum_{n=1}^{N}\sum_{i}(y_{ni} - P_{ni})x_{ni} = 0 \qquad \text{(EQ 3.2.4.7)}$$

The maximization of the log-likelihood function may be done utilizing the Newton-Raphson method, let define the gradient g and the Hessian H of the log-likelihood function as:

$$g = \left(\frac{\partial LL(\beta)}{\partial \beta}\right); \;\; H = \frac{\partial g}{\partial \beta'} = \frac{\partial^2 LL(\beta)}{\partial \beta \partial \beta'} \qquad \text{(EQ 3.2.4.8)}$$

providing the second-order Taylor's approximation of the log-likelihood function:

$$LL(\beta_{k+1}) = LL(\beta_k) + (\beta_{k+1} - \beta_k)' g_k + \frac{1}{2}(\beta_{k+1} - \beta_k)' H_k (\beta_{k+1} - \beta_k) \qquad \text{(EQ 3.2.4.9)}$$

where the value of the log-likelihood function related to β_{k+1} it is estimated on the basis on the value of the log-likelihood function related to β_k, from this approximation taking into account EQ 3.2.4.8 and EQ 3.2.4.6, it is possible to provide a numerical algorithm to find the maximum of the log-likelihood function:

$$\frac{dLL(\beta_{k+1})}{d\beta_{k+1}} = g_k + H_k(\beta_{k+1} - \beta_k) = 0 \rightarrow \; H_k(\beta_{k+1} - \beta_k) = -g_k \; \rightarrow \beta_{k+1} - \beta_k = -H_k^{-1} g_k \rightarrow$$

$$\rightarrow \beta_{k+1} = \beta_k + (-H_k^{-1}) g_k \qquad \text{(EQ 3.2.4.11)}$$

using the EQ 3.2.4.11 it is possible to estimate the β' that maximize the log-likelihood function, the coefficients β' of the linear utility function are thus estimated.

3.3 Experimental design

In this paragraph, the focus on the experimental design step is treated. In a choice experiment exercise based on state preferences (SP) data (see Section 3.1 for SP data definition), firstly respondents imagine to be in a hypothetical scenario. The hypothetical scenario it is characterized and described by a number of attributes that may assume different qualitative or quantitative levels. Respondents face a number of choice tasks, each choice task it is characterized by having different combinations of attribute levels, through statistical design theory the goal of the experimental design is to combine in an "appropriate way" the attribute levels into a number of choice tasks (that contain the choice alternatives) (Hanley et al., 2001). The statement "appropriate way" it is related to the different adoptable methodologies of experimental design that combine attribute levels utilizing different methods and criteria as presented in this paragraph. Manipulating the levels of some variables, an experimental design studies the effects that they have in another variable (Hensher et al., 2010). *Figure 3.4.1* shows the framework of the experimental design:

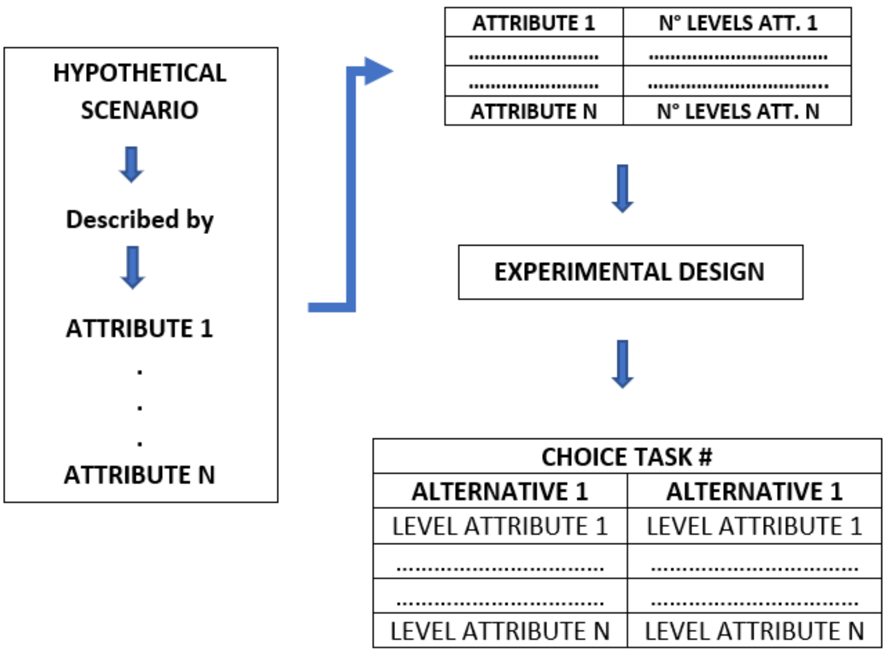

Figure 3.4.1 Framework of the experimental design

Each attribute it is characterized by a number of levels that may be qualitative or quantitative, if the levels are qualitative, they are coded using integer number or/and dummy variables as will be presented. Firstly, the choice experiment (CE) typology must be analysed, the CE may be *labelled* or *unlabelled*. As regards unlabelled experiments, choice alternatives are merely variants of the same label and they have the same utility function, unlabelled experiments are utilized for valuation of attributes (for example WTP studies). Labelled experiments have different labels (for example related to a specific brand or a specific good), each alternative may have different utility function, they can also used for forecasting market share of brands/products and elasticities estimates may be analysed; all the possible choice alternatives must be considered. The purpose of this thesis is to estimate the WTP related to benefits and co-benefits that the energy retrofit involves as mentioned in the previous paragraphs, the experiment typology as will be presented in the next chapter. In the next paragraphs the experimental design typologies will be presented, as mentioned before, all the attributes that describe the hypothetical scenario are characterized by a certain number of qualitative or quantitative levels. In a theoretical point of view, each respondent should face a number of choice tasks corresponding to all the possible combinations between the attribute levels that can be obtained, a high number of choice tasks is thus reached, the experimental design process goal is to reduce the number of choice tasks in an appropriate way obtaining good estimates of the utility function. It exists several different experimental design types and they are analysed in the next paragraphs, in order to explain the methodologies, the convention in *Figure 3.4.2* is adopted, each row of the first column of the levels combination matrix corresponds to a single choice tasks, the other columns contain the attribute levels of the choice tasks related to the specific choice alternative:

Choice task	Alternative 1			Alternative 2		
1	x_{11}	x_{21}	x_{31}	x_{12}	x_{22}	x_{32}
2						
.....						
.....						

ATTRIBUTES	CHOICE CARD 1	
	ALTERNATIVE 1	ALTERNATIVE 2
ATTRIBUTE 1	x_{11}	x_{12}
ATTRIBUTE 2	x_{21}	x_{22}
ATTRIBUTE 3	x_{31}	x_{32}

Attribute levels of Alternative 1

Attribute levels of Alternative 2

Fig 3.4.2 Attribute levels matrix convention 1

Another convention that will be utilized provides for each row a simple hypothetical combination (*s*) of the attribute levels (Fig 3.4.3):

s	Level attribute 1	Level attribute 2	Level attribute 3
1	x_1	x_2	x_3
2			
....			
....			

Figure 3.4.3 Attribute levels matrix convention 2

3.3.1 Full and factorial design, orthogonal design

A *full factorial* is a design in which all possible attribute levels are provided, the size of this typology of design depends on the number of attributes and related levels. Considering a number M of alternatives each with a number A of attributes, and each attribute it is characterized by a number L of levels, the full factorial design provides a number of choice tasks equal to:

$$Total\ number\ of\ choice\ tasks = L^{MA} \quad \text{(EQ 3.3.1.1)}$$

If different attributes have different numbers of levels, the total number of choice tasks it is the multiplication of the numbers of attribute levels over all alternatives and attributes. Considering for example (*Figure 3.3.1.1*) two attributes characterized both by two levels and assuming two choice alternatives, the total combination of choice tasks results:

Attribute	Levels
x_1	0 1
x_2	2 3

$$Total\ number\ of\ choice\ tasks = L^{MA} = 2^{2\times2}$$

Choice tasks	Alternative 1	Alternative 2
1	0 2	0 3
2	0 3	0 2
3	1 2	0 3
4	1 3	0 2
5	0 2	1 3
6	0 3	1 2
7	1 2	1 3
8	1 3	1 2

Choice tasks	Alternative 1	Alternative 2
9	0 2	1 2
10	1 2	0 2
11	0 3	1 3
12	1 3	0 3
13	0 2	0 2
14	0 3	0 3
15	1 2	1 2
16	1 3	1 3

Figure 3.3.1.1 Example of full factorial design with two alternatives

All possible attribute level combinations are computed as:

$$Number\ of\ level\ combinations = \prod_{i=1}^{N} L_i \quad \text{(EQ 3.3.1.2)}$$

where L_i is the number of levels assigned to attribute i. Considering for example (*Figure 3.3.1.2*) two attribute both characterized by three levels, the total number of combination *s* are:

Attribute	Levels
x_1	0 1 2
x_2	3 4 5

$$Number\ of\ level\ combinations = 3 \times 3 = 9$$

Combination (*s*)	x_1	x_2
1	0	3
2	0	4
3	0	5
4	1	3
5	1	4
6	1	5
7	2	3
8	2	4
9	2	5

Figure 3.3.1.2 Full factorial design total combinations example

The full factorial design provides all possible combinations of attribute levels, all possible main and interaction effects between all attribute levels may be estimated, however the number of choice situation may result too large and a subset of choice situation is selected. The goal is to reduce the number of choice tasks shown to each respondent, the *fractional factorial* design methods are utilized to select a subset of choice tasks from the full factorial design. It

exists three typologies of fractional factorial designs: the *random* designs, the *orthogonal* designs and the *efficient* designs. The random designs select a random subsect of choice tasks from the full factorial design, they are employed for very large number of choice tasks, the random algorithm selection may choose more repeated attribute levels than others and it is therefore not the best method to adopt. Efficient designs are explained in the next paragraphs, orthogonal designs are now threated.
An experimental design is defined as "*orthogonal*" if every pair of levels occurs equally often across all pairs of attributes, in this case each two attributes are uncorrelated. As example, let consider two attributes (x_1, x_2) both characterized by two levels (0,1), the design in *Figure 3.3.1.3* it is orthogonal:

s	x_1	x_2
1	0	1
2	0	1
3	0	0
4	0	0
5	0	0
6	0	1
7	1	0
8	1	1
9	1	1
10	1	0
11	1	1
12	1	0

Each pair of attribute levels (0,1); (0,0); (1,1); (1,0) appears three time

Figure 3.3.1.3 Example of orthogonal design

The covariance matrix between x_1 and x_2 vectors has all the elements outside the diagonal equal to zero thus, x_1 and x_2 are uncorrelated; the orthogonal designs provide uncorrelated attribute levels in the choice tasks, in this manner, attributes are statistically independent. This fact involves two important properties of orthogonal designs, let consider the variance-covariance (VC) matrix of a linear regression model:

$$VC = \sigma^2[X^T X]^{-1} \qquad \text{(EQ 3.3.1.3)}$$

where σ^2 is the model variance and X is the matrix of attribute levels in the design or in the data to be used in the estimation (Rose and Blimer, 2009). The model variance may be seen as scaling factor, fixing it, if the X matrix it is orthogonal, the elements of the VC matrix are minimized; the standard errors are thus minimized providing the maximization of the *t*-ratios of the model. Another important aspect is that an orthogonal design it is characterized by having all the elements outside the diagonal of VC matrix equal to zero, this property involves that parameter estimates are not affect by multicollinearity problems; thus, adopting orthogonal designs, the determination of the contribution of each attribute with respect the dependent variable it is independent (Rose and Blimer, 2009).

3.3.2 Efficient designs

The most important fractional factorial design methods developed in the last years (Huber and Zwerina, 1996; Kanninen, 2002; Rose and Bliemer 2009,2013,2012,2015; Blimer and Collins, 2016) are the *efficient* designs. This methodology provides designs that are statistically efficient in terms of little standard errors of parameter estimates, the information from each choice situation is maximized (Rose and Blimer, 2009). Let consider the representative utility in the simplest linear form that is a function of choice data (attribute levels) $X_{nsjk}$and β_k, $k = 1, \ldots, K$ parameters:

$$V_{nsj}(X, \beta) = \sum_{k=1}^{K} \beta_k X_{nsjk} \qquad \text{(EQ 3.3.2.1)}$$

where n is the index referring to the respondent, s is the index referring to the choice task, j is the index referring to the choice alternative. Let consider the multinomial Logit probabilities:

$$P_{nsj}(X, \beta) = \frac{\exp(V_{nsj}(X,\beta))}{\sum_{i=1}^{J} \exp(V_{nsi}(X,\beta))} \qquad \text{(EQ 3.3.2.2)}$$

where P_{nsj} is the probability that the respondent n chooses the alternative j in the choice task s. The model estimation is provided maximizing the log-likelihood function (Section 3.1.4):

$$L_n(X, \beta, y) = \sum_{n=1}^{N} \sum_{s=1}^{S} \sum_{j=1}^{J} y_{nsj} \log(P_{nsj}(X, \beta)) \qquad \text{(EQ 3.3.2.3)}$$

where y_{nsj} are the choice observation related to the respondent n, the alternative j and the choice task s. The second derivative of the log-likelihood function gives the Fisher information matrix:

$$I_n(X, \beta, y) = -\frac{\partial^2 L_n(X,\beta,y)}{\partial\beta\partial\beta'} = Z'Z;\ Z \epsilon R^{NSJXK};\ z_{nsjk} = (x_{nsjk} - \sum_{i=1}^{J} P_{nsi} x_{nsik})\sqrt{P_{nsj}} \qquad \text{(EQ 3.3.2.4)}$$

The negative inverse of the Fisher information matrix yields the model asymptotic variance-covariance matrix (AVC matrix):

$$\Omega_N(X, \beta, y) = I_N^{-1} \qquad \text{(EQ 3.3.2.5)}$$

The roots of the diagonals of the AVC matrix denote de standard errors:

$$\Omega = \begin{pmatrix} se(\beta_1)^2 & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \cdots & \cdots & se(\beta_k)^2 \end{pmatrix} \qquad \text{(EQ 3.3.2.6)}$$

where $se(\beta_k)$ is the standard error of parameter β_k. Considering an experimental design X and β priors (best guesses of β parameter values), it is possible to check the efficiency of the design X analysing the standard errors of β parameters through the AVC matrix. The framework to perform an efficient experimental design is illustrated in the *Figure 3.3.2.1*:

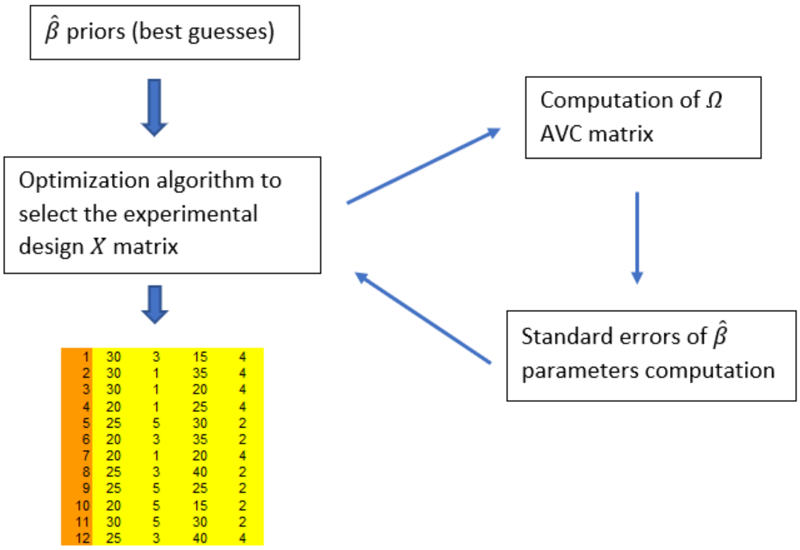

Figure 3.3.2.1 Experimental design process

From the *Figure 3.3.2.1*, the initial assumption of an efficient experimental design is that $\hat{\beta}$ priors are known a priori, their estimates may be done analysing the literature on previous similar studies, providing some pilot studies (conducing some pilot surveys) or consulting experts' judgement. Once the utility function and the attribute levels are defined, the full factorial design is performed. From the full factorial design, it is possible to implement an iterative process that select some X fractional design matrixes utilizing selection optimization algorithms, for each X design matrix the AVC matrix Ω is computed and the standard errors of $\hat{\beta}$ are estimated. In the end the design characterized by lower standard errors is selected and the choice tasks of the survey are provided.
As regards algorithms for locating efficient designs several algorithms are proposed in the literature such as the Modified Federov algorithm (Coock and Nachtsheim, 1980), the RSC (Relabelling, Swapping Cycling) algorithm (Huber and Zwerina, 1996), the Cordinate Exchange algorithm (Meyer and Nachtsheim, 1995), the Genetic algorithm (Wu et al., 2010).
The efficient designs are also able to reduce the sample size ensuring the statistical significance of $\hat{\beta}$ estimates. From EQ 3.3.2.4, assuming that all respondents observe the same choice situations:

$$I_n(X,\beta) = N\sum_{s=1}^{S}\sum_{j=1}^{J} X_{sjk}P_{sj}(X,\beta)\left(X_{sjk} - \sum_{i=1}^{J} X_{sjk}P_{is}(X,\beta)\right) \qquad \text{(EQ 3.3.2.7)}$$

therefore, the AVC matrix becomes:

$$\Omega_N(\beta,X) = I_N^{-1}\,(\beta,X) = \frac{1}{N}\Omega_1(\beta,X) \rightarrow se_N(\beta,X) = \frac{1}{\sqrt{N}}se_1(\beta,X) \qquad \text{(EQ 3.3.2.8)}$$

From EQ 3.4.2.8 it is possible to compute the Fisher information matrix and the standard errors analysing the observed choice data of only one respondent obtaining the standard errors for N respondents:

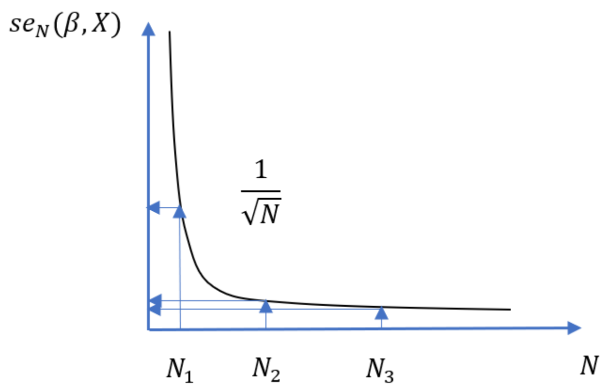

Figure 3.4.2.2 Standard error behaviour and sample size

The relationship between the standard error and the sample size is reported in the *Figure 3.3.2.2*, from a certain value of N (between N_1 and N_2), investing in more respondent it is not convenient cause of the standard error reduction of $\hat{\beta}$ coefficients decreases very little; efficient designs are thus able to reduce the sample size and guarantee in the same time the statistical significance of $\hat{\beta}$ estimates. The standard errors are reduced performing a better design as showed in *Figure 3.3.2.3*:

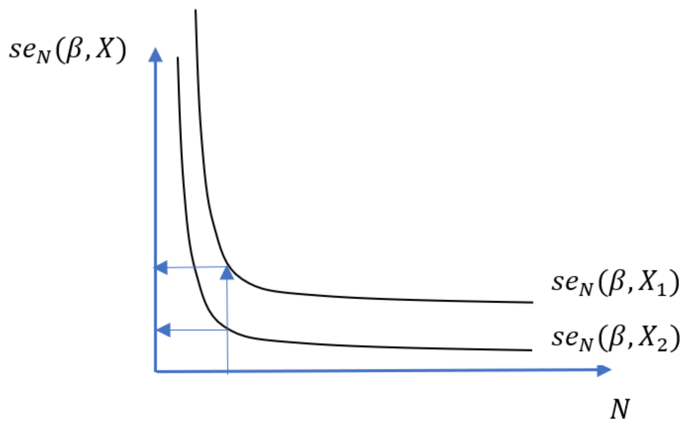

Figure 3.3.2.3 Different designs behaviour

In order to assesses the efficiency of different designs, several efficiency measures are proposed. The most widely used ones are the *D-error* and the *A-error*:

$$D - error = \det(\Omega_1)^{1/K} \quad \text{(EQ 3.3.2.9)}$$

$$A - error = \frac{tr(\Omega_1)}{K} \quad \text{(EQ 3.3.2.10)}$$

where K is the number of parameters of the $\hat{\beta}$ coefficients, $\det(\Omega_1)$ is the determinant of the AVC matrix, $tr(\Omega_1)$ is the trace of the AVC matrix, the most utilized is the *D-error* cause of considers all the element of the AVC matrix, the goal of the efficient design process is to minimize the *D-error*. It is also possible to estimate the optimal sample size N of the survey (called *S-estimate* index), let consider $\hat{\beta}$ priors and $se_1(\beta_k)$, it is possible to compute the *t*-ratio for any sample size:

$$t = \frac{\beta_k}{se_1(\beta_k)/\sqrt{N}} \geq t^* \qquad \text{(EQ 3.3.2.11)}$$

where t^* is a fixed level of statistical significance level (for example equal to 1.96 fixing the α error equal to 0.05), from the EQ 3.4.2.11 it is possible to estimate the sample size for the parameter β_k:

$$N_k = \frac{se(\beta_k)t^*}{\beta_k} \qquad \text{(EQ 3.3.2.12)}$$

the required overall sample size (for all the parameters) is the maximum of the all $N_k, k = 1, \dots, K$:

$$N = max_k\{N_k\} \qquad \text{(EQ 3.3.2.13)}$$

To perform a good efficient design, $\hat{\beta}$ priors must be assumed as better as possible, literature review, pilot surveys and expert judgments may be utilized. If no prior information is available, two methodologies may be adopted:

Methodology 1:

1. Create a D1 design using zero priors (called *D_z-efficient* design) or use an orthogonal design;
2. Use design D1 in the main survey.

Methodology 2:

1. Create a D1 design using zero priors or use an orthogonal design;
2. Use design D1 in a small pilot survey;
3. Estimate $\hat{\beta}$ parameters, use as priors;
4. Create efficient design D2;
5. Use design D2 in main survey.

Summarizing, the entire process to provide an efficient design is reported in the *Figure 3.3.2.4*

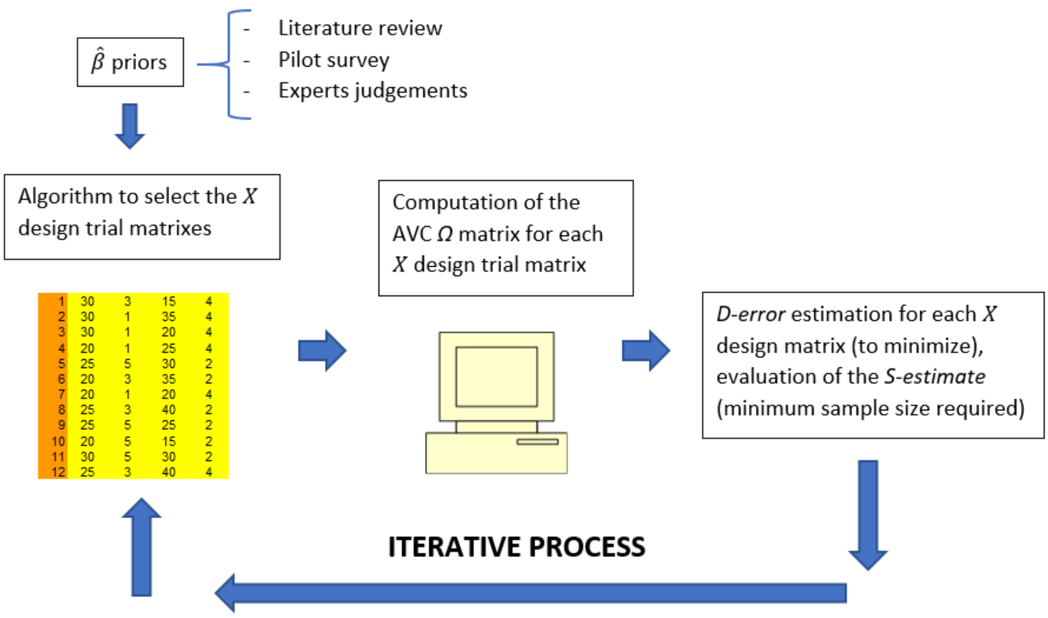

Figure 3.3.2.4 General framework of an efficient design

4: STATED PREFERENCES CHOICE MODELLING EXERCISE

4.1 Attribute and attribute levels definition

In this section the procedure to define the attributes and the attribute levels of the utility function is presented. *Table 4.1.1* reports the stages to develop a SP study (Hanley et al., 2001) according to which the following CE exercise is structured.

Stage	Description
Selection of attributes	Identification of relevant attributes of the good to be valued. Literature reviews and focus groups are used to select attributes that are relevant to people while expert consultations help to identify the attributes that will be impacted by the policy. A monetary cost is typically one of the attributes to allow the estimation of WTP.
Assignment of levels	The attribute levels should be feasible, realistic, non-linearly spaced, and span the range of respondents' preference maps. Focus groups, pilot surveys, literature reviews and consultations with experts are instrumental in selecting appropriate attribute levels. A baseline 'status quo' level is usually included.
Choice of experimental design	Statistical design theory is used to combine the levels of the attributes into a number of alternative scenarios or profiles to be presented to respondents. *Complete factorial designs* allow the estimation of the full effects of the attributes upon choices: that includes the effects of each of the *individual* attributes presented (main effects) and the extent to which behaviour is connected with variations in the *combination* of different attributes offered (interactions). These designs often originate an impractically large number of combinations to be evaluated: for example, 27 options would be generated by a full factorial design of 3 attributes with 3 levels each. *Fractional factorial designs* are able to reduce the number of scenario combinations presented with a concomitant loss in estimating power (i.e. some or all of the interactions will not be detected). For example, the 27 options can be reduced to 9 using a fractional factorial. These designs are available through specialised software.
Construction of choice sets	The profiles identified by the experimental design are then grouped into choice sets to be presented to respondents. Profiles can be presented individually, in pairs or in groups. For example, the 9 options identified by the fractional factorial design can be grouped into 3 sets of four-way comparisons.
Measurement of preferences	Choice of a survey procedure to measure individual preferences: ratings, rankings or choices.
Estimation procedure	OLS regression or maximum likelihood estimation procedures (logit, probit, ordered logit, conditional logit, nested logit, panel data models, etc.). Variables that do not vary across alternatives have to be interacted with choice-specific attributes.

Table 4.1.1 Stages of a SP study [Source: Hanley et al. (2001)]

As reported in *Table 4.1.1*, the first step it is the identification of relevant attributes and the definition of individuals' utility function and demand for BER. The attributes and the attribute levels of the utility function were selected according to the findings of the literature reviews conducted in Section 2.2 and Section 2.3 respectively, and they are related to benefits and co-benefits generated by BER as well as by the installation of specific ERMs. *Table 4.1.2* summarizes the most important benefits and co-benefits of BER founded in literature, whereas *Table 4.1.3* recalls key utility function attributes and benefit and co-benefit of BER investigated in the 7 core articles on SP approaches previously discussed (see Section 2.3).

DIRECT BENEFITS	INDIRECT BENEFITS
Energy savings	Job creation
CO_2 emissions reduction	Preservation of natural sources
Monetary savings	
Thermal comfort	
Indoor air quality	
Aesthetic appearance	
Protection against external noise	

Table 4.1.2 relevant benefits of the BER

AUTHOR	UTILITY FUNCTION ATTRIBUTES	BENEFITS AND CO-BENEFITS
Banfi et al. (2006)	Window, façade, ventilation system, price	thermal comfort, air quality and noise protection, aesthetic of the building
Kwak et al., (2010)	Window, façade, ventilation system, price	thermal comfort, air quality, noise protection, aesthetic of the building
Syahid et al., (2016)	Energy savings, interior soundproofing, ventilation system, development area set aside for landscaping and recreational users, renewable energy sources, cost	Energy savings, air quality, noise protection, environmental awareness
Carroll et al. (2016)	Distance to work/college, age of the apartment, energy label, area safety, rent, size of the apartment	Energy savings, aesthetic of the building, safety, building location, size of the apartment
Galassi and Madlener (2017)	Indoor air quality, thermal comfort, automation of some systems, noise reduction, aesthetic appearance of the building, energy savings, cost	Energy savings, air quality, noise protection, thermal comfort, aesthetic of the building, automation of some systems
Marmolejo-Duarte and Bravi (2017)	Condominium amenities, additional private spaces, quality of finishes, active conditioning, energy label, price	Energy savings, thermal comfort, aesthetic of the building, amenities
Matosovic and Tomšic (2018)	NOT DECLARED	thermal comfort, aesthetic of the building

Table 4.1.3 Utility function attribute, benefits and co-benefits in core articles on SP approaches

The lack in literature on the estimation of the WTP by the CE approach, added complexity in the experimental design and the identification of attributes and relative levels. To address these issues, the research was structured into sequential phases.

Firstly, the hypothetical scenario was defined. In the SP studies analysed in Section 2.3, two hypothetical scenarios were provided. In the former respondents had to consider their house and they had to choose among different retrofit alternatives, which varied in retrofit levels (Banfi et al., 2006; Kwak et al., 2010; Galassi and Madlener, 2017). In the latter, respondents played the role of homeowners of a hypothetical dwelling and had to choose among different retrofit alternatives, which varied in retrofit levels (Syahid et al., 2016; Carroll et al. (2016); Marmolejo-Duarte and Bravi, 2017). It may be puzzling for respondents to imagine different retrofit options of their dwelling based on those proposed in the survey. Respondents' dwellings may have different characteristics and different retrofit options, and it may result extremely difficult to standardize retrofit options for a wide range of building typologies (e.g., some retrofit options may be unrealistic or not implementable from a technical point of view on a specific building as well as a same retrofit alternative may produce different energy savings in different buildings). In addition, respondents may have imperfect or very few information on the technical characteristics of their dwellings and find it challenging to make retrofit choices based on those characteristics. As an example, if a respondent doesn't know the EL of his dwelling and consequently the building energy consumption, this respondent may not be able to choose among different EL levels proposed. It is widely acknowledged that an SP study is well-designed when respondents identifiy with the homeowner of the hypothetical dwelling and are able to perceive the changes in the attribute levels and related benefits. An SP study must represent a realistic situation in order to obtain robust WTP estimates. In the light of the above considerations, for the purpose of the present study, we defined a hypothetical building to be retrofitted. We focused on apartments, as they are the most widespread building typology in the Italian real estate market. In the survey, respondents played the role of homeowners of a hypothetical 90 m^2, G label apartment located in a condominium (photos and technical characteristics of the building were provided) and had to choose among different retrofit alternatives, which varied in retrofit levels.

Secondly, attributes and attribute levels were defined starting from D'Alpaos and Bragolusi (2019a) and according to the literature reviews previously conducted (Sections 2.2 and 2.3). In detail, D'Alpaos and Bragolusi (2019a) proposed a multiple criteria model, based on the Analytic Hierarchy Process (AHP), to identify relevant key factors in BER and rank (from best to worse) alternative energy retrofit measures. The AHP method developed by Saaty (1980) is a multiple criteria decision-making tool allows for measurement of tangible and/or intangible criteria and factors and assumes that the decision-maker is always able to express preferences/judgments and evaluate the relative importance of criteria and sub-criteria (D'Alpaos and Bragolusi, 2019a). The AHP deconstructs the initial decision problem into several levels, by developing a hierarchy, where the top of the hierarchy is represented by the main goal of the decision problem, whereas criteria and sub-criteria which contribute to the goal are placed at lower levels and alternatives to be evaluated are at the bottom level. Attributes and criteria relative importance is determined through pairwise comparisons expressed in semantic judgments, converted into numerical values according to Saaty's fundamental scale (Saaty, 1980). These judgments represent experts' subjective preference (relative importance) on the dominance of one criterion over another with respect to the goal. The priorities are then determined according to the eigenvalue approach to pairwise comparisons and the global ranking of alternatives is obtained via a weighted-sum aggregation procedure. D’Alpaos and Bragolusi (2019a) set the prioritization of the ERMs as the goal, and considered three families of criteria (i.e., economic, environmental and social) and a set of subcriteria. Economic sub-criteria accounted for indirect retrofit costs (i.e., costs related to inconveniences to occupants), the building LCC (over a 30-year period) and the payback period. Technical sub-criteria included compatibility (i.e., compatibility of new with pre-existing features and structural elements), efficiency (i.e., improvement in building technical and economic performances) and the reliability (i.e., frequency of failures and system safety). Socio-environmental sub-criteria comprise social reputation (i.e., reputation capital increase), CO_2 reduction, aesthetics of the building (i.e., facade attractiveness improvement), occupants well-being (i.e., comfort improvement). At the bottom of the hierarchy there are seven retrofit scenarios which involve the implementation of three basic ERMs and their combinations (D’Alpaos and Bragolusi, 2019a): a) installation of condensing boilers (alternative 1); installation of double-glazed windows (alternative 2); application of insulating layers on the external walls, roofs and ceilings (alternative 3); installation of condensing boilers and double-glazed windows (alternative 4); installation of condensing boilers and application of insulating layers on the external walls, roofs and ceilings (alternative 5); installation of double-glazed windows and application of insulating layers on the external walls, roofs and ceilings (alternative 6); installation of condensing boilers and double-glazed windows and application of insulating layers on the external walls, roofs and ceilings (alternative 7). *Figure 4.1.1* illustrates the hierarchy by D’Alpaos and Bragolusi (2019a), whereas *Table 4.1.4* reports the final ranking of criteria and sub-criteria obtained by processing experts’ judgements (D’Alpaos and Bragolusi, 2019a).

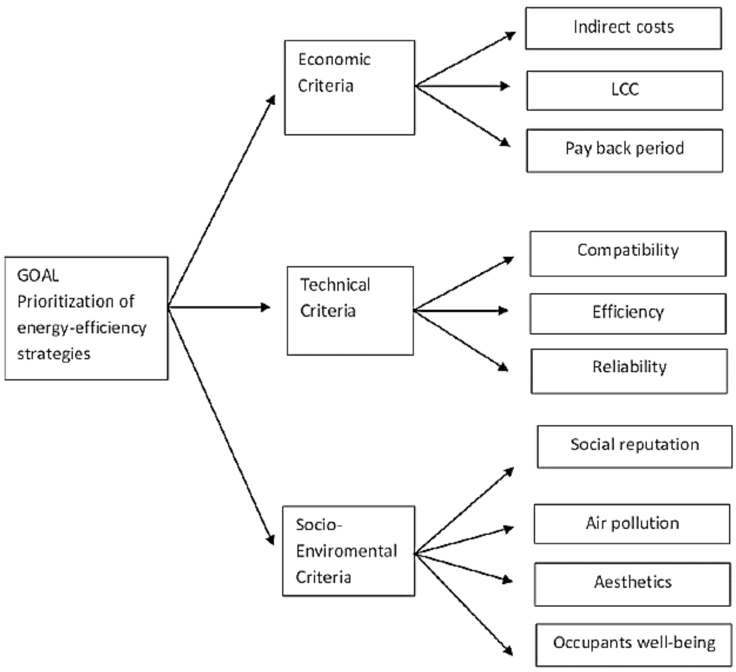

Figure 4.1.1 Hierarchy. [Source: D’Alpaos and Bragolusi (2019a)]

Criteria	Priority vector	Sub-criteria	Priority vector
Economic	0.637	Indirect costs	0.105
		LCC	0.636
		Pay back period	0.259
Technical	0.105	Compatibility	0.143
		Efficiency	0.715
		Reliability	0.142
Socio-Environmental	0.258	Social reputation	0.260
		Air pollution	0.381
		Aesthetics	0.232
		Occupants' well-being	0.127

Table 4.1.4 Criteria and sub-criteria ranking. [Source: D'Alpaos and Bragolusi (2019a)]

Metti anche la tabella con il ranking delle alternative stessa legenda dell'articolo e cita la fonte

According to priority vectors displayed in *Table 4.4.1*, Economic Criteria play a major role in the achievement of the goal, as well as Socio-Environmental Criteria which are ranked as second in terms of relative importance. In addition, alternative 3 (i.e., installation of insulating layers on external walls, roofs and ceilings), and alternative 6 (i.e., installation of double-glazed windows and application of insulating layers on external walls, roofs and ceilings) are first and second in the ranking respectively (D'Alpaos and Bragolusi, 2019a). In addition, results show that installation of condensing boiler are not considered as much preferable as application of insulating layers and installation of double-glazed windows. The analysis of sub-criteria ranking, reveals that efficiency is the most important sub-criteria followed in ascending order of importance by LCC, air pollution, payback period, aesthetic, compatibility, reliability, occupants' well-being and indirect costs, respectively.

According to these results and to evidence from literature, we identified both a utility function, depending on five attributes, and the hypothetical scenario, according to which the reference building is an average size class G-EL apartment (i.e., 90 m^2) subject to energy retrofit interventions, which will guarantee higher energy efficiency (from F-EL to A-EL), improvements in indoor comfort and in the aesthetic appearance of the building.

The five attributes are described in what follows.

The first attribute is the building EL and the relative attribute levels coincides with EL levels which rank the level of energy consumption and CO_2 emissions under ordinary use conditions from high (A) to low (G) efficiency. This is in line with literature, in which the EL attribute was adopted in several SP studies on BER (Syahid et al., 2016; Carroll et al., 2016; Galassi and Madlener, 2017; Marmolejo-Duarte and Bravi, 2017) and is coherent with the results provided by Bragolusi and D'Alpaos (2019a), who identified, as previously mentioned, energy efficiency (i.e., reduction of energy consumption) as the most important sub-criteria. The lower the EL, the lower the monetary savings (thus, the investment payback period) and the CO_2 emissions reduction. It is not possible to consider in the utility function EL, energy savings, monetary savings and CO_2 emissions reduction as separate attributes, as they are not independent as required in SP models; nonetheless in the survey ELs were reported jointly to the amount of energy saving, CO_2 emissions reduction and monetary savings.

With respect to the status-quo building (a 90 m^2 apartment, G label) and to the choice tasks and each EL, we estimated the energy annual consumption (expressed in kWh/m^2 year), the monthly monetary saving (expressed in €/month), and CO_2 emissions rate (expressed in kg/month). Monetary savings and energy savings were determined with respect the status quo, whereas CO_2 emissions rate estimations were provided by an academic expert on BER thermal analysis (*Table 4.1.5*).

ENERGY LABEL	**Energy consumption [kWh/m^2 year]**	**Energy savings with respect the G class [kWh/month]**	**CO_2 emissions [kg/month]**	**Monetary savings with respect the G class [€/month]**
A	15	1088	23	180
B	41	896	61	150
C	61	746	91	120
D	81	596	121	100
E	106	409	158	60
F	141	146	211	20
G	160	0	240	0

Table 4.1.5 Building energy consumption, energy savings, CO_2 emissions and monetary savings

To determine the WTP for different energy labels, EL attribute levels were coded as dummy variables and a β coefficient for each attribute level (EL) was estimated. The F-EL was set as the reference level, consequently the related β coefficient is automatically set to zero.

The second selected attribute is related to the installation a mechanical ventilation system, which contributes to the improvement of indoor air quality and to energy savings (See APPENDIX I). In previous SP studies on BER, a number of authors considered this attribute (Banfi et al., 2006; Kwak et al., 2010; Syahid et al., 2016; Galassi and Madlener, 2017) and their results reveals that people are willing to pay for benefits related to the installation of mechanical ventilation systems. This attribute was coded as a dummy variable (i.e., install or not the technology). Consequently, the related attribute levels are 1 if the system is installed and 0 otherwise.

The third attribute refers to improvement in aesthetical appearance of the building. Many core SP studies in literature considered this attribute in the specification of the utility function (Banfi et al., 2006; Kwak et al., 2010; Galassi and Madlener 2017; Marmolejo-Duarte and Bravi, 2017; Matosovic and Tomšic, 2018). The aesthetic appearance of the building was also ranked as the fifth most important sub-criteria in D'Alpaos and Bragolusi (2019a). It is worth noting that according to the annual report on energu efficiency by the Italian Energy Agency (ENEA, 2018), in the period 2014-2017, 54.3% of policy incentives (i.e., tax rebates) were paid for windows and doors replacement. Doors and windows replacement involves not only energy savings but also contributes to the improvement in the aesthetical appearance of the building, which in turn increases assets market price. This attribute is characterized by three levels:

- "NO": if the status quo persits;
- "WALL REPAINTING ": if external walls are repainted. This involve a small improvement in aesthetical appearance;
- "PLASTER, DOORS AND WINDOWS": if exterior walls plaster is renovated and low-emittance doors and windows are installed. This provide significant improvements in aesthetical appearance.

The attribute was coded as dummy variable. The “NO” level was set to the status-quo reference level and equal to zero), whereas the β coefficients of the utility function relative to the "WALL REPAINTING " and "PLASTER, DOORS AND WINDOWS" levels were estimated.

The fourth attribute is related to the installation of a home automation system, i.e. *Domotic* system (DS) to control, via a user interface, lighting, rooms temperature, entertainment systems, home appliances and alarm systems. The installation of a DS generates a series several benefits. For example, thermal comfort and reduction in household energy improve as DSs allow to control the HAVC (Heating, Ventilation and Air Conditioning) system and consequently optimize room temperature. In addition, when DSs guarantee home access and alarm system control, home safety increases thus providing a benefit to homeowners and tenants gain a benefit. Nonetheless, it is widely acknowledged in literature that the larger benefit provided by the installation of a DS is due to the automation of specific home systems such as lighting, entertainment systems and appliances. Galassi and Madlener (2017) investigated the benefit produced by home automation systems, which control windows opening and closing and the heating system, and showed that respondents are willing to pay for the benefits provided. By providing real-time information on household energy consumption, home automation systems contribute to raise people, and specifically end-users, awareness. This technology it is not currently widespread in Italy, since it became available the market only recently and it is still very costly. Nonetheless, requests for fiscal incentive related to home automation increased in the period 2016-2018 from 661 to 2307 (ENEA, 2017; ENEA, 2019). We therefore included this attribute in the formulation of the utility function to investigate whether Italian people are willing to pay for this technology and in turn to provide input data to support policy makers in the design of optimal incentive policies. This attribute was coded as a dummy variable (i.e., install or not a DS). Consequently, the related attribute levels are 1 if the DS is installed and 0 otherwise.

The last selected attribute is the cost attribute. In the survey choice tasks, the cost attribute reflects the price for the other attribute levels presented. The estimated coefficient of the cost attribute (β_{cost}) is used to compute the marginal WTP (see EQ 2.3.2) for attributes (e.g., DS, A-EL). Glenk et al. (2019) investigated the relation between the selected cost attribute levels and the marginal WTP estimates. They found that the marginal WTP tends to increase as cost attribute levels and respondents’ income increase; the marginal WTP estimation is consequently sensitive to the last two factors. Therefore, in order to obtain robust WTP estimates, cost attribute levels must be properly identified. In literature, the cost attribute is commonly defined in two ways. Banfi et al. (2008), Kwak et al. (2010) and Syahid at al. (2016) defined the cost attribute levels in terms of a monthly payment, such as an installation of a bank loan, an increase in the monthly rent for a dwelling or a generic monthly cost, whereas Carroll et al. (2016), Galassi and Madlener (2017), Marmolejo-Duarte and Bravi (2017) defined the cost attribute levels as a monetary expenditure, which reflects investment costs. In the present study, cost attribute levels were defined in terms of a monthly bank loan instalment.

To identify cost attribute levels, we assumed that decision makers adopts rational behaviours (i.e., individuals make choices on the basis of their optimal benefit level). In other words, we can assume that, at the lower bound, investors undertake BERP investments if the monetary savings they produce payback investment costs. Whenever individuals perceive other benefits or co-benefits than energy costs saving, they will be willing to pay more. We identified 5 attribute levels.

To set the bounds of the cost attribute levels, we considered the estimated energy costs saving due to retrofitting and buildings construction costs, respectively. We *de facto* assumed that investors' WTP for BER is less than construction costs paid to build ex-novo the asset.

Firstly, according to experts and evidence from literature, energy costs savings ranges from 180 €/month for an A-EL retrofitted dwelling to 20 €/month for an F-EL retrofitted dwelling (*Table 4.1.5*). Secondly, we estimated construction costs according to the price list provided by DEI[1] in 2018 and adjusted to account for the construction cost growth rate index provided by the Italian National Institute of Statistics (ISTAT). The estimated current construction cost for a multi-store residential building similar to the status-quo condominium is equal to CC_{2019}=784.16 €/m^2.

As we made the decision to define the cost attribute in terms of a monthly instalment of a bank loan, in order to identify the maximum cost attribute level, we performed a market analysis of bank loans amounting to 50'000 Euros to be extinguished in 30 years and compared different bank loan offers in the Web. The results of this analysis are reported in Table 4.1.6 and interest rates refer to preferential bank loans for buildings retrofit.

LOAN AMOUNT	PAYBACK PERIOD	INTEREST RATE (TAEG)	INSTALMENT	COST LEVEL SELECTED
50'000 €	30 years	2.28% (minimum)	191.89 €	200 €/month
50'000 €	30 years	2.79% (maximum)	205.18 €	

Table 4.1.6 Best and worse bank € 50.0000 loan offers (October 2018 offers)

Based on the results of the market analysis on bank loans (*Table 4.1.6*), we assumed 200 €/month as the maximum cost attribute level. This amount is higher than the maximum monetary savings obtained for an A-EL (i.e., 180 €/month) and lower than building construction costs (i.e., 784.16 €/m^2). To identify the other four cost attribute levels we performed analogous market analysis on bank loans amounting respectively to 40.000 Euros, 30.000 Euros, 13.000 Euros and 4.000 Euros. The results are displayed in Table 4.1.7. and 4.1.8 respectively.

LOAN AMOUNT	PAYBACK PERIOD	INTEREST RATE (TAEG)	INSTALMENT	COST LEVEL SELECTED
40'000 €	30 years	2.37% (minimum)	145.36 €	150 €/month
40'000 €	30 years	2.89% (maximum)	154.95 €	
30'000 €	30 years	2.52% (minimum)	109.39 €	110

[1] The DEI price list estimates construction costs for different building typologies. For each building typology, the price estimation is obtained by comparison approaches over a sample of homogeneous buildings.

30’000 €	30 years	3.07% (maximum)	116.21 €	€/month

Table 4.1.7 Best and worst bank €30.000 and €40.000 loan offers (October 2018 offers)

It is worth note that we distinguished €13.000 and €4.000 loans from €30.000 and €40.000 loans, as investors may apply for BER preferential loans (i.e., lower interest rates) for amounts equal to 30’000 Euros or more.

CAPITAL	PAYBACK PERIOD	INTEREST RATE (TAEG)	INSTALMENT	COST LEVEL SELECTED
13’000 €	20 years	6.30%	95.39 €	90 €/month
4’000 €	8 years	8.20%	53.98 €	50 €/month

Table 4.1.8 Best and worst bank €13.000 and €4.000 loan offers (October 2018 offers)

The selected attributes and attribute levels were discussed in a focus group with a panel of experts from the *Choice Modelling Centre* at the University of Leeds, who validated the estimates. *Table 4.1.9* summarizes attributes and attribute levels selected to define BER utility function.

ATTRIBUTE	DESCRIPTION	ATTRIBUTE LEVELS	BENEFITS AND CO BENEFITS
Energy Label (EL)	Energy performance label of the building (dummy coded)	A, B, C, D, E, F	Energy savings, monetary savings, CO_2 emissions reduction
Indoor air quality (AQ)	Attribute related to the possibility to install a mechanical ventilation system to improve the indoor air quality (dummy coded)	“YES”, “NO”	Indoor air quality, energy savings
Aesthetic appearance of the building (AHB)	This attribute contains three levels to improve the aesthetic appearance of the building (dummy coded)	“NO”, “External wall repainting”-(AHB-L) and “Plaster, doors and windows”-(AHB-H)	Aesthetic appearance of the building
Domotic system (DS)	This attribute is related to the possibility to install a *Domotic* system (dummy coded)	“YES”, “NO”	Building automation, thermal comfort, safety
Cost (COST)	Monthly bank loan instalment	200, 150, 110, 90, 50 €/month	-

Table 4.1.9 Set of attributes and attribute levels selected

4.2 Experimental design

In this section, we described the Experimental design step (see Section 3.3 for theoretical aspects), which is the third step in SP studies according to Hanley et al. (2001).
The experimental design phase provides the survey choice tasks and is a crucial step in any CE exercise. During years, *Orthogonal* and *Full Factorial* designs were widely adopted to design SP studies, nonetheless in the last years researchers switched to a class of designs known as *Efficient* designs. These designs allow to reduce the sample size and ensure, at the same time, the statistical significance of β parameters estimates. By reducing the sample size, the costs to conduct the survey are minimized as well. The basic hypothesis to perform an *Efficient* design is to know *a priori* the estimates of the $\hat{\beta}$ parameters. To develop the *Efficient* design for the present SP study, we implemented the following iterative process:

1. We created a design D1 assuming that all the $\hat{\beta}$ parameters (i.e. the priors) are equal to zero and we performed the so called *Dz-Efficient* design (Rose and Blimer, 2009);
2. We used the design D1 to provide the choice tasks for the pilot survey;
3. We estimated the $\hat{\beta}$ parameters of the pilot survey which are used as $\hat{\beta}$ priors for the main survey;
4. We created a new efficient design D2;
5. We used the design D2 to provide the choice tasks for the main survey.

Once the main survey was conducted, we obtained the final $\hat{\beta}$ parameters estimates of the utility function. To generate the Efficient design, we implemented the software *NGENE*, with respect to design D1, 14 choice tasks were chosen. *Table 4.1.2* reports the coding of the attribute levels, where "AHB-L" and "AHB-H" stands for the attribute levels "external walls repainting" and "plaster, doors and windows" (see Section 4.1).

ATTRIBUTES	ATTRIBUTE LEVELS CODING					
Energy Label (EL)	A	B	C	D	E	F
	6	5	4	3	2	1
Indoor air quality (AQ)	"YES"			"NO"		
	1			0		
Aesthetic appearance of the building (AHB)	"NO"		"AHB-L"		"AHB-H"	
	0		1		2	
Domotic system (DS)	"YES"			"NO"		
	1			0		
Cost (COST)	200	150	110	90	50	

Table 4.2.1 Attributes and attribute levels coding in NGENE software (design D1)

Table 4.2.2 illustrates the results of the design D1 generated by *NGENE* software.

CHOICE TASKS	ALTERNATIVE	EL	AQ	AHB	DS	COST
1	ALTERNATIVE 1	3	0	2	1	150
	ALTERNATIVE 2	3	1	0	0	90
2	ALTERNATIVE 1	2	0	2	0	200
	ALTERNATIVE 2	5	1	0	1	50
3	ALTERNATIVE 1	2	0	0	1	110
	ALTERNATIVE 2	4	1	2	0	90
4	ALTERNATIVE 1	6	0	1	0	50
	ALTERNATIVE 2	1	1	1	1	200
5	ALTERNATIVE 1	3	1	1	0	200
	ALTERNATIVE 2	3	0	1	1	50
6	ALTERNATIVE 1	1	0	0	0	110
	ALTERNATIVE 2	6	1	2	1	110
7	ALTERNATIVE 1	5	0	0	0	90
	ALTERNATIVE 2	2	1	2	1	150
8	ALTERNATIVE 1	1	1	0	1	50
	ALTERNATIVE 2	5	0	1	0	150
9	ALTERNATIVE 1	4	1	0	1	150
	ALTERNATIVE 2	2	0	2	0	50
10	ALTERNATIVE 1	1	1	2	0	50
	ALTERNATIVE 2	6	0	0	1	200
11	ALTERNATIVE 1	6	1	1	0	150
	ALTERNATIVE 2	1	0	1	1	90
12	ALTERNATIVE 1	4	0	2	1	90
	ALTERNATIVE 2	2	1	0	0	110
13	ALTERNATIVE 1	5	1	1	1	90
	ALTERNATIVE 2	1	0	0	0	150
14	ALTERNATIVE 1	2	1	1	1	110
	ALTERNATIVE 2	4	0	1	0	110

Table 4.2.2 Attributes and attribute levels in Design D1

Design D1 is characterized by a *D-error* equal to 0.035944 (see Section 3.3 for detail); as the *D-error* resulted to be very low, the choice tasks obtained were used for the pilot survey. The pilot survey was conducted by administering a questionnaire to 42 respondents and the MNL model was estimated implementing the *Apollo* R-package tool. *Table 4.2.3* reports the pilot survey $\hat{\beta}$ priors estimates.

COEFFICIENTS	$\hat{\beta}$ PRIORS ESTIMATES
EL-A	1.1251
EL-B	0.3721
EL-C	0.3789
EL-D	0.3
EL-E	0.2
EL-F	0
AQ	0.2247
AHB-L	0.5
AHB-H	0.8627
DS	0.5152
COST	-0.0068

Table 4.2.3 Pilot survey β priors estimates

As mentioned before, the pilot survey $\hat{\beta}$ priors were used in the main survey *Efficient* design D2. To generate design D2, several combinations of different numbers of choice tasks and blocks were performed. The *blocking* is a methodology used in experimental designs and it consists in subdividing a design in a number of *N* sub-designs (defined as “blocks”). When a CE is characterized by a large number of attributes and attribute levels, a large number of choice tasks is provided and it might be arduous for respondents to face such a number of choice tasks. By *blocking* a design, each respondent faces a subset of choice tasks from the main design. *NGENE* software allows to manage the *blocking* process, by adopting specific algorithms and subdividing the main design in *N* blocks (sub-designs) in a proper way. *Table. 4.2.4* shows the new coding for the D2 design used to create the main survey choice tasks.

<table>
<tr><th>ATTRIBUTES</th><th colspan="30">ATTRIBUTE LEVELS CODING</th></tr>
<tr><td rowspan="2">Energy Label (EL)</td><td colspan="5">A</td><td colspan="5">B</td><td colspan="5">C</td><td colspan="5">D</td><td colspan="5">E</td><td colspan="5">F</td></tr>
<tr><td colspan="5">4</td><td colspan="5">3</td><td colspan="5">2</td><td colspan="5">1</td><td colspan="5">0</td><td colspan="5">5</td></tr>
<tr><td rowspan="2">Indoor air quality (AQ)</td><td colspan="15">“YES”</td><td colspan="15">“NO”</td></tr>
<tr><td colspan="15">1</td><td colspan="15">0</td></tr>
<tr><td rowspan="2">Aesthetic appearance of the building (AHB)</td><td colspan="10">“NO”</td><td colspan="10">“AHB-L”</td><td colspan="10">“AHB-H”</td></tr>
<tr><td colspan="10">2</td><td colspan="10">0</td><td colspan="10">1</td></tr>
<tr><td rowspan="2">Domotic system (DS)</td><td colspan="15">“YES”</td><td colspan="15">“NO”</td></tr>
<tr><td colspan="15">1</td><td colspan="15">0</td></tr>
<tr><td>Cost (COST)</td><td colspan="6">200</td><td colspan="6">150</td><td colspan="6">110</td><td colspan="6">90</td><td colspan="6">50</td></tr>
</table>

Table 4.2.4 Attributes and attribute levels coding in NGENE software - design D2

For attributes which are dummy coded, a β coefficient is estimated for the entire set of attribute levels. In *Table 4.2.4* attribute levels marked in red colour represents the reference levels of the dummy variables, whose related β coefficients were automatically set to 0. The *NGENE* software permits to introduce dummy variables in the model and it automatically process these variables during the design phase. *Table 4.2.5* reports different efficient designs trials performed to provide the main survey choice tasks.

D2_1	**D2_2**	**D2_3**	**D2_4**	**D2_5**
2 blocks	2 blocks	4 blocks	3 blocks	3 blocks
32 choice tasks	28 choice tasks	48 choice tasks	36 choice tasks	42 choice tasks
D error = 0.125955	D error = 0.144051	D error = 0.128688	D error = 0.111479	D error = 0.095543
S estimate = 66.858343	S estimate = 79.359495	S estimate = 72.958889	S estimate = 60.610806	S estimate = 50.369734

Table 4.2.5 D2 design trials for the main survey

We implemented Design D2_5 which is characterized by the lowest *D error*. The *S estimate* indicates the minimum number of respondents (sample size) necessary to reach the statistical significance of all the $\hat{\beta}$ coefficients estimates. The design is characterized by 3 blocks. As the minimum number of respondents is equal to the number of blocks multiplied by *S estimate,* the minimum sample size is equal to 150 respondents. In this CE, each respondent faced 14 choice tasks and 3 different versions of the design were administered in the main survey. *Table 4.2.6*, *Table 4.2.7* and *Table 4.2.8* illustrates respectively the three different versions administered in the main survey.

VERSION 1						
CHOICE TASKS	**ALTERNATIVE**	**EL**	**AQ**	**AHB**	**DS**	**COST**
1	ALTERNATIVE 1	5	1	1	0	50
	ALTERNATIVE 2	1	0	0	1	200
2	ALTERNATIVE 1	4	1	0	0	200
	ALTERNATIVE 2	5	0	1	1	50
3	ALTERNATIVE 1	0	0	1	1	150
	ALTERNATIVE 2	1	1	2	0	90
4	ALTERNATIVE 1	2	1	2	1	150
	ALTERNATIVE 2	3	0	0	0	90
5	ALTERNATIVE 1	5	0	2	1	150
	ALTERNATIVE 2	2	1	0	0	90
6	ALTERNATIVE 1	3	1	0	0	110
	ALTERNATIVE 2	4	0	2	1	90

7	ALTERNATIVE 1	1	0	2	0	90
	ALTERNATIVE 2	5	1	0	1	110
8	ALTERNATIVE 1	1	1	0	0	200
	ALTERNATIVE 2	0	0	2	1	50
9	ALTERNATIVE 1	1	0	2	0	50
	ALTERNATIVE 2	2	1	1	1	200
10	ALTERNATIVE 1	4	0	2	1	110
	ALTERNATIVE 2	2	1	0	0	110
11	ALTERNATIVE 1	3	1	1	1	200
	ALTERNATIVE 2	4	0	0	0	50
12	ALTERNATIVE 1	4	0	0	0	110
	ALTERNATIVE 2	0	1	2	1	110
13	ALTERNATIVE 1	2	0	0	1	50
	ALTERNATIVE 2	4	1	1	0	200
14	ALTERNATIVE 1	5	1	0	1	200
	ALTERNATIVE 2	2	0	2	0	50

Table 4.2.6 Main survey - Version 1

VERSION 2						
CHOICE TASKS	**ALTERNATIVE**	**EL**	**AQ**	**AHB**	**DS**	**COST**
1	ALTERNATIVE 1	2	0	1	0	150
	ALTERNATIVE 2	1	1	2	1	90
2	ALTERNATIVE 1	1	1	2	1	90
	ALTERNATIVE 2	3	0	0	0	150
3	ALTERNATIVE 1	3	1	2	1	90
	ALTERNATIVE 2	1	0	1	0	150
4	ALTERNATIVE 1	1	1	1	1	90
	ALTERNATIVE 2	4	0	0	0	110
5	ALTERNATIVE 1	0	1	1	0	110
	ALTERNATIVE 2	5	0	2	1	90
6	ALTERNATIVE 1	0	1	2	0	50
	ALTERNATIVE 2	2	0	1	1	200
7	ALTERNATIVE 1	4	0	2	0	90
	ALTERNATIVE 2	1	1	0	1	150
8	ALTERNATIVE 1	1	0	1	0	90

	ALTERNATIVE 2	2	1	2	1	150
9	ALTERNATIVE 1	4	1	2	1	200
	ALTERNATIVE 2	3	0	1	0	50
10	ALTERNATIVE 1	0	0	0	1	50
	ALTERNATIVE 2	4	1	1	0	200
11	ALTERNATIVE 1	0	0	1	0	90
	ALTERNATIVE 2	3	1	2	1	150
12	ALTERNATIVE 1	5	1	0	0	50
	ALTERNATIVE 2	3	0	2	1	200
13	ALTERNATIVE 1	3	0	2	1	50
	ALTERNATIVE 2	0	1	1	0	150
14	ALTERNATIVE 1	2	0	0	1	110
	ALTERNATIVE 2	5	1	1	0	110

Table 4.2.7 Main survey - Version 2

VERSION 3						
CHOICE TASKS	**ALTERNATIVE**	**EL**	**AQ**	**AHB**	**DS**	**COST**
1	ALTERNATIVE 1	1	1	0	1	90
	ALTERNATIVE 2	4	0	2	0	150
2	ALTERNATIVE 1	0	1	0	1	200
	ALTERNATIVE 2	1	0	1	0	50
3	ALTERNATIVE 1	3	0	1	1	150
	ALTERNATIVE 2	5	1	2	0	90
4	ALTERNATIVE 1	2	0	0	0	90
	ALTERNATIVE 2	3	1	1	1	150
5	ALTERNATIVE 1	5	0	1	1	200
	ALTERNATIVE 2	3	1	2	0	50
6	ALTERNATIVE 1	2	1	1	0	110
	ALTERNATIVE 2	4	0	0	1	110
7	ALTERNATIVE 1	3	0	1	0	150
	ALTERNATIVE 2	2	1	2	1	50
8	ALTERNATIVE 1	2	0	1	0	150
	ALTERNATIVE 2	0	1	0	1	90
9	ALTERNATIVE 1	4	1	1	1	200
	ALTERNATIVE 2	0	0	0	0	50

10	ALTERNATIVE 1	3	1	2	0	50
	ALTERNATIVE 2	0	0	0	1	200
11	ALTERNATIVE 1	0	0	2	1	150
	ALTERNATIVE 2	5	1	0	0	90
12	ALTERNATIVE 1	5	0	0	1	110
	ALTERNATIVE 2	0	1	1	0	110
13	ALTERNATIVE 1	5	1	2	0	50
	ALTERNATIVE 2	1	0	1	1	200
14	ALTERNATIVE 1	4	1	0	0	110
	ALTERNATIVE 2	5	0	1	1	110

Table 4.2.7 Main survey - Version 3

4.3 Focus group and pilot survey design

In this section, the design of the pilot survey and the main survey are presented. We firstly designed a pilot survey to obtain the β priors for the experimental design of the main survey (see Section 4.2). We identified a representative sample of Italian population recruited from cities in the North, Centre and South of Italy and the questionnaire was self-administrated using computer assisted web interviewing by a total of 218 respondents. The questionnaire (see APPENDIX I for detail) was structured into five main parts (*Figure 4.3.1*).

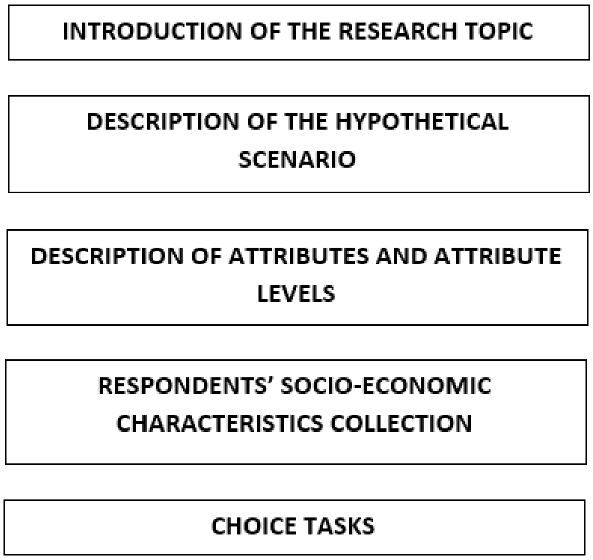

Figure 4.3.1 Survey format

In the first part, the research topic is introduced and relevant information on BER are given to respondents to provide common knowledge if necessary and motivate the research. In detail, the introduction to the survey provides: a) some information on the issue of buildings energy consumption in Italy; b) a synthesis on both European energy and climate targets and energy policies on BER; c) a description of potential implementable ERMs and of related; d) a presentation of the aim and motivation of the research.

In the second part of the survey, the building *status-quo* and the hypothetical retrofit scenarios are described. It is clarified to respondents that they are required to play the role of the homeowners of a 90 m^2 G-label apartment in a condominium and choose among different retrofit alternatives which varies in retrofit levels. The apartment is presented by means of pictures (*Figure 4.3.1*) and the technical characteristics of the building are described. The hypothetical status-quo apartment consists of two bedrooms, a bathroom, a kitchen, a living room and two balconies.

Figure 4.3.2 Survey hypothetical scenario

We specified that in the status quo the cooling system is not installed and the heating system consists in traditional radiators powered by a standard open chamber boiler characterized by low energy efficiency. The apartment has poor quality finishes and there is no thermal insulation of external walls, roof and ceiling. Energy consumption is described in terms of primary annual energy consumption, annual energy costs and rate of CO_2 emissions:

- Primary energy consumption > 160 kWh/m^2 year (G-EL)
- Annual energy costs equal to 2400 €/year
- CO_2 emissions > 2.7 tons/year

In the third part of the questionnaire, instructions to compile the survey are provided and the choice tasks are described. Attributes and attribute levels are explained and described in detail, as well as the benefits and co-benefits that each attribute involves. We devoted great attention to this section of the questionnaire as respondents have to correctly understand attributes and attribute levels and the effect of changes in attribute levels and in turn to perceive changes in BER benefits associated to each choice task.
The fourth part of the questionnaire included the usual questions about socio-demographics (family status, education, income, etc.).
Respondents engaged in a total of 14 such choice tasks, then moved on to a series of debriefing questions to assess the respondent's beliefs and information about energy efficiency and improvement, and to measure his or her energy literacy.
A sample choice card is displayed in *Figure 4.3.3*, where in the first column there is a synthetic description of the attributes and an image representing each attribute, whereas in the other two columns choice alternatives and related attribute levels are reported.

ATTRIBUTES		APARTMENT A	APARTMENT B
	Energy Label (% of annual energy savings and CO_2 emissions level)	Energy Label: **C** Monthly saving: **120 €/month** CO_2 emissions: **Low Level**	Energy Label: **D** Risparmio mensile: **100 €/month** Emisioni CO_2: **Medium Level**
	Installing or not a ventilation system to improve air quality	**YES**	**NO**
	Quality of finishes	**PLASTER, DOOR AN WINDOWS**	**WALL REPAINTING**
	Domotic system	**YES**	**NO**
	Monthly cost	**200 €/month**	**100 €/month**

Figure 4.3.3 Example of choice card used in the survey

The main survey was designed starting from the pilot survey, which was a self-administrated questionnaire sent via e-mail to 41 respondents and provided important feedback from respondents to improve the main survey. The pilot survey questionnaire included the following debriefing questions on the efficacy of the questionnaire, to assess if the hypothetical scenario is realistic, if the choice tasks are clearly described and investigate and whether respondents made choices considering all the attributes in each choice tasks.

Q1: The hypothetical scenarios here presented were realistic:

Not agree Fully agree

1 2 3 4 5

Q2: I was able to fully understand the choice tasks:

Not agree Fully agree

1 2 3 4 5

Q3: I was able to make choices as in a real world situation:

Not agree Fully agree

1 2 3 4 5

Q4: When evaluating buildings energy retrofit, I took into account all attributes:

Not agree Fully agree

1 2 3 4 5

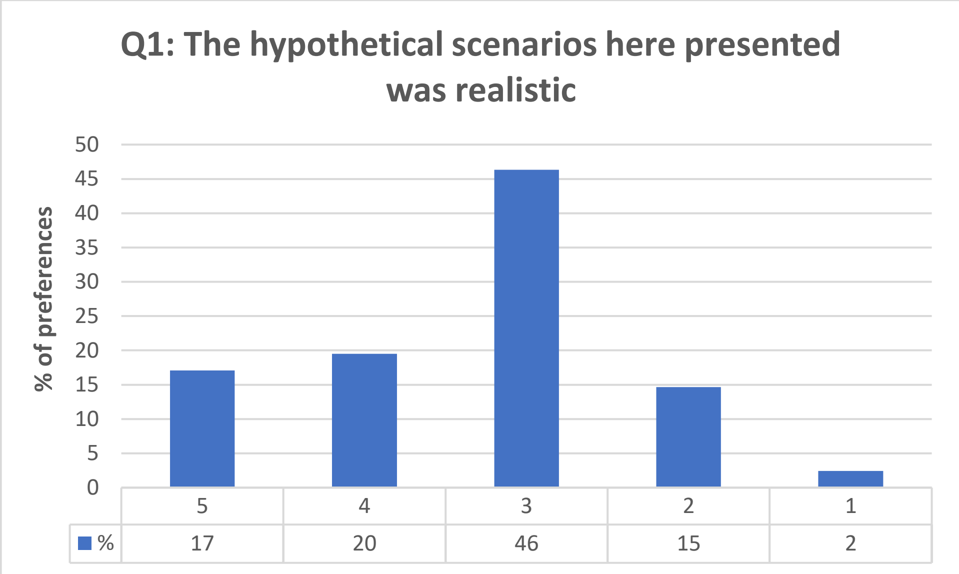

Figure 4.3.4 Stated preferences statistics on question Q1

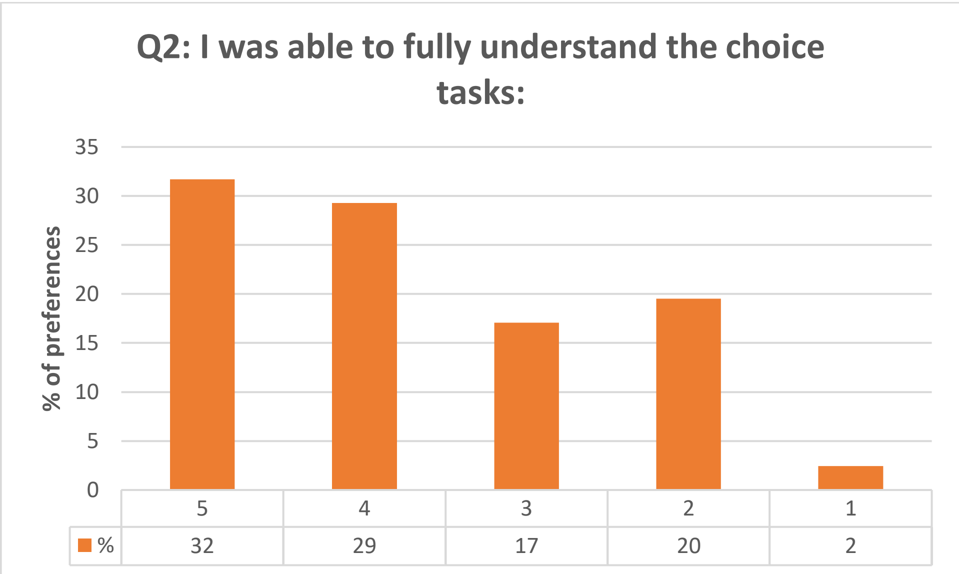

Figure 4.3.5 Stated preferences statistics on question Q2

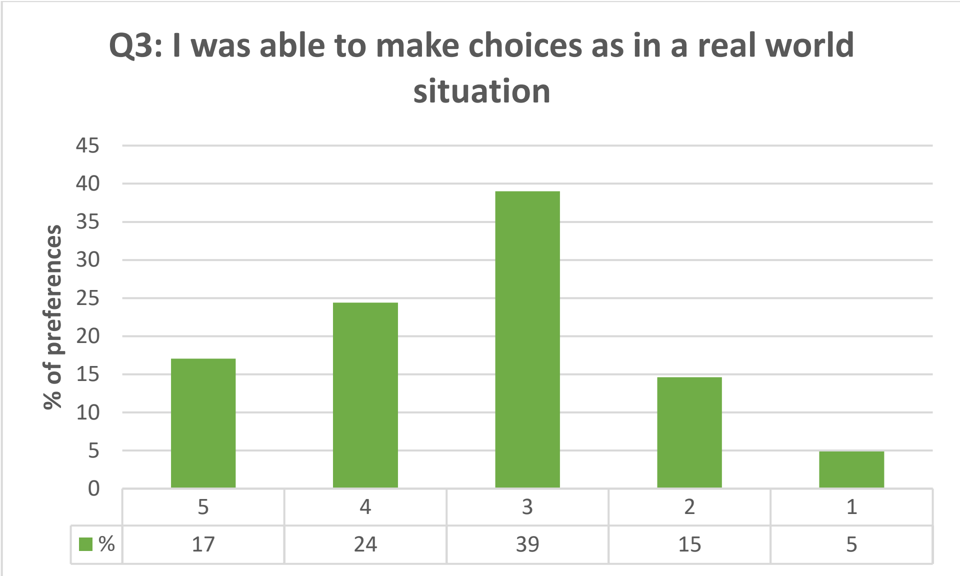

Figure 4.3.6 Stated preferences statistics on question Q3

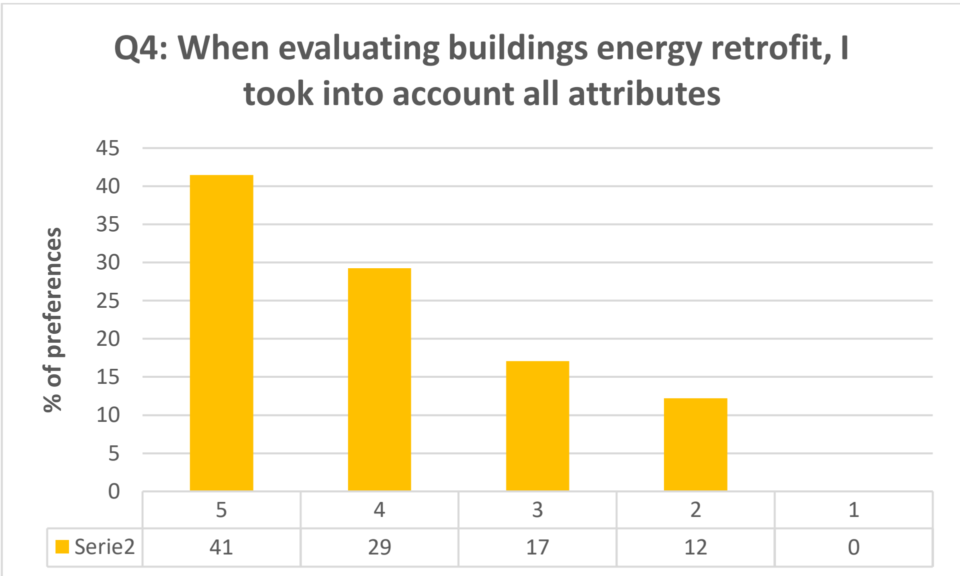

Figure 4.3.7 Stated preferences statistics on question Q4

Statistics on responses to questions Q1 and Q3 (*Figure 4.3.4* and *Figure 4.3.6*) provided useful insights to improve hypothetical scenarios description of the in the main survey. In a CE it is a key issue that hypothetical scenarios and choice alternatives are described and presented as their best to simulate a real world situation.

According to the results of statistics on responses to question Q2 (*Figure 4.3.5*), 61% of respondents by voting scores 5 or 4 declared that choice tasks were fully understandable, whereas only 22% of respondents by voting score 1 or 2 declared were not able to fully understand them. Statics on responses to question Q4 provided a key insight on the selection of attributes: 70% of respondents by voting scores 5 or 4 declared that they considered all attributes in their choices. As no SP studies on BER were performed in Italy previously, we were not sure whether Italian population may be interested in all the attributes selected to define utility function. The most important step in an SP study is in fact the definition of the utility function as it drives respondents' choices. As utility functions depend on attributes, if some attributes are not valued by respondents, these functions may be not correct or realistic. With respect to the EL attribute, it is not possible to insert in the utility function separate attributes for buildings energy performances, such as EL, energy savings (ES), monetary savings (MS) and CO_2 emissions reduction (CORED) as they are not independent (see Section 4.1). EL certifications account for specific levels of energy savings, which in turn produce a certain amount of monetary savings and CO_2 emissions and therefore they were all reported as a unique attribute. In order to investigate whether respondents when making choices preferred some factors more than others, we implemented in the pilot survey the *best-worst scaling* (BWS) analysis (Flynn et al., 2007; Louviere et al., 2015) and analysed the relative importance of EL, ES, MS and CORED attributes respectively. The importance scale was obtained by requiring respondents to make discriminating choices for the best and the worst factors from each EL attribute level in order to elicit preference patterns. Sample questions are listed below.

1) With respect to ***A-EL*** *evaluate which factor you consider more important or less important:*

MOST IMPORTANT	ATTRIBUTE CHARACTERISTICS	LEAST IMPORTANT
	Energy Label: A	
	Energy savings: 1088 kWh/month	
	Monetary savings: 180 €/month	
	CO_2 emissions: 23 Kg/month	

2) With respect to ***B-EL*** *evaluate which factor you consider more important or less important:*

MOST IMPORTANT	ATTRIBUTE CHARACTERISTICS	LEAST IMPORTANT
	Energy Label: B	
	Energy savings: 896 kWh/month	
	Monetary savings: 150 €/month	
	CO_2 emissions: 61 Kg/month	

3) With respect to ***C-EL*** *evaluate which factor you consider more important or less important:*

MOST IMPORTANT	ATTRIBUTE CHARACTERISTICS	LEAST IMPORTANT
	Energy Label: C	
	Energy savings: 746 kWh/month	
	Monetary savings: 120 €/month	
	CO_2 emissions: 91 Kg/month	

4) With respect to ***D-EL*** *evaluate which factor you consider more important or less important:*

MOST IMPORTANT	ATTRIBUTE CHARACTERISTICS	LEAST IMPORTANT
	Energy Label: D	
	Energy savings: 596 kWh/month	
	Monetary savings: 100 €/month	
	CO_2 emissions: 121 Kg/month	

*5) With respect to **E-EL** evaluate which factor you consider more important or less important:*

MOST IMPORTANT	ATTRIBUTE CHARACTERISTICS	LEAST IMPORTANT
	Energy Label: E	
	Energy savings: 409 kWh/month	
	Monetary savings: 60 €/month	
	CO_2 emissions: 158 Kg/month	

*6) With respect to **F-EL** evaluate which factor you consider more important or less important:*

MOST IMPORTANT	ATTRIBUTE CHARACTERISTICS	LEAST IMPORTANT
	Energy Label: F	
	Energy savings: 146 kWh/month	
	Monetary savings: 20 €/month	
	CO_2 emissions: 211 Kg/month	

The best-minus-worst (B-W) scores can be obtained by subtracting the total count of the factor being chosen as the worst from the total count of the same factor being chosen as the best across all respondents. *Figure 4.3.8* displays the results of the pilot survey BWS.

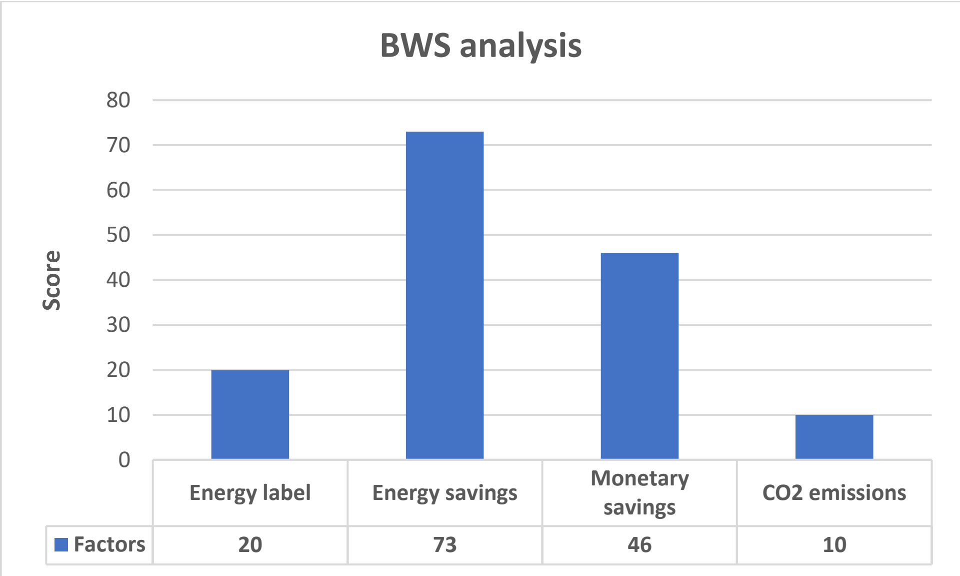

Figure 4.3.8 BWS analysis results

The preferential factor that mostly influenced respondent choices is related to energy savings, whereas monetary savings resulted the second important factor, EL is ranked as third and CO_2 emissions is the less important (*Figure 4.3.8*). According to these preliminary results, people are not very interested in buildings EL and CO_2 emissions reduction, although emission reduction is a key European target on mitigation of climate change effects. In the near future, costs to reduce CO_2 emissions will affect people who are not yet fully aware of this issue. In this respect, Governments might implement information campaigns to increase people awareness on the crucial role of CO_2 emissions reduction in mitigation of climate change effects.

4.4 Model estimation and results

We estimated model parameters using the *Apollo* R-package tool developed by the *Choice Modelling Centre* at the University of Leeds (UK). *Table 4.4.1* recalls attributes and attribute levels which describe alternatives (see Section 4.1 for detail).

ATTRIBUTE	DESCRIPTION	ATTRIBUTE LEVELS	BENEFITS AND CO BENEFITS
Energy Label (EL)	Energy performance label of the building (dummy coded)	A, B, C, D, E, F	Energy savings, monetary savings, CO_2 emissions reduction
Indoor air quality (AQ)	Attribute related to the possibility to install a mechanical ventilation system to improve the indoor air quality (dummy coded)	"YES", "NO"	Indoor air quality, energy savings
Aesthetic appearance of the building (AHB)	This attribute contains three levels to improve the aesthetic appearance of the building (dummy coded)	"NO", "External wall repainting"-(AHB-L) and "Plaster, doors and windows"-(AHB-H)	Aesthetic appearance of the building
Domotic system (DS)	This attribute is related to the possibility to install a *Domotic* system (dummy coded)	"YES", "NO"	Building automation, thermal comfort, safety
Cost (COST)	Monthly bank loan instalment	200, 150, 110, 90, 50 €/month	-

Table 4.4.1 Attributes and attribute levels selected

To implement the *Apollo* R-package tool, we specified the utility function by dummy coding attributes EL, AQ, AHB and DS:

$$V = const + \beta_{EL-A}d_{EL-A} + \beta_{EL-B}d_{EL-B} + \beta_{EL-C}d_{EL-C} + \beta_{EL-D}d_{EL-D} + \beta_{EL-E}d_{EL-E} + $$
$$+\beta_{AQ}d_{AQ} + \beta_{AHB-L}d_{AHB-L} + \beta_{AHB-H}d_{AHB-H} + \beta_{DS}d_{DS} + \beta_{cost}X_{cost} \quad \text{(EQ 4.4.1)}$$

where $\beta_{EL-A}, \beta_{EL-B}, \beta_{EL-C}, \beta_{EL-D}, \beta_{EL-E}, \beta_{AQ}, \beta_{AHB-L}, \beta_{AHB-H}, \beta_{DS}, \beta_{cost}$ are the coefficients of the dummy coded attribute levels; $d_{EL-A}, d_{EL-B}, d_{EL-C}, d_{EL-D}, d_{EL-E}, d_{AQ}, d_{AHB-L}, d_{AHB-H}$ and d_{DS} are the attribute levels of dummy variables; β_{cost} is the cost attribute coefficient and X_{cost} is the cost attribute.

In each choice question, respondents were asked to choose between two alternatives. in RUMs only differences in utility matter (see Section 3.2 for detail), in this CE we set the constant term ($const$) in the utility function relative to alternative 1. In *Table 4.4.1*, attribute levels marked in red colour are the reference levels of dummy variables. Descriptive statistics of the 218 respondents are reported in *Table 4.4.2.*

VARIABLE		%
GENDER	M	50.00
	F	50.00
AGE	< 20	0.00
	20 -29	16.51
	30 - 39	17.89
	40 - 49	24.77
	50 - 60	22.02
	> 60	18.81
EDUCATIONAL LEVEL	Middle school or lower	11.47
	High school	58.72
	Master Degree	26.61
	Master/PhD	3.21
INCOME	< 5000 €	9.17
	5000 € - 10000€	12.39
	10000 € - 20000€	24.31
	20000 € - 30000€	30.28
	30000 € - 50000€	18.81
	50000 € - 100000€	4.59
	> 100000 €	0.46

Table 4.4.2 Descriptive statistics of the respondents (percent)

As showed in *Table 4.4.2*, the sample is even in gender, and varies in terms of respondent age, educational attainment and income. Nearly 60% of the sample has completed high school and about one third of the respondents have a college or post-graduate degree. 30% of the respondents have an annual income ranging between 20000 – 30000 Euros and about 24% have an annual income ranging between 10000 – 20000 Euros, which mirrors the share in the general population of the country (ISTAT, 2018). We fit the MNL model and report the results in *Table 4.4.3*.

	Coefficients	Standard error	t-value
β_{EL-E}	0.1749***	0.0846	2.07
β_{EL-D}	0.4168****	0.0858	4.86
β_{EL-C}	0.6952****	0.0885	7.86
β_{EL-B}	0.818****	0.0892	9.17
β_{EL-A}	1.0818****	0.1066	10.15
β_{AQ}	0.0271	0.0396	0.68
β_{AHB-L}	-0.0261	0.0593	-0.44
β_{AHB-H}	0.1358***	0.0675	2.01
β_{DS}	0.0703*	0.0458	1.54
β_{cost}	-0.005****	0.0005	-9.66
$cost$	0.0936***	0.0378	2.47

N◦ of Obs. 3852 — **** $p < \alpha = 0.01$
N◦ of Resp. 218 — *** $p < \alpha = 0.05$
LL(0) : -2115.485 — ** $p < \alpha = 0.1$
LL(C) : -2112.543 — * $p < \alpha = 0.2$
LL(final) : -1987.653
Estimated parameters: 11
Rho-sq (0) : 0.06
Adj. rho-sq (0): 0.06

Rho-sq (C)   : 0.06 Adj. rho-sq (C): 0.05 AIC 3997.31 BIC 4063.56

Table 4.4.3 MLN model estimates

From direct inspection of *Table 4.4.3*, it emerges that coefficient A-EL is characterized by the highest *t-value*, and the other EL coefficients are statistically significant as well, indicating that that Italian population is concerned with in building energy efficiency.
The AHB-H coefficient is statistically significant (*t-value* equal to 2.01), whereas the AHB-L coefficient is not (*t-value* equal to -0.44). The AQ coefficient is not statistically significant as well (*t-value* equal to 0.68). These results are not affected by experimental design issues, they reveal that Italian population is not interested in the installation of mechanical ventilation systems and in small improvements in buildings aesthetical appearance.
The DS coefficient (*t-value* equal to 1.54) can be considered statistically significant if we accept α<0.2. Nonetheless it reflects that in Italy there is still little attention paid to benefits related to home automation.
Table 4.4.4 displays summary of marginal WTP figures obtained by solving EQ 2.3.2.

	mWTP [€/month]
β_{EL-E}	34.98
β_{EL-D}	83.36
β_{EL-C}	139.04
β_{EL-B}	163.6
β_{EL-A}	216.36
β_{AQ}	-
β_{AHB-L}	-
β_{AHB-H}	27.16
β_{DS}	14.06 (if $\alpha < 0.2$)
β_{cost}	-
$cost$	-

Table 4.4.4 Summary of Marginal WTP figures

Figure 4.4.1 plots the marginal WTP for energy label.

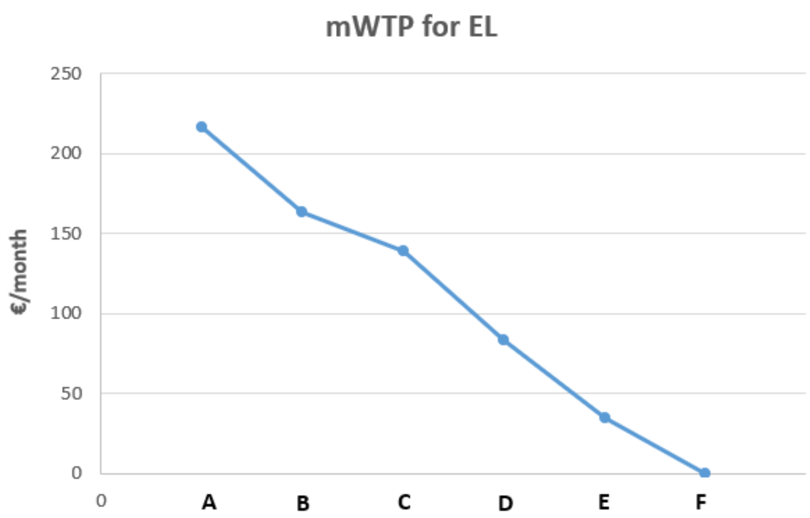

Figure 4.4.1 Marginal WTP of Els

Our findings show that Italian population is are willing to pay higher prices for more energy efficient assets (i.e., for A, B and C energy performance labels) and the demand curve exhibits a decreasing linear form. The marginal AHB-H WTP of the F-EL is equal to zero as it was set as the reference level for dummy coded ELs, and the marginal WTPs for the other was estimated in incremental terms (Figure 4.4.1).
Our results provides interesting policy implications and support Governments in the design of optimal incentive policies. Governments can in fact introduce a wide range of policy instruments to boost investments in BERPs such as financial and fiscal instruments (e.g. tax rebates, subsidies, and preferential loans schemes), regulatory instruments (e.g., performance and technology standards), economic and market-based instruments, support information and voluntary actions (D'Alpaos and Bragolusi, 2018).
In this respect, it is worth note that the LCC method weighs more economic performances rather than energy performances. In Italy, a minimum target for buildings energy efficiency with respect to the cost-optimal BERP has not been provided by Laws and regulations. Our estimates on the WTP for different levels of energy efficiency indicate that energy efficiency targets should be set in the guidelines for BERPs economic valuation. Regulatory instruments should be provided in order to reach the 2030 medium-term goals and the 2050 long-term goals on decarbonisation.
More recently, EU Directive 2018/844/UE promotes investments to improve buildings indoor air quality. In this respect we found striking results from this CE exercise according to which Italian population is not willing to pay for the installation of mechanical ventilation systems and seems to slightly care about indoor air quality and thermal comfort.

This is contrast with evidence from Malaysia and other European Countries, where this technology is widely adopted and homeowners value more indoor air quality and thermal comfort and appreciate benefits provided by mechanical ventilation systems in terms of energy consumption reduction (Banfi et al., 2008; Syahid et al., 2016; Galassi and Madlener, 2017).

To comply with the Directive 2018/844/UE requirements, and encourage investments the Italian Government should design proper incentive policies (e.g., tax rebates or subsidies) and promote information campaigns to increase social awareness on the benefits generated by mechanical ventilation systems installation.
The same considerations apply for home automation systems as, according to our results, Italian population is not willing to invest to install DSs.
Based on the Italian Annual Energy Efficiency Report by the Italian Energy Agency (ENEA, 2018), there is evidence that during the period 2014-2017, 56.1% of incentive requests for investments in BER were related to the replacement of doors and windows. Nonetheless, from this CE exercise, it emerges that the marginal WTP of doors and windows replacement is quite low (27.16 €/month). This seems to prove that the national incentive policy was well designed with specific reference to this ERM. In addition, no *free-rider* behaviour is observed, as it is likely that in the absence of such incentives individuals would not have invested. The replacement of doors and windows involves not only energy savings but it also contributes to improve the aesthetical appearance of the building. Italian homeowners are probably more concerned with improvements in buildings aesthetical appearance rather than energy savings. This hypothesis is supported by the fact that only 7.4% of the requests for fiscal incentives in

Italy referred to investments thermal insulation of building envelope (ENEA, 2018) and this number of requests is lower than those for doors and windows replacement, although thermal insulation of walls, ceiling and roof can produce higher energy savings and in turn energy cost savings.

CONCLUSIONS

The aim of this research was to provide innovative valuation approaches of BERPs. We analysed the cost-effectiveness of BERPs taking into account the trade-offs between costs and direct, indirect, tangible and intangible benefits of retrofit solutions. In detail, the research focused on the estimation of the monetary value of benefits and co-benefits related to BER which may boost investment in BERPs. In the end, we provided interesting policy implications to support the Italian Governments in the design of optimal incentive policies.

A literature review on BER valuation approaches was firstly provided. Several valuation methodologies were analysed and the LCC method resulted as the most investigated and applied valuation approach. Nonetheless, some concerns on the implementation of the LCC method emerged: this methodology, based on the cost-minimization principle, weighs more BERPs economic performances rather than energy efficiency performances and it favours the objective of policy makers and Governments to minimize costs and public expenditure related to financial and fiscal incentives. By purely implementing the LCC method, it might not be possible to reach the 2050 European long-term targets, which requires the building sector to reach higher energy-efficiency levels, by adopting more energy-efficient BERPs. To reach 2050 European long-term targets, high energy-efficient retrofit measures, which contribute to reduce energy consumption and CO_2 emissions, must be adopted. These measures indeed might not be the least-cost. According to our literature investors may be willing to pay more for sustainable solutions due to intrinsic value, environmental awareness and warm glow; stakeholders' preferences may play a crucial role in investments effective implementation.

BER provides de facto a wide range of benefits and co-benefits in addition to significant energy savings. To address this issue, we firstly proposed a valuation approach based on the comparisons of the net benefits generated by the set of alternative BERPs with those generated by the non-retrofitted building in order to define the optimal BERP taking into account all the costs and relevant benefits provided by BER and the novel combining the LCC method and the cost-benefit analysis. We applied the above valuation approach to a case study and evaluated investments in alternative ERMs in public housing. The sensitivity analysis showed that the results were more robust compared to those provided by the implementation of LCC, NPV and Araujo et al (2016) approaches. We found that market price premiums for high energy efficient assets (e.g., A and B-label assets) contributed significantly to pay-back investment costs and it might play a key role in boosting investments in BERPs. Secondly, we performed a CE exercise following the protocol provided by Hanley et al. (2001), to fill the existing gap in literature and estimate the WTP for BER and determine its market demand in the Italian context. We then identified an utility function and in our CE we described alternative ERMs by 5 attributes: a)energy performance label of the building (EL); b) indoor air quality (AQ); c) aesthetic appearance of the building in terms of external wall repainting (AHB-L) and plaster, doors and windows replacement (AHB-H); d) installation of home automation systems (DS); and a cost attribute (IC). In the experimental design phase, we implemented a D-efficient design and we firstly conducted a pilot survey to identify the priors for the experimental design of the main survey. Finally, we identified a representative sample of Italian population recruited from cities in the North, Centre and South of Italy and we administered the questionnaire using computer assisted web interviewing to a total of 218 respondents. We then estimated the MNL model parameters using the *Apollo* R-package tool. Our results show that Italian population is concerned with BER: homeowners are willing to pay higher prices for more energy efficient assets and the related demand curve exhibits a decreasing linear form. Our results reveal that Italian population is not willing to pay for the installation of mechanical ventilation systems and seems not to care about indoor air quality. In addition, Italian homeowners are not willing to invest in home automation systems, although home automation can contribute to the improvement of indoor thermal comfort and guarantee remote control of home devices and appliances as well as home functions. To comply with EU Directive 2018/844/EU requirements and encourage investments, on the basis of our estimates, the Italian Government should design target-specific incentive policies (e.g., tax rebates or subsidies) and promote information campaigns to increase social awareness on the benefits generated by installation of mechanical ventilation and home automation systems. It is worth mentioning that, according to our findings, it emerged that the marginal WTP of doors and windows replacement is quite low. The annual report on energy efficiency provided by the Italian National Energy Agency in 2017 reports that, during the period 2014-2017, the higher percentage of tax rebates requests on BER were related to the replacement of doors and windows. This seems to prove that the current national incentive policy was well designed with specific reference to this specific ERM and no free-rider behaviour was observed. By providing estimates of WTPs for energy performance labels, indoor air quality, aesthetic appearance of the building and installation of home automation systems, we contribute to the improvement of BER economic valuation and our results can support policy makers in the optimal design of incentive policy to boost investments in BER. Optimal design of policy incentives to boost investments in the building and transport sectors, cannot prescind from a proper valuation of monetary benefits produced by these investments and the extent to which these benefits are perceived and gained by homeowners. Our estimates can be useful, on the one hand, to verify whether or not current incentives in Italy are optimally designed and are cost-effective; on the other hand, to test the cost-effectiveness in promoting buildings energy retrofit of innovative regulatory instruments. In detail, with respect to the recent EU Directive 844/2018 which promotes long-term renovation strategy to support the renovation of Member States building stocks into highly energy efficient and decarbonised ones by 2050, our findings suggest that a minimum target for buildings energy efficiency with respect to the cost-optimal BERP should be set in the guidelines for BERPs economic valuation and regulatory instruments should be provided to push investment in higher energy-efficiency BERPs.

APPENDIX I: Survey

INTRODUCTION

Il patrimonio immobiliare Italiano è il più vecchio d'Europa e gli edifici sono responsabili della quota principale del consumo di energia primaria (33%). La riqualificazione energetica del patrimonio immobiliare esistente ha il più grande potenziale al fine del raggiungimento degli obiettivi fissati dall'Unione Europea sulla riduzione del consumo energetico complessivo, la riduzione delle emissioni di gas serra e l'aumento della produzione energetica utilizzando energie rinnovabili (obiettivi 2030 *2030 "Quadro per il Clima e l'Energia"* e 2050 "*Impatto climatico zero*").

L'efficienza energetica degli edifici può essere migliorata attraverso l'installazione di diverse misure di riqualificazione che variano da quelle volte alla riduzione del consumo energetico a quelle che prevedono l'adozione di tecnologie a basse emissioni di carbonio. Tra le più importanti vi sono:

- la realizzazione di un isolamento termico di pareti, solai e tetti (cappotto termico);
- l'installazione di serramenti (es. porte e finestre ad alto grado di isolamento termico);
- l'installazione di pannelli solari e fotovoltaici per produrre elettricità e acqua calda sanitaria;
- l'installazione di sistemi di ventilazione meccanica controllata;
- l'installazione di sistemi di riscaldamento e raffreddamento ad alta efficienza.

La riqualificazione energetica degli edifici garantisce: a) **risparmi sui costi energetici** che negli anni possono ripagare in parte o totalmente i costi iniziali sostenuti per la realizzazione degli interventi; b) un miglioramento de**l comfort termico** e della **qualità dell'aria** percepiti all'interno dell'edificio; c) un miglioramento della **qualità** e dell'**aspetto estetico**. Attraverso la realizzazione degli interventi di riqualificazione è possibile **mantenere il valore di mercato dell'immobile** nel corso degli anni (**Entro il 31 dicembre 2020 tutti i nuovi edifici dovranno essere ad "Energia Quasi Zero "**).

Lo scopo di questo sondaggio è stimare la disponibilità a pagare degli Italiani per gli interventi di riqualificazione energetica degli edifici, considerati i benefici da essi generati.

COME CONDURRE L'INDAGINE, SCENARIO DI RIFERIMENTO

Immagina di essere proprietario e di vivere in un appartamento di medie dimensioni (90 m^2), che si compone di due camere da letto, un bagno, una cucina, un soggiorno e due poggioli:

Figura 1 Pianta, viste interna ed esterna dell'ipotetico appartamento

L'appartamento **è privo di impianto di climatizzazione estiva**. Per quanto riguarda l'impianto di riscaldamento, sono presenti i radiatori tradizionali alimentati da una **caldaia a camera aperta standard** caratterizzata da una **bassa efficienza energetica**. L'appartamento è caratterizzato dall'avere la **classe energetica G** (che è la più bassa, nel seguito sarà spiegato nel dettaglio cosa si intende per classe energetica qualora non lo si sappia). Il **costo energetico annuo** che allo stato attuale si deve sostenere per il riscaldamento e la produzione di acqua calda sanitaria è pari a **2400 €**. L'appartamento genera un **alto livello di emissioni di CO_2** (Anidride Carbonica) che risulta essere **maggiore di 2.7 tonnellate/anno**.
L'appartamento ha **finiture di scarsa qualità** e gli **intonaci sono fessurati**. **Non è presente alcun tipo di isolamento termico** delle pareti e del tetto (vedi Figura 1).

Per partecipare al sondaggio, **immagina di intraprendere** degli interventi di miglioramento sia dal punto di vista estetico che dal punto di vista energetico (riqualificazione energetica) dell'appartamento in questione. Per ogni **CASO DI SCELTA** che ti verrà proposto (per un totale di 14) dovrai scegliere quale tra le due possibili alternative (**APPARTAMENTO A** o **APPARTAMENTO B**) preferisci. Ogni alternativa è caratterizzata da diversi ipotetici livelli e costi (esempio di un **CASO DI SCELTA** a pagina successiva) di riqualificazione.

Alternative di scelta

CASO DI SCELTA 1:

ATTRIBUTI	APPARTAMENTO A	APPARTAMENTO B
Classe energetica dell'edificio, risparmi mensili e livello di emission di CO_2:	Classe Energetica: **D** Risp. energetico: **596 kWh/mese** Risp. monetario: **100 €/mese** Emisioni CO_2: **121 Kg/mese**	Classe Energetica: **D** Risp. energetico: **596 kWh/mese** Risp. monetario: **100 €/mese** Emisioni CO_2: **121 Kg/mese**
Installazione Sistema di Ventilazione Meccanica per miglioramento qualità dell'aria interna:	NO	SI
Livello di qualità delle finiture	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO
Installazione sistema domotico	SI	NO
Costo mensile:	150 €/mese	90 €/mese

Attributi che caratterizzano l'appartamento

Livelli caratteristici di ogni attributo

DESCRIZIONE ATTRIBUTI

Prima di compilare il questionario **leggi attentamente** la descrizione **di ogni attributo** relativo ai diversi **CASI DI SCELTA,** che identificano differenti livelli di ammodernamento e comfort dell'ipotetico appartamento oggetto di interventi di riqualificazione energetica:

ATTRIBUTO 1: Classe Energetica

La **Classe Energetica** è utilizzata per classificare la prestazione energetica di un edificio in funzione del consumo energetico che lo caratterizza. La classe energetica dipende dalle caratteristiche strutturali e fisiche dell'edificio, nonché dalla tipologia degli impianti installati per il riscaldamento (inverno), il raffrescamento (estate), la produzione di acqua calda sanitaria e il per il consumo di energia elettrica in generale. La suddivisione in classi avviene sulla base di numeri e lettere in riferimento ad una **scala** che classifica i consumi in ordine crescente, a partire **dalla classe G fino alla A4**, per un totale di 10 classi. L'unità di misura è indicata con il simbolo *EP*. Nello specifico *EP* misura il consumo di energia prodotta da fonti non rinnovabili:

CLASSE ENERGETICA	RISPARMIO MEDIO DI OGNI CLASSE IN TERMINI DI CONSUMO ENERGETICO, EMISSIONI E COSTI ENERGEICI RISPETTO ALLA CLASSE ENERGETICA G PIÙ BASSA
A	90%
B	75%
C	60%
D	50%
E	30%
F	10%

Tabella delle Classi Energetiche

Nel questionario ci sono **sei** possibili livelli di efficienza energetica che potrebbero essere raggiunti, **dalla classe A** (che è la classe A1) **alla classe F**: l'ipotesi di base è che l'appartamento sia inizialmente in classe energetica **G** (la più bassa). Per **ogni alternativa** (**APPARTAMENTO A** o **APPARTAMENTO B**) vengono identificati la **Classe Energetica** che **potrebbe essere raggiunta** attraverso l'installazione di misure di riqualificazione energetica, il **risparmio energetico medio mensile in kilowattora e il risparmio economico medio mensile in euro** che è possibile ottenere grazie agli interventi di riqualificazione energetica, ed infine il **livello di emissione di CO_2 medio mensile** espresso in chilogrammi.

 **<u>ATTRIBUTO 2</u>: Installazione Sistema di Ventilazione Meccanica per il miglioramento della qualità dell'aria interna**

L'impianto di *Ventilazione Meccanica Controllata* permette di avere un ricambio di aria in casa e consente, inoltre, di recuperare dall'aria il calore che viene espulso. Questo sistema funziona in maniera continuativa e sostituisce l'azione di apertura manuale delle finestre per il ricambio quotidiano dell'aria. Esso comporta molti benefici. Si avrà la sensazione di respirare un'aria più "pulita" nell'ambiente interno. Attraverso la filtrazione, il riciclo e il controllo dell'umidità dell'aria, consente di evitare la formazione di eventuali muffe, spore, anidride carbonica e consente di ridurre la presenza di composti organici volatili. Tale impianto, inoltre, consente di filtrare pollini, polvere, spore e altre sostanze dannose provenienti dall'ambiente esterno; consente di evitare la formazione di fastidiose correnti d'aria, che potrebbero nascere con il ricambio manuale dell'aria, attraverso l'apertura di porte e finestre. L'impianto di ventilazione meccanica controllata permette inoltre di evitare gli sprechi energetici dovuti alle dispersioni termiche causate dall'apertura delle finestre quando, tra ambiente interno ed esterno, vi è una significativa differenza di temperatura (estate e inverno). Il sistema è caratterizzato da un'alta efficienza energetica e da consumi elettrici contenuti. Questo attributo presente due livelli: "**SÌ**" e "**NO**" a seconda che l'impianto sia o meno presente.

 **<u>ATTRIBUTO 3</u>: Qualità delle finiture**

Tale attributo riguarda il possibile miglioramento dell'aspetto estetico dell'edificio. Sono presenti tre livelli:

- **"NO"** se non è previsto alcun miglioramento estetico dell'edificio;
- **"RITINTEGGIATURA MURI"** se è prevista la ritinteggiatura dei muri esterni;

- **"RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI"** se sono previsti il rifacimento dell'intonaco esterno dell'edificio e la sostituzione degli infissi con nuovi infissi ad alto isolamento termico:

<u>ATTRIBUTO 4</u>: Installazione impianto domotico

L'**impianto domotico per uso abitativo** è un sistema strutturale e funzionale che consente l'impiego di tecnologie e dispositivi tramite i quali l'utente attiva e gestisce, anche a distanza, l'automazione degli impianti di casa. Tra le principali funzioni vi è la possibilità di gestire la regolazione delle luci in funzione della presenza delle persone nell'ambiente. L'impianto domotico consente inoltre di: regolare la temperatura in ogni parte dell'abitazione garantendo un **miglior comfort termico**; automatizzare l'apertura e e la chiusura di porte, cancelli, tende, tapparelle e simili; settare, programmare o controllare a distanza le funzioni di elettrodomestici; gestire il sistema di allarme e videosorveglianza dell'appartamento. Il sistema domotico consente di gestire tutte le sue funzioni attraverso un'applicazione installata su smartphone o tablet. Questo attributo presenta due livelli: "**SÌ**" e "**NO**" a seconda o meno che sia installato o meno il sistema domotico nelle alternative di scelta.

<u>ATTRIBUTO 5</u>: Costo mensile

Questo attributo identifica **per ogni alternativa di scelta** il **costo mensile** (equivalente alla rata di un mutuo) che **sei disposto a sostenere** per i **miglioramenti ottenuti** e identificati attraverso i diversi livelli dei relativi attributi nei **CASI DI SCELTA** analizzati. Tale **costo** deve essere inteso **<u>come la tua eventuale disponibilità a pagare</u>** **<u>per godere</u>** dei **<u>benefici/miglioramenti ottenuti attraverso la realizzazione degli interventi di riqualificazione energetica</u>**. Sono previsti **5 livelli di costo: 200 €** (equivalente ad un capitale di 50'000 € preso a prestito in 30 anni)**, 150€** (equivalente ad un capitale di 40'000 € preso a prestito in 30 anni), **110€** (equivalente ad un capitale di 30'000 € preso a prestito e da restituire in 30 anni), **90€** (equivalente ad un capitale di 20'000 € preso a prestito da restituire in 20 anni), **50€** (equivalente ad un capitale di 4'000€ preso in prestito da estinguere 7 anni).

SURVEY

Inserisci i tuoi **dati personali** (il questionario rimarrà anonimo):

Sesso	M	
	F	
Età	< 20	
	20 -29	
	30 - 39	
	40 - 49	
	50 - 60	
	> 50	
Livello di scolarizzazione	Diploma Elementari/Scuole medie	
	Diploma scuole superiori	
	Laurea	
	Master/Dottorato	
Reddito annuale	< 5000 €	
	5000 € - 10000€	
	10000 € - 20000€	
	20000 € - 30000€	
	30000 € - 50000€	
	50000 € - 100000€	
	> 100000 €	

CHOICE TASKS (VERSIONE 1)

ATTRIBUTI	CE	SVM	AE	ID	COST	CE	SVM	AE	ID	COST
CARTA DI SCELTA	**APPARTAMENTO A**					**APPARTAMENTO B**				
1	F	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	50	D	NO	RITINTEGIATURA MURI ESTERNI	SI	200
2	A	SI	RITINTEGIATURA MURI ESTERNI	NO	200	F	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	50
3	E	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	150	D	SI	NO	NO	90
4	C	SI	NO	SI	150	B	NO	RITINTEGIATURA MURI ESTERNI	NO	90
5	F	NO	NO	SI	150	C	SI	RITINTEGIATURA MURI ESTERNI	NO	90
6	B	SI	RITINTEGIATURA MURI ESTERNI	NO	110	A	NO	NO	SI	90
7	D	NO	NO	NO	90	F	SI	RITINTEGIATURA MURI ESTERNI	SI	110
8	D	SI	RITINTEGIATURA MURI ESTERNI	NO	200	E	NO	NO	SI	50
9	D	NO	NO	NO	50	C	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	200
10	A	NO	NO	SI	110	C	SI	RITINTEGIATURA MURI ESTERNI	NO	110
11	B	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	200	A	NO	RITINTEGIATURA MURI ESTERNI	NO	50
12	A	NO	RITINTEGIATURA MURI ESTERNI	NO	110	E	SI	NO	SI	110
13	C	NO	RITINTEGIATURA MURI ESTERNI	SI	50	A	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	200
14	F	SI	RITINTEGIATURA MURI ESTERNI	SI	200	C	NO	NO	NO	50

CHOICE TASKS (VERSIONE 2)

ATTRIBUTI	CE	SVM	AE	ID	COST	CE	SVM	AE	ID	COST
CARTA DI SCELTA	APPARTAMENTO A					APPARTAMENTO B				
1	C	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	150	D	SI	NO	SI	90
2	D	SI	NO	SI	90	B	NO	RITINTEGIATURA MURI ESTERNI	NO	150
3	B	SI	NO	SI	90	D	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	150
4	D	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	90	A	NO	RITINTEGIATURA MURI ESTERNI	NO	110
5	E	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	110	F	NO	NO	SI	90
6	E	SI	NO	NO	50	C	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	200
7	A	NO	NO	NO	90	D	SI	RITINTEGIATURA MURI ESTERNI	SI	150
8	D	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	90	C	SI	NO	SI	150
9	A	SI	NO	SI	200	B	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	50
10	E	NO	RITINTEGIATURA MURI ESTERNI	SI	50	A	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	200
11	E	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	90	B	SI	NO	SI	150
12	F	SI	RITINTEGIATURA MURI ESTERNI	NO	50	B	NO	NO	SI	200
13	B	NO	NO	SI	50	E	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	150
14	C	NO	RITINTEGIATURA MURI ESTERNI	SI	110	F	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	110

CHOICE TASKS (VERSIONE 3)

ATTRIBUTI	CE	SVM	AE	ID	COST	CE	SVM	AE	ID	COST
CARTA DI SCELTA	APPARTAMENTO A					APPARTAMENTO B				
1	D	SI	RITINTEGIATURA MURI ESTERNI	SI	90	A	NO	NO	NO	150
2	E	SI	RITINTEGIATURA MURI ESTERNI	SI	200	D	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	50
3	B	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	150	F	SI	NO	NO	90
4	C	NO	RITINTEGIATURA MURI ESTERNI	NO	90	B	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	150
5	F	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	200	B	SI	NO	NO	50
6	C	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	110	A	NO	RITINTEGIATURA MURI ESTERNI	SI	110
7	B	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	150	C	SI	NO	SI	50
8	C	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	150	E	SI	RITINTEGIATURA MURI ESTERNI	SI	90
9	A	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	200	E	NO	RITINTEGIATURA MURI ESTERNI	NO	50
10	B	SI	NO	NO	50	E	NO	RITINTEGIATURA MURI ESTERNI	SI	200
11	E	NO	NO	SI	150	F	SI	RITINTEGIATURA MURI ESTERNI	NO	90
12	F	NO	RITINTEGIATURA MURI ESTERNI	SI	110	E	SI	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	NO	110
13	F	SI	NO	NO	50	D	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	200
14	A	SI	RITINTEGIATURA MURI ESTERNI	NO	110	F	NO	RIFACIMENTO INTONACO E SOSTITUZIONE INFISSI	SI	110

APPENDIX II: MNL R-Code

```
# ################################################################# #
#### LOAD LIBRARY AND DEFINE CORE SETTINGS                    ####
# ################################################################# #
### Clear memory
rm(list = ls())
### Load Apollo library
install.packages("apollo")
library(apollo)
### Initialise code
apollo_initialise()
### Set core controls
apollo_control = list(
  modelName ="DEMETRA MNL PSPACE",
  modelDescr ="NA",
  indivID   ="ID",
  mixing    = FALSE,
  nCores    = 1
)
# ################################################################# #
#### LOAD DATA AND APPLY ANY TRANSFORMATIONS                  ####
# ################################################################# #
database = read.csv("db_DEMETRA.csv",header=TRUE,sep=",")
# ################################################################# #
#### DEFINE MODEL PARAMETERS                                  ####
# ################################################################# #
### Vector of parameters, including any that are kept fixed in estimation
apollo_beta = c(belE   = 0.,
            belD   = 0.,
            belC   = 0.,
            belB   = 0.,
            belA   = 0.,
            bvs    = 0.,
            bqfwr = 0.,
            bqfpdw   = 0.,
            bte    = 0.,
            bpr    = 0.,
            asc1 = 0.)

### Vector with names (in quotes) of parameters to be kept fixed at their starting value in apollo_beta, use apollo_beta_fixed = c() if none
apollo_fixed = c()

# ################################################################# #
#### DEFINE RANDOM COMPONENTS                                 ####
# ################################################################# #
```

```
### Set parameters for generating draws
apollo_draws = list(
  interDrawsType = "mlhs",
  interNDraws    = 0,
  interUnifDraws = c(),
  interNormDraws = c("draws1","draws2","draws1_2","draws2_2"),
  intraDrawsType = "mlhs",
  intraNDraws    = 0,
  intraUnifDraws = c(),
  intraNormDraws = c()
)
### Create random parameters
apollo_randCoeff = function(apollo_beta, apollo_inputs){
randcoeff = list()
return(randcoeff)
}

# ################################################################# #
#### GROUP AND VALIDATE INPUTS                               ####
# ################################################################# #
apollo_inputs = apollo_validateInputs()
# ################################################################# #
#### DEFINE MODEL AND LIKELIHOOD FUNCTION                    ####
# ################################################################# #
apollo_probabilities=function(apollo_beta, apollo_inputs, functionality="estimate"){
### Function initialisation: do not change the following three commands
### Attach inputs and detach after function exit
  apollo_attach(apollo_beta, apollo_inputs)
  on.exit(apollo_detach(apollo_beta, apollo_inputs))

  ### Create list of probabilities P
  P = list()

  ### List of utilities: these must use the same names as in mnl_settings, order is irrelevant
  V = list()
  V[['alt1']]   =  asc1  +  belE*(el1==0)  +  belD*(el1==1)  +  belC*(el1==2)  +  belB*(el1==3)  +
belA*(el1==4) + bvs*vs1 + bqfwr*(qf1==0) + bqfpdw*(qf1==1) + bte*te1 + bpr*pr1
  V[['alt2']]  = belE*(el2==0) + belD*(el2==1) + belC*(el2==2) + belB*(el2==3) + belA*(el2==4)
+ bvs*vs2 + bqfwr*(qf2==0) + bqfpdw*(qf2==1) + bte*te2 + bpr*pr2
  ### Define settings for MNL model component
  mnl_settings = list(
    alternatives  = c(alt1=1, alt2=2),
    avail         = list(alt1=1, alt2=1),
    choiceVar     = choice,
    V             = V
  )

  ### Compute probabilities using MNL model
```

```
  P[['model']] = apollo_mnl(mnl_settings, functionality)

  ### Take product across observation for same individual
  P = apollo_panelProd(P, apollo_inputs, functionality)

  ### Average across inter-individual draws
  #P = apollo_avgInterDraws(P, apollo_inputs, functionality)

  ### Prepare and return outputs of function
  P = apollo_prepareProb(P, apollo_inputs, functionality)
  return(P)
}

# ################################################################# #
#### MODEL ESTIMATION                                          ####
# ################################################################# #

model = apollo_estimate(apollo_beta, apollo_fixed,
                apollo_probabilities,                                    apollo_inputs,
estimate_settings=list(hessianRoutine="maxLik"))

# ################################################################# #
#### MODEL OUTPUTS                                             ####
# ################################################################# #

# ----------------------------------------------------------------- #
#---- FORMATTED OUTPUT (TO SCREEN)                           ----
# ----------------------------------------------------------------- #

apollo_modelOutput(model)

# ----------------------------------------------------------------- #
#---- FORMATTED OUTPUT (TO FILE, using model name)               ----
# ----------------------------------------------------------------- #

apollo_saveOutput(model)
```

APPENDIX III: Cost-benefit trade-offs in buildings energy retrofit

INTRODUCTION

In Europe, buildings are responsible for 40% of the total energy consumption and 36% of CO_2 emissions (BPIE, 2015) [1]. Increasing the energy efficiency of buildings through the implementation of energy retrofit measures represents a great opportunity to reduce energy consumption, polluting emissions and preserve energy resources Ma Z. et al., 2012; Pérez-Lombard L. et al., 2008 [2-3] and it contributes to the achievement of the European Union energy and climate 2020 [4], 2030 [5], 2050 [6] targets whose aim is to reduce primary energy consumption and CO_2 emissions as well as promote the use of renewable energy. To reach these goals, the Energy Performance of Buildings Directive (EPBD) (Directive2010/31/EU [7] has been enacted. The EPBD recast promotes the improvement of building energy performance and the application of minimum energy efficiency requirements. The EPBD recast promotes national plans to increase the number of nearly zero energy building (NZEB) and introduces the energy certification of buildings. With respect to the economic analysis of investments in buildings energy retrofit, the EPBD recast and the European Regulation 244/2012 [8] provide the Life Cycle Cost (LCC) method. This methodology consists in determining the cost-optimal levels of building energy retrofit projects (BERPs) respecting minimum energy performance requirements. The method can be applied to both new and existing buildings. Firstly, it is necessary to define a *Reference Building* that represents, in geometric, technical and functional terms the typical building typology analysed.

The primary energy consumption and all the related building costs are estimated for every combination of possible implementable energy retrofit measures (ERMs) that define an implementable BERP, the present value sum of all costs related to each implementable BERP is defined "*Life Cycle Cost*" (LCC), the BERP or a subgroup of BERPs characterized by having the minimum LCC are selected.

The LCC method prioritizes economic performance rather than energy performance, it favors policy-makers and governments and is not focused on private investors interests Araújo C. et al., 2016 [9]. Stakeholders may be willing to invest in more energy-efficient solutions, and this will lead to a higher saving potential of EU's residential buildings and will consequently optimize the use of energy resources (Bonifaci and Copiello, 2015; Araujo et al., 2016; D'Alpaos C. and Bragolusi P., 2018 Metti tutte le nostre pubblicazioni) [40-41, 9]. The energy retrofit of buildings involves other co-benefits such as: better overall quality of the building, users well-being and comfort, increase in assets'market value, carbon emission's reduction, job creation, increase in energy security by reducing dependence on imported energyCapelletti F. et al, 2015; D'Oca S. et al, 2018; Ferreira M. and Almeida M., 2015; Ferreira M. et al, 2017 [10-13]. The LCC method does not consider all these co-benefits that might involve stakeholders' investments in more efficient retrofit solutions. The LCC methodology is based on the sum of all discounted costs related to the building during its life cycle. The lower energy costs, due to the energy retrofit measures installed and other further cost reductions, are accounted together in a single cost value (the LCC). Hence, the methodology "hides" the investment profitability of the BERP. Some authors overcome this problem using classical economic valuation methods, such as the *Net Present Value* (NPV), the *Payback Period* and the *Internal Rate of Return* (IRR) which evaluate the energy retrofit investment in terms of profitability according to the usual theories on economic evaluation of projects Guardigli L. et al., 2018; Kumbaroglu G. et al., 2012; Preciado-Pérez O. A. and Fotios S. 2017; Valdiserri P. and

Biserni C. 2016; Wu Z. et al., 2016 [14-18]. However, these methodologies mainly consider only energy saving benefit. Some authors Diakaki et al., 2008; Diakaki et al., 2010; Krarti e Bichioua, 2011; Asadi et al., 2012; Petersen e Svedsen, 2012; Wu et al., 2017 [19-24] developed several methodologies in the *Decision Making* field in order to determine the best building energy retrofit project considering multiple objectives and using optimization algorithms. These methodologies are very efficient but are only used in research field for their complexity. The Article 2 of Italian D.Lgs. 192/2005 defines the "*cost-optimal level*" for the economic evaluation of building energy retrofit projects. It recalls the LCC method and the *Cost-Benefit* analysis too: "*the cost-optimal level is located within the scale of performance levels in which the cost-benefit analysis calculated on the economic life cycle is positive*". Thus, the Legislative Decree allows the use of *Cost-Benefit* analysis to evaluate BERPs. The use of the *Cost-Benefit* analysis makes it possible to consider further benefits not analyzed by the LCC method. Some authors utilized the *Choice Experiment* method on the Contingent Evaluation field to estimate the *Willingness To Pay* (WTP) for the co-benefits that the energy retrofit of building involves. Authors estimated the WTP related to: CO_2 emissions reduction Alberini et al., 2018 [25], improving in building occupants' comfort Galassi e Madlener, 2017 [26], buildings aesthetics appearance Vanstockem et al., 2018 [27] and building added market value Banfi S. et al., 2008; Marmolejo-Duarte e Bravi, 2017 [28-29].

The aim of our research is to provide a novel economic methodology to evaluate BERPs considering all relevant benefits that the energy retrofit of building involves. Starting from possible implementable BERPs, the methodology is able to determine the best one through the maximization of the net benefit which is given by the difference of benefits and costs related to a Reference Scenario (the *status quo* of the building to be retrofitted) and to all feasible energy retrofit projects.

METHODOLOGY

In this paper, we provide a cost-benefit analysis to compare different implementable BERPs considering energy performances, economic performances and other relevant co-benefits.

LCC

According to Directives 2010/31/EU [7] and 2012/27/EU [31] transposed in Italy by the Ministerial Decree DM 25/06/2015 [30], we base our analysis on the comparison of the building to be retrofitted in its current state (*status quo*) with a set of alternative retrofit projects BERPs, which represent different investment scenarios.

In detail we firstly calculate the LCC for each BERP as follows:

$$LCC(\tau) = \sum_j C_{I,j} + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \cdot R_d(i) - V_{f,i}(j)\right)\right] \qquad (1)$$

where:

τ: is the calculation period (30 years as set by Delegate Regulation 2012/244/EU

$C_{I,j}$: is the investment cost paid for implementing ERM *j*;

$C_{a,i}(j)$: represents the annual cost at year *i* for ERM *j*;

$V_{f,i}(j)$: represents the residual value of ERM *j* at the end of the calculation period;

$R_d(i)$: represents the discount factor relative to year *i* and it depends on the discount rate *r*.

All costs related to the life cycle of building must be considered, such as: operating costs, energy costs and disposal costs. The law states that the BERP that minimize the LCC must be selected.

NPV

The second analyzed methodology is the estimation of the Net Present Value (NPV) used in projects economic evaluation. Several authors Guardigli L. et al., 2018; Kumbaroglu G. et al., 2012; Preciado-Pérez O. A. and Fotios S. 2017; Valdiserri P. and Biserni C. 2016; Wu Z. et al., 2016 [14-18] utilized this methodology in the economic evaluation of BERPs. The Net Present Value method is based on the estimation of the difference between current and future discounted benefits and costs related to an investment project. A positive value indicates that the project is profitable, whereas a negative value indicates that the project it is not economically feasible. The formula for computing the NPV of each BERP is the following:

$$NPV = -\sum_{j} C_{I,j} + \sum_{i=1}^{\tau} \frac{ES_i - C_i}{(1+r)^i}$$

where:

where:

τ: it is the calculation period;
$C_{I,j}$: it is the initial investment cost for ERM *j*;
r: is the discount rate;
ES_i: energy savings at year *i* related to ERMs installed;
$C_{j,i}$: maintenance costs at year *i* of the ERM *j*.

Araùjo et. al Cost-Benefit analysis method (AAA)

This methodology was developed by Araújo C. et al., 2016 [9]. It compares different BERPs with respect to the *status quo* of the building to be retrofitted. The goal is to determine the cost-optimal BERP computing a cost-benefit ratio considering both economic and energy performances. The first step is to compute the difference between annual energy costs and energy consumptions between building status quo and each BERP *k*:

$$\Delta En_k = En_{ref} - En_k \quad (3)$$

$$\Delta LCC_k = LCC_k - LCC_{ref} \quad (4)$$

where:

En_k is the energy consumption of BERP *k*;
En_{ref} is the energy consumption of the reference solution;
LCC_k is the life cycle cost of solution *k*;
LCC_{ref} is the life cycle cost of the reference solution.

For each BERP, the ratio between $\Delta LCC_k$and ΔEn_k is compared to a cost-benefit ratio provided by Portugal Decree Law 79/2006 [32] which represents the stakeholder's willingness to invest in energy-efficient measures:

$$\frac{\Delta LCC_k}{\Delta En_k} = A \cdot \sum_{i=1}^{PB} Ecost(i)_k \cdot R_d(i) \qquad (5)$$

where:

ΔEn_k is the primary energy needs variation (kWh/m^2 year);
ΔLCC_k is the LCC variation (€);
A is the net area (m^2);
PB is the payback period (years);
$Ecost(i)_k$ is the primary energy cost (€/kWh);
$R_d(i)$ is the discount rate for year *i*.

Relation (5) is plotted in Fig (1) where it is possible to define a reference line representing the ideal $\Delta LCC_k$and ΔEn_k ratio. The line starts from the origin and its gradient represents an ideal relationship between economic and energetic performances. The dots in the plane ($\Delta En, \Delta Cost$) represent a possible solution. The best solution is the one characterized by the largest negative distance (*d*) or the smallest positive distance from the reference line as this represents the best cost-benefit ratio.

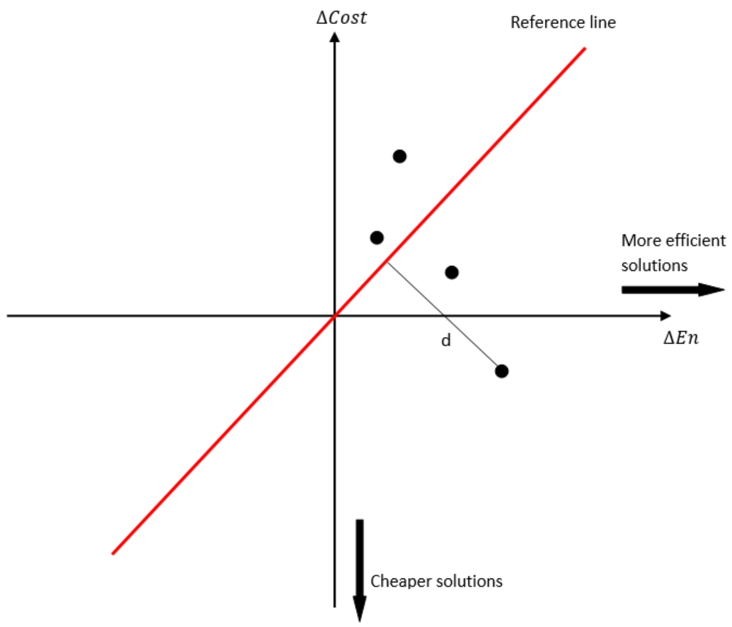

Fig. 1 Graphical solution by Araùjo's et al. 2016 (Source: our processing from Araùjo's et al. 2016)

Differential Cost-Benefit analysis method

In projects economic evaluation, the cost-benefit analysis is used to evaluate the feasibility and the selection between several project alternatives. In our proposal, the goal is to analyze costs and benefits deriving from the implementation of building energy retrofit measures. For each possible retrofit scenario that defines a possible implementable project, the novel methodology is based on the estimation of incremental costs and benefits due to energy retrofit measures installed with respect to *Reference Scenario*. Liu et al., 2014 [33] used a similar methodology to evaluate energy efficiency technology application projects on green buildings in China. The economic evaluation of possible implementable building energy retrofit projects was made using the usual economic indicators such as the *Payback Period* and the *Internal Rate of Return (IRR)*. The indicators were computed through the difference between related benefits and costs. Following this principle, it is possible to develop an algorithm able to evaluate energy retrofit investment projects. The estimation of incremental costs and benefits allows the direct estimation of the profitability and feasibility between two possible projects to determine the best one. In our proposal we calculated the incremental costs and benefits of every possible building energy retrofit project compared to the *Reference Building* maximizing the *differential net benefit*. Indicating with the subscript *k* every feasible BERP, the one that maximizes the differential net benefit is as follows:

$$max_k\left[\left(B_k - B_{Ref}\right) - \left(C_k - C_{rEF}\right)\right] \qquad (6)$$

where:

B_k are benefits related to k-th BERP;
B_{Ref} are benefits related to *Reference Building*;
C_k are costs related to k-th BERP;
C_{Ref} are costs related to *Reference Building*;

According to the Ministerial Decree 25/06/2015 [30], initial investment costs (for building energy retrofit measures installation), operating costs, energy costs and disposal costs have to be analyzed in order to estimate building costs. From formula (6), if the cost of the k possible BERP is lower than the cost related to the Reference Building, the difference C_k-C_Ref results in a positive value (a cost reduction due to the retrofit becomes a benefit) and it contributes to the maximization of the algorithm. When it comes to benefits estimation, the task becomes more difficult. The energy retrofit of buildings does not provide only energy cost savings, but it may lead to other benefits, such as: a better thermal comfort and indoor air quality and protection against external noise Prete et al., 2017; Galassi e Madlener, 2017 [34-35]. The retrofitted building could also have a higher price premium that is another benefit (Achtnicht, 2011; Popescu et al., 2012; Banfi et al., 2008; Zalejska J.A., 2014; Bonifaci e Copiello, 2015) [36-40]. Stakeholders may also be willing to pay regarding intrinsic value that concerns environmental awareness and warm glow due to the retrofit D'Alpaos C., Bragolusi P., 2018 [41]. The proposed algorithm implies that all relevant tangible and intangible benefits that have to be considered in the economic analysis must have an economic value. It is very difficult to estimate; therefore, we have considered the most important ones that can easily be included in the algorithm. Tab. 1 illustrates all the benefits that have been considered and those that can be developed in the future.

Table 1
Benefits

Benefits usually considered on economic analysis	Other benefits for future developments
DV: Added-value of building due to building energy retrofit	Increase of thermal comfort Better indoor air quality Better protection against external noise

DC_e: Monetized annual energy savings due to building energy retrofit FI: Tax incentives	Environmental awareness CO_2 reduction

To identify which of the *k* feasible BERP maximizes the differential net benefit, we need to write the following relationship:

$$max_k\ [\Delta V_{Lref,Lk} + FI + \left(V_{f,j} - V_{f,ref}\right) - C_I - \sum_{i=1}^{CP}\left(C_{mi,k} - C_{mi,ref}\right)R_d(i) -$$

$$- \sum_{i=1}^{CP}\left(C_{ri,k} - C_{ri,ref}\right)R_d(i) - \sum_{i=1}^{CP}\left(C_{ei,k} - C_{ei,ref}\right)R_d(i)] \qquad (7)$$

where:

CP is the calculation period;
C_I is the initial investment cost of the feasible BERP *k*;
$\Delta V_{Lref,Lk}$ is the market price premium of the building due to energy performance;
FI is the current value of tax incentives, if a_{FI} is the annual installment:
$FI = \frac{a_{FI}(q^n - 1)}{rq^n}$
$V_{f,j} - V_{f,ref}$: is the difference between residual values of the measure or set of measures at the end of the calculation period related to reference building and energy retrofitted building;
$C_{mi,k} - C_{mi,ref}$: is the difference between the maintenance costs between reference building and energy retrofitted building;
$C_{ri,k} - C_{ri,ref}$: is the difference between the replacement costs between reference building and energy retrofitted building;
$C_{ei,k} - C_{ei,ref}$: is the difference between the energy costs between reference building and energy retrofitted building;
$R_d(i) = (1/(1 + r))^i$: is the discount factor related to the i year;
r: is the discount rate.

The residual value of the energy retrofit measures V_f is not considered, at the end of the calculation period the building exhausts its useful life and will be demolished; the installed technologies will also not be reusable.

CASE STUDY

Building typology and energy retrofit measures adopted

The case study is a four storey public housing building which comprises fifteen apartment units (five for each floor) and related garages on the ground floor. It is in the north of Italy at an altitude of 22 m in a suburb of the city of Padova. Fig 2 and Fig 3 represent the case-study building and the layout of the building typical floor:

Fig. 2 Building case-study

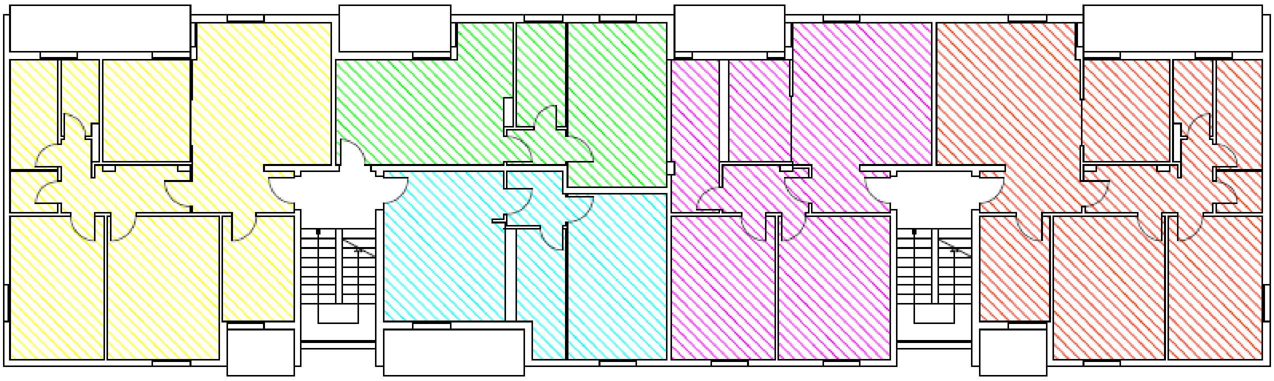

Fig. 3 Layout of the building typical floor

The building case-study is a public housing managed by a regional agency and represents the most frequent typology of the entire real estate stock managed by the agency itself. The building was built in 1984 and consists on precast concrete elements with a frame structural typology with brick wall. Internal and external walls and floors are not thermally insulated. Table 2 shows the thermal characteristics of walls and floors.

Table 2

Walls and floors characteristics

Typology	s [cm]	U [W/m²K]
External walls	24	1.219
Internal walls	10	2.801
Floors	30	1.733

s: thickness

U: thermal trasmittance

As for doors and windows, the building is characterized by having wooden frames with single glass with a low thermal and acoustic insulation. Table 3 presents the characteristics of doors and windows.

Table 3

Doors and windows characteristics

Typology	Ag [m^2]	Ug [W/m^{2}K]	Af [m^2]	Uf [W/m^{2}K]	Uw [W/m^{2}K]
Two shutters window	1.99	5.78	0.77	2.465	4.85
One shutter French windows	0.99	5.75	0.39	2.54	4.85
Two shutters French windows	1.99	5.75	0.77	2.465	4.83

Ag: glasses surface

Ug: glass thermal transmittance

Af: frame surface

Uf: frame thermal trasmittance

Uw: window thermal transmittance

All the apartments have an autonomous heating and domestic hot water system. The installed generator is a standard atmospheric gas boiler characterized by having a 70% efficiency level. Heating system consists on radiators. The cooling system is not installed.

The energy retrofit of public housing is a complex task. This building typology is frequently owned and managed by public institutions Aranda J. et al., 2019 [42]. There are stringent public budget constraints, lack of financial and public resources to properly renovate it D'Alpaos C., Bragolusi P., 2018; Santangelo A. et al. 2018 [43-44]. Thus, the choice of implementable ERMs must be cost-effective and the discounted monetized energy-savings have to pay back the initial investment costs over years. Therefore, we take into account three basic ERMs and their combinations obtaining seven scenarios. The first energy retrofit measure consists on the optimization of the heating system by replacing the old boilers with new condensing gas high efficiency boilers (98%), reducing fuel consumption, low pollutant emissions and maintenance costs. Most importantly, the other two basic energy retrofit measures adopted Ferrara M. et al., 2014; Pal S.K., 2014; Tadeu S. et al., 2015; Mangan S.D. and Oral G.K., 2016; Krarti M. and Bichioua Y., 2011; Krarti M. and Ihm P., 2016; De Vasconcelos et al., 2016; Fregonara E. et al, 2017; Zangheri P. et al, 2017; [45-53] consist in replacing existing doors and windows with low emittance ones and installing external walls thermal insulation. The use of external wall insulation provides the highest energy saving potential and the replacement of windows is the most cost-effective energy retrofit measure Zhou Z. and Dong, C., 2014; Liu Y. et al., 2018 [54-55]. These two energy retrofit measures also have low maintenance costs and maintain technical performance during the cycle life of the building Fregonara E. et al., 2016; D'Alpaos C. and Bragolusi P., 2018 [53,43]. The energy retrofit measures to be implemented have to respect the technical requirements set by the Italian Ministerial Decree DM 25/06/2015 [30]. This Decree provides minimum requirements for energy retrofit measures and defines the different levels of building energy retrofit. Table 4 synthetizes all the requirements (defined with respect to the climatic zone of the building defined by law) and Table 5 shows the energy retrofit scenarios and the technical characteristics of the energy retrofit measures chosen.

Table 4
DM 25/06/2015 requirements

Type of intervention	Levels of intervention	Requirements for the case - study
First level retrofit (FLR)	Interventions regarding building envelope affecting more than 50% of the gross dispersing surface and the heating and cooling systems.	Maximum thermal transmittance of external opaque vertical structures of the envelope equal to 0.30 W/m²K (for "E" thermal zone defined by law)
Second level retrofit (SLR)	Interventions concerning building envelope that affect between 25% and 50% of the gross dispersing surface and/or the heating and cooling systems.	Maximum thermal transmittance of transparent and opaque technical closures equal to 1.90 W/m²K (for "E" thermal zone defined by law)
Energy retrofit (ER)	Interventions concerning building envelope that affect less then 25% of the gross dispersing surface and/or the heating and cooling systems.	The minimum yield for liquid and gaseous fuel boilers must be is equal to: h=90+2log(P_n), P_n is the rated power of the boiler

Table 5
Scenarios

Scenario	Level of intervention	Energy Retrofit Measures	Technical features
S1	ER	Condensing Boiler	P_n = 25 kW, h=98%
S2	ER	Double-glazed low-emittance doors and windows with wooden frame	Windows and doors (1.20X2,30 m): U = 1.80 W/m²K, doors (0.80X2.30 m): U = 1.75 W/m²K
S3	SLR	External wall thermal insulation	Expanded polystyrene thermal insulation, r=30 kg/m³, C_s = 1200 J/kgK, U = 0.29 W/m²K, s(width) = 10 cm
S4	ER	S1+S2	
S5	FLR	S1+S3	
S6	SLR	S2+S3	
S7	FLR	S1+S2+S3	

The BIM *TerMus* software was used to compute the primary energy consumption of the building. BIM *TerMus* is a professional software utilized for building energy certification and building energy performance computations. The software also checks automatically whether all energy retrofit measures adopted and related performance respect requirements provided by Italian laws and regulations. It provides the Energy Performance Certificates (*APE, Attestato di Prestazione Energetica*) and the Energy Labeling of the building. Table 6 shows software thermal analysis results for the entire building.

Table 6
TerMus software results for the entire building

Scenario	Annual energy consumption [kWh/m²y]	Annual gas consumption [m³]
Reference scenario	161.5	16319.05
S1	155.8	14700.38
S2	144.6	14429.55
S3	115.6	11309.09
S4	141.9	13057.58
S5	115.6	10415.84
S6	100.6	9506.89
S7	99.1	8738.65

COSTS AND BENEFITS ESTIMATION

The proposed approach involves the analysis of costs and benefits deriving from the energy retrofit measures adopted. To estimate costs, we carried out a market analysis using websites, consulting specialized firm brochures and price lists. Costs are inclusive of material, installation and labor. Tab. 7 illustrates all the estimated costs for all the energy retrofit measures considered.

Table 7

Energy retrofit measures costs

Energy retrofit measure	Installation cost [€]	Maintenance costs [€]	Replacement costs [€]
Condensing boiler	46500	75 € every year for boiler check up, 120 € every 4 years for boiler smoke control	46000€ every 15 years for condensing boilers replacement
Double-glazed low-emittance doors and windows with wooden frame	67847	-	-
External wall thermal insulation	56279	-	-

In particular:

- The condensing boiler cost was carried out through a market analysis using websites and analyzing related brochures, ten prices were collected and a mean price was estimated (46500 €);
- Maintenance costs (boiler check up and boiler smoke control) are estimated consulting specialized technicians;
- External wall thermal cost was estimated using the Veneto region pricelist of public works;
- Double-glazed low-emittance doors and windows with wooden frame costs were estimated through a website market analysis, four estimation costs using apposite website were estimated and a mean price was computed (67847 € and 56279 €).

To estimate building energy consumption cost, it is necessary to analyze the natural gas market prices. The estimation depends on the geographical area in which the building is located. The reference gas market provides preferential prices for the tenants who have a low income (the building is a public housing). The analysis of the historical data series of natural gas prices in the decade 2007-2017 provided by the Italian Authority for Electricity, Gas and Water System (AEGSI) a 2% annual rate increase was estimated starting from an actual price of 0.773 €/m^3. As regarding the tax incentive benefit, we considered the tax rebates provided for by Italian laws. Tax rebates consist on a tax income reduction by a certain percentage, depending on energy retrofit measures adopted and building typology Documento Agenzia delle Entrate sulle Agevolazioni Fiscali [56]. The incentive is computed by considering a percentage of the initial investment cost related to energy retrofit measures that is pay back through ten annual installments. In our case-study (apartments block), a 70% of building envelope costs reduction and 65% of condensing boilers costs reduction are provided

Documento Agenzia delle Entrate sulle Agevolazioni Fiscali [56]. Another benefit concerns the market price premium of the building due to energy retrofit measures adopted, several authors studied this aspect De Ayala A. et al., 2016; De Ruggiero M. et al. 2017; Fuerst F. et al., 2015; Fuerst F. et al., 2016; Hyland M. et al., 2013; Jafari A. et al., 2017; Koirala B. et al,, 2017; Stanley S. et al., 2016; Wee S., 2016; Bonifaci P. and Copiello S., 2015 [57-65,40]. They estimated it using the Hedonic Price Method Rosen S., 1974 [66] through a real estate market prices analysis, however very few authors consider the building price premium in the economic analysis. Popescu et al., 2012 [67] utilized the Net Present Value (NPV) on building energy retrofit economic analysis taking into account also the market price premium due to the retrofit. In our differential cost-benefit analysis we consider the market price premium due to the retrofit and we estimate it using the Sales Comparison Approach (SCA) and results obtained by the Hedonic Price Regression performed by Bonifaci and Copiello (2015) [40] that estimated the market price premium of the building due to the energy label in the same market area of the case study. Through the SCA, the market price of the building is estimated by comparing it with recent sales of comparable buildings in the same market area [You S.-M. and Chang C., 2009; Kontrimas and Verikas, 2011; Thanos S. et al, 2016] [70-72]. Comparables may have the same positional extrinsic and intrinsic characteristics, technological characteristics and productive characteristics as possible with respect the building analyzed. Once the comparables are selected, their market prices are adjusted (through a price increase or decrease) to make them similar to the building analysed, this is done comparing the characteristics of the analyzed building and comparables. We carried out a market analysis and we collected market prices of similar apartments typology, the comparables were characterized by having the G energy label (the least energy efficient), an estimated market price of 800 €/m2 was obtained. In order to estimate the market price premium due to the retrofit of all the apartments, for each apartment and retrofit scenario the apartment price was increased with respect the percentages obtained by Bonifaci and Copiello (2015) [40]. Comparing the energy label of the apartments before e after the retrofit, the market price premium was estimated using Tab. 8 which reports the energy label price premium estimated by Bonifaci and Copiello (2015) [40]. Tab. 9 reports for each retrofit scenario the market price premium of the building that is the sum of the market prices premium of all the building apartments.

Table 8

Percentage of market price premium due to the retrofit with respect the G energy label, Bonifaci e Copiello, 2015

Energy Label	% of market price increment
G	0
F	2.3
E	9.5
D	17.1
C	17.4
B	20.2
A	21.9

Table 9
ΔV [€] entire building

Scenario	ΔV [€]
S1	0
S2	28269
S3	42096
S4	19584
S5	47479
S6	74774
S7	76015

SENSITIVITY ANALYSIS

To test the four methodologies, we made a sensitivity analysis to using four discount rates (as indicated by the Italian legislation [43]): 1%, 2%, 3%, 4%. Tables 10 and 11 summarize the results obtained. Considering a 2% of gas price increase for all discount rate adopted, the proposed methodology and the NPV methodologies favor Scenario 6 (external thermal wall insulation installation, windows and doors replacing). The two methodologies favor the scenario that ensures maximum stakeholder's investment profitability, maximizing the net benefit derived from the energy retrofit measures adopted. However, LCC method favors Scenario 3 which minimizes the LCC value. In all cases the NPV of Scenario 3 is lower than the NPV of Scenario 6. Hence, Scenario 6 is the most profitable energy retrofit investment project (characterized by having a lower energy consumption too). Araùjo's method agrees with LCC method except when r = 1%. A relatively low discount rate increases the value of money, thus, solutions with higher energy performances will be more profitable because the sum of discounted energy savings increases.

Table 10
Sensitivity analysis r = 1,2%; + 2% Energy price increase

ΔE_{price} = +2%	r = 1%				r = 2%			
	NPV	LCC	ARAUJO	B-C	NPV	LCC	ARAUJO	B-C
S1	-15960	494431	5.24	12534	-18008	430201	8.94	6582
S2	725	494100	-6.19	57489	-5194	432898	-0.34	47665
S3	90641	**396515**	-101.43	161231	72727	**347704**	**-89.92**	139412
S4	6459	516993	6.72	54538	-4432	459286	15.79	39742
S5	97391	418392	-86.52	173365	74453	373128	-71.79	146522
S6	**117455**	414683	**-104.13**	**221965**	**90063**	373028	-86.95	**190668**
S7	106546	454219	-78.72	209815	76580	413662	-59.48	175943

Table 11
Sensitivity analysis r = 1,2%; - 2% Energy price decrease

ΔE_{price} = -2%	r = 1%				r = 2%			
	NPV	LCC	B-C	ARAUJO	NPV	LCC	ARAUJO	B-C
S1	-40617	270509	-12122	716.33	-38345	245498	617.12	-13756
S2	-28056	274304	28707	772.36	-28934	251598	698.80	23924
S3	**14327**	**224251**	84918	**-143.49**	**9779**	**205610**	**-30.37**	76465
S4	-43221	318095	4858	1545.66	-45411	295224	1360.41	-1237
S5	7471	259734	83445	485.28	282	242258	527.66	72351

S6	13689	269871	**118199**	649.80	4472	253579	684.94	**105077**
S7	-8921	321108	94347	1556.23	-18664	303865	1449.15	80699

Considering a 2% of gas price decrease for all discount rates, the actual value of future energy savings decreases. This is due to the fact that it is more difficult to pay back the initial investment cost during years. All the methods, except for the new proposed, envisage that Scenario 3 is the best. However, the proposed methodology indicates that Scenario 6 is the best for all discount rates because of the increment of the building in the market caused by the energy retrofit works. Over years, there might be possible gas price falls that reduce energy savings to pay back the initial investment cost. Tables 12 and 13 summarized the obtained results.

Table 12

Sensitivity analysis r = 3,4%; + 2% Energy price decrease

ΔE_{price} = +2%	r = 3%				r = 4%			
	NPV	LCC	ARAUJO	B-C	NPV	LCC	B-C	ARAUJO
S1	-19599	377807	12.26	1665	-20867	334781	-2441	15.28
S2	-10109	383046	4.96	39424	-14244	342164	32451	9.83
S3	58117	**307914**	**-79.95**	121476	46094	**275258**	106616	**-71.22**
S4	-13470	412190	24.02	27379	-21060	373495	16950	31.58
S5	55595	336218	-58.83	124338	39950	305917	105855	-47.31
S6	**67494**	339049	-71.81	**164773**	**48728**	311145	**143169**	-58.33
S7	51835	380490	-42.39	147872	31205	353183	124404	-27.05

Table 13

Sensitivity analysis r = 3,4%; - 2% Energy price decrease

ΔE_{price} = -2%	r = 3%				r = 4%			
	NPV	LCC	ARAUJO	B-C	NPV	LCC	ARAUJO	B-C
S1	-36496	224358	547.85	-15232	-35005	206386	497	-16579
S2	-29832	232424	645.52	19701	-30747	216134	605	15948
S3	**5820**	**189864**	**42.13**	69180	**2336**	**176483**	**91**	62858
S4	-47514	275888	1229.50	-6666	-49546	259448	1132	-11537
S5	-6025	227492	550.03	62718	-11610	214944	561	54295
S6	-3615	239812	701.21	**93664**	-10770	228111	707	**83670**
S7	-27293	289272	1367.32	68745	-35003	276858	1302	58196

CONCLUSIONS

[IN PROGRESS….]

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