Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Curriculum in Civile, Edile, e Architettura

Design of cardboard prefabricated temporary dwellings through economic and hygrothermal assessment

According to nZEB requirements in warm-temperate climates

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Abstract

One of the most important targets enforced by EPBD recast is that by end of 2020, all new buildings have to be nearly zero energy buildings. In the current regulation, some building type categories are excluded from this assessment procedure, including temporary buildings with usage period less than two years.

Although prefabricated construction has been developed lately, energy performance studies have rarely been carried out for them. However, one crucial stage in post-disaster housing is the accommodation period in temporary homes which may last three years or more. Therefore, it necessitates more serious attention to their energy efficiency. This research addresses the aforesaid concerns.

In this study, the cost-effective and energy efficient design of emergency temporary homes suitable for Italian context with a focus on regions with warm temperate climate is considered.

As an innovative, 100% recycled, and low environmental impact material, honeycomb cardboard was taken for wall insulations; experimental and analytical investigations were carried out to determine its thermal and environmental characteristics.

A building typology was designed with flexibility and expandability features to be taken as reference building. Its wall, roof, and floor envelopes were designed, assessed regarding heat and moisture transfer, and modified to be compatible with the latest energy performance requirements. Whole building energy simulations were carried out in three warm Italian climate zones (B, C, and D) to investigate effect of climate conditions on their thermal energy needs. Performing a parametric study on the opaque envelope thermal transmittance in the required ranges of regulations, it was analyzed that from cost-effectiveness energy efficiency viewpoint, in milder climates envelope variants with less thermal resistance and in warmer climates with higher ones rather than the required limits could be located in the cost-optimal corridor. In addition, various time horizons were assessed and it is suggested that by considering the most influential capital and replacement costs, the most appropriate life time for the prefabricated building must be chosen for the "second life" after occupancy period. Details of the optimum solution ranges found are presented in this study.

Abstract (Italian)

A causa dei cambiamenti climatici e della sempre più limitata disponibilità di risorse non rinnovabili, sono state introdotte regolamentazioni sempre più stringenti riguardo al consumo energetico sia nei paesi della UE che nel mondo.

Uno dei più importanti target tracciato dalla direttiva EPBD per la fine del 2020 è che tutti i nuovi edifici devono essere a consumo quasi zero. Nella legislazione corrente gli stati membri possono tuttavia escludere alcuni tipi di categorie di edifici da tali regolamentazioni. Tra questi anche gli edifici "temporanei" e cioè con periodo d'uso inferiore ai 2 anni.

Tuttavia la realizzazione di edifici ad uso temporaneo sta divenendo sempre più frequente ed utile a risolvere problematiche, come ad esempio la fase di vita post emergenza, che richiedono un periodo di vita dell'edificio che può essere anche di molti anni, come dimostrato dalle fasi post-sisma succedutisi in Italia ed in altri paesi. Ciò nonostante gli edifici temporanei raramente vengono analizzati sotto il profilo delle performance ed in particolare della performance energetica.

In questo studio si affronta pertanto la progettazione e la verifica in termini di sostenibilità economica ed ambientale di edifici temporanei per il contest climatico Italiano o per regioni con climi similari.

Il progetto si basa sull'impiego di un materiale riciclabile al 100% costituito da pannelli in cartone a nido d'ape. Sono state condotte analisi sperimentali ed analitiche utili a verificare l'idoneità per lo scopo specifico.

E' stata quindi progettata una tipologia edilizia caratterizzata da capacità di essere flessibile ed espandibile. Sono stati progettati con l'edificio I component edilizi di parete e di copertura con particolare riguardo alle loro prestazioni termo-igrometriche nell'ottica delle prestazioni previste alla fine del 2019.

Simulazioni relative alle prestazioni offerte in diversi contesti climatici (classi B,C,D del contest nazionale) sono state condotte anche a riguardo della sostenibilità economica della Costruzione in una ottica costi-benefici tenendo in considerazione diversi scenari temporali.

Dettagli relativi alla soluzione ottimale sono infine presentati nello studio.

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Chapter 1.

1 Introduction

1.1 Motivation

Buildings account for 40% of total energy consumption in the European Union. As this sector is constantly expanding, energy consumption is expected to increase even more (Figure1.1). Therefore, reduction of energy consumption and use of energy from renewable sources in the buildings sector are important measures needed to reduce the Union's energy dependence and greenhouse gas emissions [1].

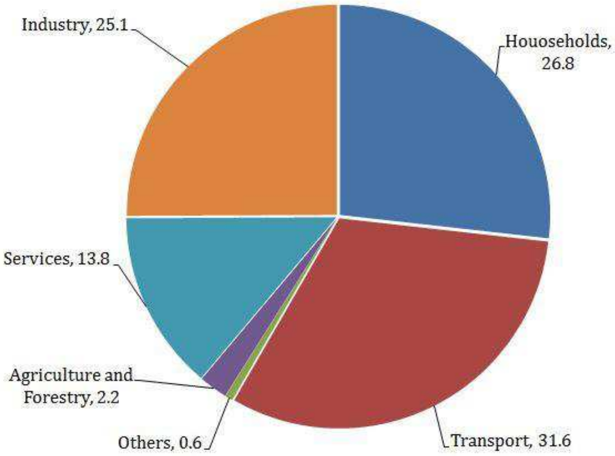
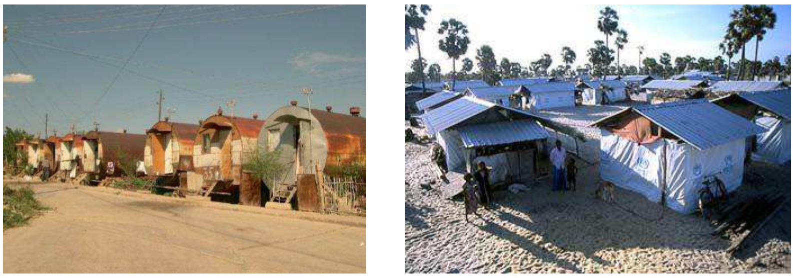


Figure 1.1: share of final energy consumption, 2013 (% of total) [2]

As one of the resolving approaches to this goal, the world is shifting toward automation and off-site construction. Hereby, prefabrication has developed as a sustainable construction method in last decades. Prefabrication could provide improved sustainable performance in construction industry in many different ways. By industrialized housing production, waste generation is reduced and waste management as well as recycling process is more controllable. Easiness of recycling building components at the end of their life time is another benefit which is due to removability of factory-made elements. Additionally, less fossil fuel for transportation of labor and materials to the site leads to considerable reduction in energy consumption.

Prefabrication also plays an important role in providing temporary shelters in unpredicted humanitarian or natural catastrophes. The number of natural disasters has drastically increased in the last decades and had a considerable impact on the built environment. Most of the buildings suffer extensive damages, many of them collapse entirely, and the destruction of houses is one of the most visible effects of a disaster, causing high numbers of homeless people [3]. Majority of prefabricated homes which are built for temporary purposes such as disaster, war and other sudden incidents, are operated due to urgent need and tight budgets and therefore are mostly treated as living containers or inhabitable spaces with very low level of efficiency in term of energy (Figure1.2.a & b). After a disaster, several decisions must be made on issues such as site selection of temporary dwellings, facility providing, and finance supplement; hence, it would be a great benefit in time saving to have high energy performance buildings in hand in advance. Due to aforementioned reasons, prefabricated homes have grown dramatically recently and it is predicted that in near future role of prefabricated buildings in construction sector will be emphasized; however there is a lack of scientific study on their energy performance assessment and improvement.

According to D. Félix et al.[4], significant research efforts in the area of prefabrication construction have been devoted to design, production, transport and assembly strategies (28%), development and application (27%), and industry prospect (26%), while relatively less attention has been paid to performance evaluation (9%) and environment for technology application (10%). Future research should therefore be conducted to bridge this research gap and to understand the evolution and application of prefabrication technology in residential buildings in private enterprises [5].



(a) (b)

Figure 1.2: (a) Containers at the outskirts of Yerevan, Armenia, August 2003[6], (b) Transitional shelters for tsunami survivors waiting for permanent houses, Sri Lanka

1.2 Objectives

In 2010, EPBD recast, has requested investigations on numerous building types to achieve cost effective nZEB energy performance level; although a large number of researches have been carried out on residential buildings in various contexts, no study has been undertaken on prefabricated building category. There are some specific features which distinguish prefabricated homes from conventional residential buildings that necessitate a different trend of research on the subject, e.g. shorter life time, non-associated to a specific site, particular construction techniques, and particular allocated budget for construction.

Thermal behavior improvement of this building type as well as reducing their life cycle costs will end in significant benefits both in economic and environmental aspects. Despite the general perception among public that sustainable projects are more expensive in a harmful way which is mostly due to their higher initial costs, it's impossible to decide on their cost-efficiency without assessment of their global costs which considers running costs during life cycle as well.

1.3 Structure and Articulation

Purpose of this work is to perform studies on Cost-optimal levels and minimum energy performance requirements in prefabricated temporary dwellings. This thesis is aimed at demonstrating the optimal solution among examined Energy Efficiency Measures (EEMs) that could be chosen for temporary prefabricated building units in design stage in term of energy performance and cost efficiency. In this way, dynamic thermal simulations were carried out to assess the impact of different design scenarios and various solutions were compared from the viewpoint of energy savings and global cost. For this aim, a basic prototype with different configuration possibilities and surface areas were designed for dwelling units based on various consumers' functional preferences. City of Ancona located in central Italy with a warm temperate climate is taken as the representative context of prefabricated prototype units.

As it is demonstrated in literature [7], time period length plays an important role in cost calculations. The longer the study period, the more cost-effective energy efficiency designs become because the energy savings occurs year after year while the first costs are constant and the additional cost of maintaining the building is relatively small. Therefore, in order to increase feasibility of low energy design and application of energy efficiency measures, one possible solution is to consider longer life time rather than the

life time currently expected for emergency temporary dwellings. This requires proposing a different usage scenario as well as a study to realize the correlation of cost effectiveness of energy efficiency measures and building life time.

Focus of the study was put on building walls as the largest share of building enclosure area with the greatest impact on its energy performance. Cardboard as a recycled and recyclable material was chosen for thermal insulation of wall envelope to be replaced conventional insulation materials. Its thermal characteristics were examined by experimental tests and its actual thermal conductivity obtained. Accordingly, wall envelope stratification was developed and its thermal and hygrometric properties were assessed. A range of variants, i.e. design packages which consider varieties in envelope insulation level and climate conditions of potential emergency site were defined and investigated.

Next phase of study encompasses dynamic energy simulations on prototypes under warm temperate climate in order to find out their energy needs and through life cycle cost calculation methodology seeks for the possible cost-optimal solutions. In this way, effects of each of aforementioned variant parameters have been observed in cost-optimal nZEB level; by performing the analysis for all three dwelling prototypes, the impact of unit size was also investigated in obtained results.

Findings of this study could be generalized in identical climates with economical characteristics close to Italy. In addition, new fields of study are raised to re-apply the suggested methodology in different climates and geographical contexts to obtain more comprehensive results for achievement of optimal solution in term of energy efficiency and cost effectiveness.

Chapter 2.

2 Literature Review

This chapter provides an overview of the relevant research that has been conducted within the study area and develops an extensive literature review concerning the state of the art. According to the subject of research, this survey is classified in such a way to shape the entire project. This research addresses the main themes e.g. temporariness of buildings, prefabricated methods in construction, utilization of cardboard in buildings, requirements of nearly zero energy buildings, thermal assessment of envelops, and Life Cycle Cost (LCC) analysis of buildings. Within each category, the major existing knowledge which was taken into account as the pillars of current study is highlighted.

2.1 Temporary prefabricated buildings

'Temporary dwelling' first of all is the physical structure in which people live in a temporary period, due to extraordinary circumstances [8]. After a disaster, a shelter can be provided quickly, and this fulfils the most basic needs, however, it is not the recovery that people want in a longer term. It is linked to urgent and life-threatening situations. Therefore, it is crucial for the designer to combine architectural aspects with urgency. In addition, according to the reported cases, in many occasions the recovery process after a disaster is slower than predictions; this fact justifies dwelling with a higher quality of life since there is no guarantee for time duration that residents would live in them. Since reconstruction lasts long, there is a time gap that needs to be covered and temporary housing seems to be the appropriate solution [9]. Hence, longer periods of living in temporary housing must be predicted and they should be designed in such quality and functional characteristics in order to manage extra inhabit periods.

2.1.1 Terms

According to UNDRO [10], temporary housing is one of the eight basic types of post-disaster shelter provision. The classification proposed by UNDRO reflects what Quarantelli [11] also considers the variety of unclear ways the terms "shelter" and "housing" are used in the literature of post-disaster housing.

Four different stages in housing recovery are defined by Quarantelli [11]: (1) 'Emergency sheltering'; supplied during the peak of the emergency immediately; it may be as simple as a plastic tarp. (2) 'Temporary sheltering' is generally used for several days to several weeks after disaster; these may be tent camps, or public buildings to be used as collective shelters. (3) ‘Temporary housing’ stage in which families are able to resume their daily activities, such as school, work, and other social functions; they might be a small prefabricated house or a rented apartment. (4)‘Permanent housing’ is the final stage in the housing recovery, when families have found their pre-disaster housing conditions again with a long-lasting solution that has a similar or better quality.

This way, a temporary housing can be firstly defined as the physical structure in which people lives after a disaster; secondly a part of the post-disaster re-housing program; and thirdly a place to shelter victims during the period since the disaster occurs until they are resettled in their permanent place [12].

For prefabricated, mass-produced and standardized construction, two main groups can be identified: ready-made units and kit supplies (Figure 2.1, 2.2). The ready-made units are housing solutions totally factory- constructed that just need to be transported to the site where they will be placed. Main challenge regarding these unit types is their movement to installation location, particularly in an area with difficult access which require heavy transport systems; that’s why many projects are developed based on kit solutions. On the other side, the kit concept also tries to benefit from the advantages of prefabrication, but instead of producing finished units, it produces small elements that constitute the unit and need to be assembled in place [4].

2.1.2 Challenges

As mentioned in [4], Hidayat et al. shows that previous studies have presented many problems related to post-disaster housing. As a consequence, very often post-disaster housing solutions fail their own objective [13], [14].

Temporary housing has been mainly criticized in the literature due to problems of sustainability and cultural inadequacy issues [12], [13], [15], [16]. Sustainability problems in post-disaster temporary housing solutions seem to be in two ways; they are unsustainable firstly in terms of costs and secondly in terms of environmental issues. According to UNDRO [10], a temporary unit can cost more than a permanent house and some authors refer that it may be three times more expensive. As Johnson [17] stated in this way, temporary housing is an expensive solution compared to its lifespan because it comprise considerable investments in units that will only be used during a short period of time. This problem requires improvements in term of their life-time frame.

As Arslan [18] discusses in his study, the units are still usable after their intended period of use and the problem is how to treat a lot of remained structures; since most of the times there is no plan for that, the units are simply disassembled without any concern about the future of residual components.

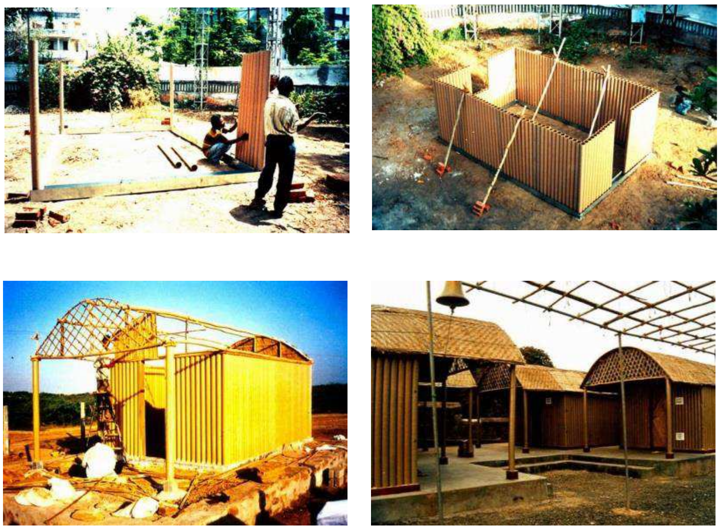


Figure 2.1: Kit concept, Paper log house by shigeru ban, India, 2001

Figure 2.2: Ready-made concept, FEMA Trailers. After Hurricane Katrina, US, 2005

This procedure is a notably unproductive approach that causes great resource losses ending in great environmental consequences. Therefore, re-use of temporary houses plays an important role and waste management following a natural disaster should not be underestimated. Johnson [17] suggested that these issues must be on top priorities of attention and recyclability plans for houses, land and infrastructure should be considered. In other words, temporary housing 'second life' must be properly defined.

Regarding second life of temporary housing, Arslan and Cosgun [19] reveal some possibilities for re-use and recycle of units; (1) for the same function and without additions; (2) for the same function with some extensions to enlarge the house according to resident's demand; (3) for different functions, such as youth camps, holiday camps, etc.

Similarly Jonhnson [12] introduced five possibilities as following: (1) long-term use of the units; which often causes problems due to social issues, (2) dismantling units and storing them to reuse in future disasters; which may be as costly as a new unit, (3) selling the units or parts of them; which partially recovers the costs, (4) demolishing the units to sell or to donate its parts; which due to their final condition they often have little value, (5) reusing the units; which may involve extra costs to disassemble, transport and reassemble in the new location. Johnson also concluded that rental of temporary housing to low income residents, reuse as new community buildings, and applying units as core for permanent housing are the most economic, social and environmental sustainable methods. In conclusion, independently from the functions of reuse, a 'second life' is an opportunity to enrich the high investments needed to provide units and to avoid sustainability problems [4].

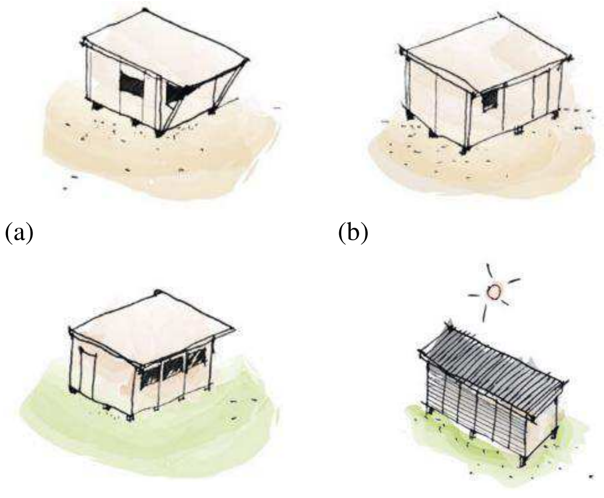
Time management in supplying temporary houses is another fundamental issue; Import of units means long delays in the process of victims' settlement due to the time required to produce, transport and place the units on the site and people have to stay in temporary shelters longer than planned time. Since those temporary settlements are not planned for long periods, some social problems can appear [16]. Therefore, providing temporary homes within the predicted schedule and in a quick manner is crucial in post-disaster accommodation management.

Neglecting cultural and geographical conditions as well as users' needs is another problem. concept of a universal or standard solution is not feasible because it ignores users' real needs, climatic variations, cultural values variations, family size variations, etc. which end in unsustainable products [10].

2.1.3 Advanced movements

FEMA trailers as previously presented in Figure 2.2, is one of successful emergency home examples executed after Hurricane Katrina in 2005 in the US. They have both possibilities to be constructed on site or placed on wheels and transported. In addition, some of them have been recycled to become permanent houses for utilization in different states.

In Chile which is subject to several political and natural disasters and the consequent problem of homelessness is an important issue, a specific design process has been raised that responds to catastrophes from the very beginning moment and evolves through time. Besides, it considers energy efficiency strategies and sustainability policies. The evolving logic in design process covers all stages of inhabiting described by Quarantelli [11] in 2.1.1. (1) Survival module which meets basic needs immediately after a catastrophe in emergency period; (2) Mechanical module in which bath, kitchen, and technical core are added during relief period; (3) Living module, the house is expanded more than basic needs, transforming modules to a definitive home; (4) Sunspace, which applies passive solar strategies (Figure 2.3) [20].



(a) (b)

(c) (d)

Figure 2.3: (a) Survival module, (b) Mechanical module, (c) Living module, (d) Sunspace [20]

2.2 Prefabricated building industry

According to Sparksman [21], prefabrication is defined as a manufacturing process taking place in a specialized facility where various materials are joined together and form a component which is prepared for the final installation procedure. In the construction field, prefabrication is considered as the first stage of industrialization followed by mechanization, automation, robotics, and reproduction [22].

There has been a great demand for housing due to World War II; to address the housing shortage, several Asian and European countries utilized prefabrication techniques to accelerate housing production. For example, mass production of housing using prefabrication was found in Japan since 1965 [23].

Also in the UK, in the 1960s and 1970s, lots of prefabricated buildings were built, mainly reinforced concrete structures [24].

Key advantageous features of prefabricated buildings which make them suitable in numerous project types are better supervision on the quality of the building, reduction of overall construction costs, shorter construction time and waste generation reduction, noise and dust reduction, low resource depletion, and reduced labor demand [5],[25]. Nowadays prefabrication has become dramatically important to the entire construction industry; however, there are hindrances associated with current practice in application of prefabrication techniques that limits its spread, e.g. inflexibility for changes of design, higher initial construction cost, leakage problems and low thermal performance, aesthetics issues and monotonicity of building; which this study seeks to propose solutions to lessen mentioned deficiencies [25].

In terms of the level of prefabrication, according to [26], four types are defined: conventional, semi-prefabrication, comprehensive prefabrication, and volumetric. Also, in other sources in the literature [15],[22] degree of prefabrication in buildings is described in the order as following: (1) component manufacturing and sub-assembly that are always done in a factory instead of on-site production, (2) non-volumetric pre-assembled units which do not enclose usable space, (3) volumetric pre-assembled units which enclose usable space and usually being manufactured inside factories but do not form a part of the building’s structure such as toilets and bathrooms, and (4) whole buildings which are pre-assembled volumetric units including the actual structure and fabric of the building such as motel rooms.

In last decades, although a great number of prefabricated construction projects have been implemented, little research has been done on their architectural effectiveness, energy efficiency, and cost-benefit analysis for different construction projects; In Hong Kong, effectiveness of prefabrication in public and private sectors was evaluated through the two leading case studies adopting precast structural elements and volumetric precast modular units. Financial comparison of material usage alternatives and benefit analysis of gross floor area between the case studies were examined and discussed and explorations for effective use of prefabrication are also carried out [28].

In the following section, a few number of advanced implementation of prefabricated projects which apart from providing a basic dwelling, have paid sufficient attention to energy and architectural issues, are presented.

2.2.1 Recent achievements in prefabrication

Prefabrication has been developed since the 1970s; within the past thirty years, its related technologies have been developed remarkably. In the past, most of prefabricated buildings were in an inadequate comfort condition and with high energy consumption and were known as poor quality products; but nowadays the strategies to reduce energy consumption and increase comfort of residences are also carried out on prefabricated homes. A large number of manufacturers all over the world are involved in this area and have supplied advanced examples of prefabricated homes to the market which vary widely in terms of construction technologies and materials.

An example of inexpensive prefab cabin in the US firstly built in 2003 and gained international attention developed through the following years. Building in a factory setting allows for increased accuracy. It takes benefit from a number of sustainable strategies e.g. rain water collection, solar thermal and solar

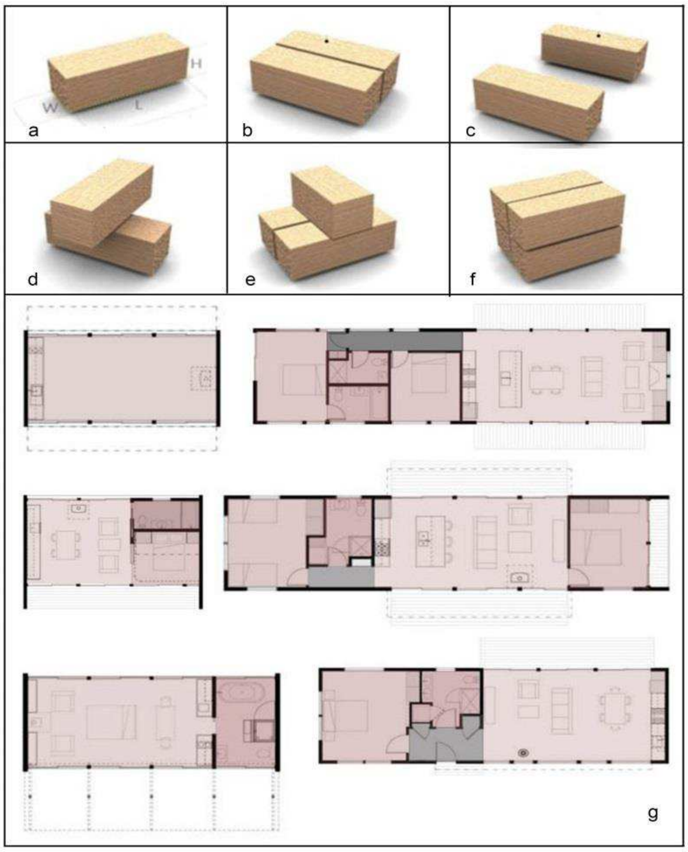


Figure 2.4: (a) One module, (b) Two modules-Pair, (c) Two modules-Twin, (d) Two modules-Cross, (e) Three modules, (f) Four modules, (g) various configurations of linear one module example [29]

photovoltaics. Building blocks are considered from one to four modules which form a wide variety of compositions for each. A review of their planning layouts with a particular focus on smaller size modules was carried out to study the optimized arrangement for spatial minimization and obtained lessons be applied in the typology design of this study (Figure 2.4) [29].

There are also other leading bodies in this field who presents avant-garde images of prefabrication industry by their performed buildings; buildings which are not distinguishable from common conventional ones and have an equal level of comfort or even more [30]–[32]. Technological aspects of their experiences provide valuable information on state-of-the-art in market and possibilities of the construction industry. Some of outstanding examples are seen in Figure 2.5 and 2.6.

2.2.2 Sustainable issues in prefabrication methods

“Triple Bottom Line” which is the conceptual framework of sustainable development comprises environmental, social, and economical dimensions.

Li et al. [5], who provided a systematic summary on the research development in the management of prefabricated construction, advised that the existing literature should be further extended to establish a more holistic indicator systemin order to cover all economic, social, and environmental perspectives in assessing the effectiveness of prefabricated construction.

Figure 2.5: Living home series, US, (a) construction phase, (b) Installation phase, (c) Completed project, (d) Custom Ray, Designed by Ray Kappe, US [30]

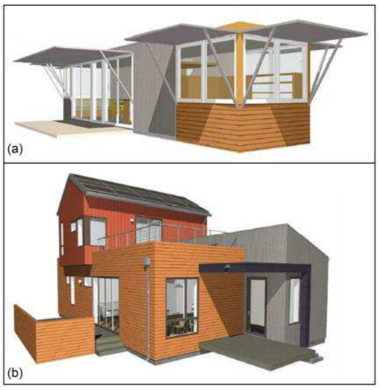


Figure 2.6: PieceHome series, (a) No320, (b) net Zero [31]

In general, construction of buildings generates significant quantities of waste, on average up to 10% of the volume of materials used in constructing conventional buildings are the waste [33]. Several statistics have been reported waste reduction through prefabrication methods which could be a considerable benefit in term of sustainable development. Tam et al. [26] in their research revealed that waste generation can reduce by 100% through adopting prefabrication [25]. Another prefabricated home manufacturer [30] reports that in a traditional home, 30-40% of materials are as waste; but in a modular building process, it could be reduced into about 2%. Results of a comparative analysis among prefabricated and non-prefabricated examples reported that using prefabricated modular technologies could reduce total waste generated during a building's life cycle to 60%; And among studied technologies with various level of prefabrication, the case with the highest degree of prefabrication showed the lowest solid waste generation [34].

Life cycle Assessment (LCA) of prefabricated buildings is also dealt with in several publications; Aye et al. [33] investigated the potential life cycle environmental benefits of prefabricated modular buildings to determine possible advantages of construction method over conventional construction methods in term of environmental performance. It showed that reuse of materials help in reducing the required space for landfill. Additionally, the requirement for raw materials and in this manner can lead to environmental benefits compared to conventional construction systems. Also, it was observed that potential for embodied energy savings by reuse of materials is significantly greater in prefabricated steel construction system compared to timber and concrete [33].

Similar LCA analysis carried out on a number of prefabricated schools built in Spain [34] classified in three categories based on their building technologies and structural material composed of concrete, steel, and timber. CO_2 emission and generated waste were studied as two main indicators in LCA method and obtained results were compared with a non-prefabricated one. In both indicators, these prefabricated school buildings showed a lower environmental impact respect to those built with other techniques. Regarding solid waste generation, non-prefabricated is about two times worse than steel prefabricated technology while in CO_2 emission comparison, steel is at a level relatively similar to non-prefabricated technology. Additionally, Steel technology showed the highest level of recyclability of material in demolition phase.

2.3 Application of cardboard in building construction

In recent years, significant progress has implemented in advanced materials research for building envelope applications. Most of the latest developments of materials come from renewable sources. Cardboard is one of the eco-materials which has been the subject of study and practice in last decade. Corrugated cardboard, is one of the main products used in packaging today [35].

Corrugated cardboard consists of straight liner layers and a corrugated middle core that are glued together at the corrugation tips. Single, double and triple wall boards - i.e. boards having one, two or three layers of corrugated paper - are being produced (Figure 2.7). However, the majority of the production is single wall boards [36].

(a) (b) (c)

Figure 2.7: (a) single board, (b) double board, (c) triple board

2.3.1 Background

First tracks of cardboard application in architecture dates back to periods after World War II, specifically in the project known as “The 1944 House” made of 1-inch corrugated cardboard. In later decades, Buckminster Fuller [37] performed his geodesic dome construction projects by paperboard. In the first decades after the birth of cardboard application in construction, it progressed relatively slowly due to serious limitations against moisture, fire, and mechanical resistance as well as the availability of other competitive new materials. It’s noteworthy that environmental issues and were not at the highest importance to weigh cardboard because of its sustainable potentials.

More recently Shigeru Ban [38] carried out valuable experiences using cardboard and demonstrated its capacity as an architectural and structural material.

In the last two decades, cardboard as a building material has appeared both in executed projects and scientific studies in order to recognize its potentials and characteristics. Both these two fields are reviewed in the following sections.

2.3.1.1 Implementation

In a number of performed building projects, cardboard has been used as a structural element in construction mostly for temporary purposes.

As seen in Figure 2.8, in a project in the UK in 2001, “Westborough after school club” the idea of utilization of cardboard as a recyclable, low cost, and widely available material in the forms of panels and tubes was considered. Folding panels were taken as the perfect solution to stiffen elements and increase their mechanical resistance. Technical verifications confirmed an acceptable thermal performance; the 160 mm thick composite panel made of honeycomb cardboard guarantees thermal transmittance of 0.32 W/m^{2}K.

In 2009 in Switzerland in the project ran by Architect Dirk Donath, benefits of honeycomb cardboard considered to present a housing solution to be implemented in developing countries for emergency situations based on a modular system with the basic dimensions of 1.25 m × 1.25 m (Figure 2.9). Cardboard panels applied in this project produced by a swiss manufacturer with the varying thickness from 25 mm to 250 mm which are connected to each other by heavy duty adhesives and corner profiles and provide the fundamental

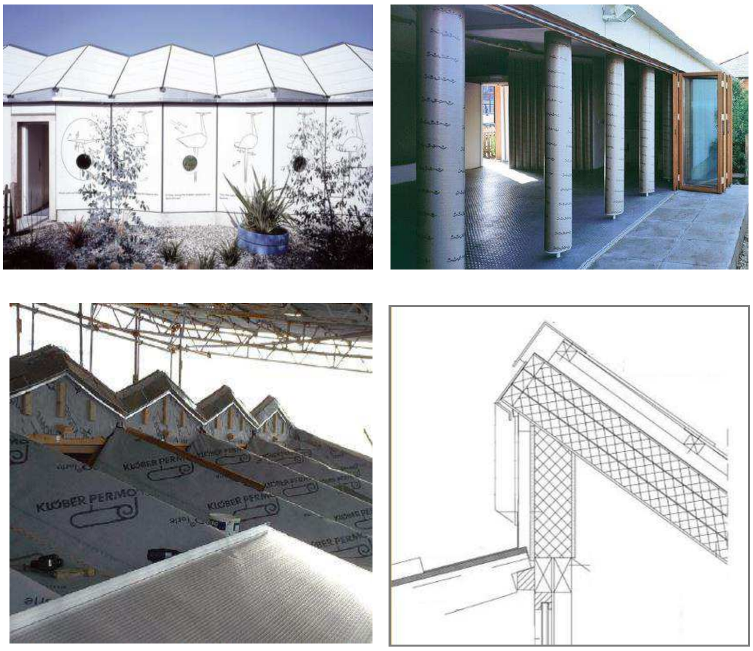


Figure 2.8: Westborough after school club, UK, 2001[39]

characteristics e.g. light-weight properties, insulating capacity, fire, heat, humidity, and mechanical resistance, cheapness, and recyclability.

In another outstanding student project in Milan, 2009 (Figure 2.10) cardboard was applied as the main construction element for visitors' resistance unit in Expo 2015. Cardboard panels produced by an Italian manufacturer [40] are 200 cm high, 60 cm wide, and varying thickness from 5 to 60 cm and specific mass of 30 and 45 kg/m^3. Regarding their assembly system, panels can be positioned both vertically and horizontally and fixed by inserting in appropriate metal or plastic guides. Several materials are chosen as the coating that provide different durability level. Tests showed resistance of 350 kg/m^2 for 30-thick slabs with 5m×5m clear span and excellent thermal, acoustic, and permeability performance (Thermal conductivity is reported as 0.11 W/mK and 0.07 W/mK for two different types).

Figure 2.9: Universal World House, Switzerland, 2009 [41]

Figure 2.10: Bertech System [42]

2.3.1.2 Research studies

Recently in several research and academic centers, cardboard has become as the target of study to make it suitable for longer life span respect to previous experiences for short-term purposes. Valuable studies for development of cardboard as a potential building material have been executed in Building technology Department at TU Delft university comprising various activities in order to find a solution to utilize cardboard in both architectural and structural terms[43].

In a doctorate dissertation by Pelosi [44] has been previously conducted in Università Politecnica delle Marche, corrugated cardboard was considered for the construction applications in building envelopes, particularly in emergency cases and an innovative assemblage method was suggested and implemented in a pilot experimental project by means of modular 7 mm thick cardboard pieces.

In the research of Pohl [36], the behavior of light weight corrugated cardboard in sandwich load bearing elements in different dimensions and characteristics both analytically and experimentally was studied and its relevant properties e.g. thermal conductivity as well as the elastic moduli and strengths in shear and compression were determined. The performance of cardboard in humid environments was studied and proper impregnation treatment methods were suggested for material protection against moisture.

In a parallel research project carried out in the same institute- Swiss Federal Institute of Technology- by Ayan [45], corrugated cardboard was chosen as a potential building material due to its advantages, specifically as sandwich composites in wall component. It had a comprehensive in-depth look into societal, environmental, thermal behaviour, structural, and architectural aspects and demonstrates the feasibility of corrugated cardboard employment as the main wall element in contemporary housing industry.

2.3.2 Physical properties

Various types of corrugated cardboards must meet certain quality standards in terms of appearance, thermal and mechanical properties.

2.3.2.1 Thermal properties

In a honeycomb paperboard filled with air, heat transfers through the fiber network by conduction between the fibers and also by convection of air and water vapor in the pores. Heat transfer by radiation is negligible. Thermal resistance of corrugated cardboard depends on the thermal conductivity of its components and the size of the corrugations. Because air is a good insulator, boards with larger cavities provide superior thermal insulation properties [36]. Different references have reported various values for thermal conductivity of corrugated cardboard. Thermal conductivity of paper through its thickness at room temperature has been reported to range between 0.013 - 0.15 W/mK by Bohmer [46]; Ramaker [47] states that at room temperature its transverse thermal conductivity ranges from 0.045 W/mK for boards with larger corrugations to around 0.29 W/mK for boards with small corrugations. To the author’s knowledge, no measurements of its in-plane conductivity are available yet.

2.3.2.2 Mechanical properties

Corrugated cardboard is considered as a byproduct of paper which inherits its properties from cellulose fiber bondings. However, its composite structure maximizes its stiffness due to bending layers in the core. Overal, the better tensile strength belongs to the perpendicular direction to the waves and conversely compression strength in the parallel direction of waves. If greater resistance for vertical compression is desired, higher waves must be considered for corugations.

According to Pohl [36], sensitivity to moisture and combustibility of cardboard are two downsides for its application as a construction material. Just like the paper layers themselves, corrugated cardboard loses strength in moist conditions, and its elastic moduli decrease considerably. It was found that the compressive strength of the paper honeycomb in humid environments may be reduced by about 25% of its strength in dry environments, and that wet honeycomb does not offer any resistance to compressive loads. To eliminate this deficiency, it has to be protected against moisture e.g. by an environmentally friendly cementitious impregnation liquid coating to improve its moisture resistance and makes the material almost non-combustible. In experimental studies carried out in this research, maximum measured tensile load for the sample with 32 mm thickness were found to be 23 kN and 46 kN in two different configurations.

2.3.3 Sustainability potentials

Paper is essentially an environmentally friendly material, because it mainly consists of natural fibers that are extracted from renewable resources. Some parts of the production process can have damaging effects on the environment. However, the extracted wood fibers can be reused for paper production for several times and can be composted at the end of their lives, releasing only the carbon dioxide in the atmosphere that was originally bound by the trees. Corrugated cardboard is also as environmentally friendly as its paper layers. It generally consists of recycled paper and a starch-based adhesive and can be recycled and reintroduced into the paper production process with minimal impact on the environment [36].

2.4 Building energy performance

Buildings are the largest energy consuming sector in the world and account for over one-third of total final energy consumption and an equally important source of CO_2 emissions [48]. These concerns have ended in tighter building regulations.

In Italy, building energy performance requirements are indicated in the mandatory national standards D.Lgs. 311/06 and D.P.R 59/09. Later, Decree n 63/2013 came into force in Italy as the instruction provided based on EPBD recast 2010/31/EU as a modification of previous national regulations.

There are other European criteria which are taken as voluntary regulations like Standard PassiveHaus and Standard Casa Clima. The PassivHous criteria allow buildings to go by either criterion - the 15 kWh/m²yr heat demand or the 10W/m² heating load. Also, conventional Primary energy use may not exceed 120 kWh/m²yr. their air leakage is supposed to be no more than 0.75 m^3/m^2hr @ 50 Pa (0.6 air changes per hour) and the entire building must be thermal bridge free design [49].

Due to very different climatic conditions in geographic locations worldwide, no unique values are established for energy needs of low energy buildings [50].

2.4.1 Nearly zero energy building (nZEB) Principles and standards

In the last two decades in line with concerns of climate change and shortage on non-renewable energy, several new standards emerged and have come in force with increasing levels of exigency.

On 16 December 2002, the first European Directive for the Energy Performance of Buildings (EPBD) [51] - provided by the European parliament and the council of European Union- was adopted and the Member States had to adjust the Directive into their national laws. This regulation was adjusted for Italian national legislations in D.Lgs. 192/2005 and established methodologies for energy loss calculations in buildings. Later it was modified in 311/06 and subsequently D.Lgs. 59/09 which have determined minimum requirements of thermal transmittance as well as space heating and cooling demands.

Later in 2010, EPBD recast requested member states to ensure that by 31 December 2018 public buildings and by 31 December 2020, all new buildings are nearly zero-energy buildings. According to definition presented in EPBD recast, 'Nearly zero-energy building' is a building that has a very high energy performance which nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. The measure of "significant" is not defined. When determining the renewable energy share, regulations must consider both possibilities and constraints. However with a high renewable energy utilization, it is technically possible to reach zero or positive energy buildings, limitations in the renewable energy potential in buildings must be taken into account [52]. The Member State's definition of nearly zero-energy buildings reflects their national, regional or local conditions and includes a numerical indicator of primary energy use expressed in kWh/m^{2}yr. The primary energy may be defined as the energy potential presented by the non-renewable energy sources in their natural form without applying any conversion process. According to szalay [52], advantage of the qualitative definition for nearly zero- energy buildings in the EPBD recast is that it depends on Member States to adapt the definition according to their specific conditions and climate.

EPBD recast also requested member states that their minimum energy performance requirements for buildings must be complied with a view to achieve cost-optimal levels. Main purpose of this type of study is to make a proper link between financial targets and building energy performance [1]. This regulation recommends a two-step approach, i.e. application of energy efficiency measures to a cost-optimal level and suppressing the remaining energy needs through on-site renewable energy production.

2.4.2 Energy performance analysis methodologies

In accordance with building energy performance legislations, several buildings design optimization studies have been carried out to minimize energy consumption through modifying different characteristics of buildings [53]. In these studies different kinds of quantitative models have been developed and various fields of application have been investigated e.g. envelope insulation level, insulation material, thermophysical properties, thermal mass, windows properties, HVAC systems, lighting, etc. In some researches, individual impacts of design variables are considered and in others, their effects in an interactive way studied. These methods mostly have an aim for seeking the most economically profitable solution by analyzing financial indicators. Boeck et al. [54] in their paper provided a comprehensive review on available literature related to possibilities of energy efficiency in the residential sector. In their review, it could be seen that many studies were carried out on the correlation of energy performance improvement of buildings and building envelope. Since thermal loads of buildings depend on the thermal transmittance of its envelope significantly, high focus of researches on this issue is reasonable.

Balaras et al. [4] investigated the potential for energy conservation in apartment buildings, in three climatic zones of Greece. They used a methodology which includes several scenarios that perform energy-related calculations in order to provide an initial assessment of energy consumption and savings obtained from various retrofit actions focused on space heating and cooling, domestic hot water production and lighting. Among the examined scenarios, they identified the most effective ones, suitable for different building constructions and system characteristics.

In another study [55], a calculative methodology-suitable for early stages of design- was developed to identify economic efficient design solutions for residential NZEB. In this methodology which benefits from a computer simulation program developed in Matlab, energy demand-supply as well as the economic indicator of the building for each design alternative are characterized. This methodology was performed on a case study building to illustrate main results that could be derived. Their study confirmed that in most climates, cost-optimal solution is not the extreme energy efficient solution and is achieveble in most European countries only by pushing a few steps toward energy efficient buildings.

Verbeeck and Hens [56] have presented the following hierachy as the optimal choice of energy-saving measures for purpose of retrofit; roof insulation, floor insulation, applying higher performant glazing, more energy efficient heating system, and utilization of renewable system.

2.5 Hygrothermal behavior of building envelope

Overall energy efficiency of buildings can be highly affected by heat and moisture behaviour of building envelope. Higher insulated walls of nowadays are more vulnerable to surface condensation particularly in winter months and colder climatic regions with higher humidity levels and may result in undesirable microbial growth which might deteriorate wall quality and inteior comfort conditions. In addition moving air via envelope due to infiltration phenomenon occurring through cracks or microscopic openings of the envelope may condense when faces colder temperature and generate mold growth.

The great expectation from interior comfort conditions and building envelope performance has put growing importance to the development of hygrothermal analysis methods. The main purpose of hygrothermal analysis is to evaluate the transient heat and moisture transfer through the building assemblage in order to modify them in the case of problem occurrence e.g. condensation or moisture accumulation. As the temperature is accepted to be driving force for heat transfer, moisture transport is linked to various sets of driving forces, such as moisture content and temperature, suction and vapor pressure, generalized relative humidity and vapor pressure, suction and temperature, etc [57].

According to [58] three main reasons to conduct a hygrothermal analysis is described as (1) understanding of enclosure response, e.g. existence of condensation and significance level of thermal bridging, (2) Identification and consequently avoidance of a performance problem, e.g. excessive condensation, decay, (3) Quantification of energy flow through the enclosure and its impact on comfort and mechanical systems.

Generally two major method types –field study and analytical models - are used to assess the hygrothermal performance of envelopes. However, integration of modeling and field monitoring brings extra benefits to achieve valuable data e.g. the research done by Kunzel et al. [59] the model based on WUFI advanced hygrothermal envelope calculation was validated by performing a series of field experiments Perfect agreement between experiment andCnumerical simulation was found.

Regarding hygrothermal performance assessment of light-weight construction, in a study in Slovenia [60] a comparative study on various light-weight building blocks was carried out and their temperature and relative humidity profiles were studied. Measurements in real test houses were performed and supported by simulation techniques.

2.5.1 Experimental methods

Mainly in retrofit projects in which building envelopes already existed experimental evaluation techniques are desired. Besides, in design stages parallel to theoretical analysis, there is a need for reliable hygrothermal assessment with building scale testing of envelope assemblies in real climatic conditions. There are different types of field monitoring techniques of building envelopes; critical areas in building envelopes in term of moisture existence could be identified using in situ moisture measurement procedures. Surface scanning dielectric meters and penetrating conductance meters are used to quantify the presence of moisture in non-conductive porous building material while the former is advantegeous because they do not damage the envelope surface and the latter damages the surface [61]. The thermal infrared (IR) imaging in another method for detecting building envelope problems e.g. heat losses, discrepancies in the temperature field on the external surface, thermal bridges, air leakage, and moisture accumulation.

In several research projects [60], [62]–[65], experimental assessments were performed by applying proper instrumentation e.g. thermoresistance, heat fluxmeter, relative humidity sensor, moisture content sensor, air velocity meter, and thermo-hygrometer to different layers of envelope and ambient in order to measure environment and surface conditions according to instructions described in relevant standards.

2.5.2 Analytical methods

Computer simulation programs have aided considerably in this regard to facilitate modeling and assessment of envelope design to predict the dynamic one-dimensional and two-dimensional heat, air, and moisture transport in them and consequently recognize problematic points. Modeling provides practitioner/researcher with quantitative output and are available in the market in a variety of forms for different applications that can be utilized depending users' purpose. Simplified models are utilized to prepare sufficient information for designers whereas more complex models are for real behavior predictions. Numerous researches [66]–[68] focused on analytical modeling for prediction of heat and moisture transfer through multi-layer building components and their relevant water content and relative humidity and consequently their durability were investigated.

In order to calculate energy losses through thermal bridges, there are softwares which enable the user to calculate thermal properties of assembly as well as taking benefit of visual forms. Their modeling both demonstrates possible deficiencies in thermal performance and probable moisture accumulation in critical junctions. To evaluate the hygrothermal performance of envelope, major input information must be in hand for modeling and simulation, e.g. envelope geometry, material properties, and boundary conditions. Capozzoli et al. [69] used this methodology to analyze a considerable number of typical junctions to identify occurring thermal bridges as a function of design variables. Other authors [70] have run studies regarding the comparison of simplified 1D model to more complex 2D or 3D models to evaluate efficacy of simulation modeling.

2.6 Cost-benefit analysis related to energy requirements

In 2010 Energy Performance of Buildings Directive (EPBD recast) by the council of European union requested the Member States to set minimum requirements for the energy performance of buildings and building elements with a view to achieve the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. In the case of significant discrepancies, i.e. exceeding 15 %, between the calculated cost-optimal levels of minimum energy performance requirements and the minimum energy performance requirements in force, Member States should justify the difference or plan appropriate steps to reduce the discrepancy. EPBD recast clarifies that it is up to member states whether apply the requirements to specific building categories or not. “Temporary buildings with a time of use of two years or less” is also one of the indicated optional categories [1].

As a supplementary document to EPBD recast, in Regulation EU No 244/2012 the Commission has established a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements [71]. ‘cost-optimal level’ means the energy performance level which leads to the lowest cost during the estimated economic lifecycle.

BPIE recommends setting the nZEB requirement in a corridor with the upper limit is the cost-optimal and the lower limit is the best available technology [72]. These levels must be on the balance line since if the requirements are too ‘soft’, it will not reach energy saving purposes and the European standard requirements will not be met, but if the limitations are too strict, many buildings cannot comply with regulations.

In the other hand, the relatively high construction cost of prefabricated technologies has been recognized as the main obstacle of their utilization by public. However, a lot of savings could be achieved during buildings’ life time that is not observable in the construction phase. Therefore, for the development of building prefabrication industry, a more detailed study is required on its life cycle cost to have a more realistic vision of costs for owners and investors [73]–[75].

Then many studies across Europe were done on life cycle cost assessment of various building types which most of them have carried out a comparative LCC analysis among a number of alternatives through variation of different building elements. In this section, an overall look on those previous experiences is presented.

2.6.1 Building life cycle cost (LCC) analysis

Economic analysis assists both sides of builders/designers and stakeholders not to see some items only as added costs at the purchase time and to inform them of the benefits they could be brought through the whole life time of building and the overall profitability. There are numerous economic methods of investment analysis that are often used in the phase of decision-making for buildings; such as payback period, net benefit analysis, savings-to-investment ratio (SIR), adjusted internal rate of return (AIRR), and life cycle cost (LCC) analysis [76].

LCC is a commonly used tool to assess the financial viability of projects. According to the Directive 2010/31/EU, the minimum LCC solution (global cost-optimal solution) determines the minimum energy performance requirements. In LCC calculations, the upfront capital costs at the construction stage and recurring energy costs at the operational stage are taken into account. The lowest LCC of the measured energy options is regarded as the most cost effective. LCC calculations of buildings are executed according to European Standard EN 15459 and supplementary regulation EU no 244/2012 as mentioned in 2.6.

2.6.2 Cost-optimal level achievements in literature

Apart from building energy directives, from a user perspective, the attractiveness to invest in an energy-saving measure strongly depends on its ability to combine cost-effectiveness with good environmental performance [77]. Therefore, before the establishment of new regulations in EPBD recast in 2010, a number of authors performed researches for determination of optimum insulation thickness combined with other design parameters based on their cost analysis e.g. energy saving and payback period [78]–[83].

Later, from 2010 onwards there has been a growing body of research projects in which numerous energy-saving measures were studied as variables and the comparative economic analysis carried out to determine the optimal range of solutions. Among all influential design variables, it is not strange that most of the studies have focused on insulation of building envelope; since it has been proved that insulation optimization is the most effective item in improvement of energy performance and providing cost efficiency as well as CO2 emission reduction.

A study by Audenaert et al. [84], is aimed to realize the economically most profitable combination of insulation in facade, roof, floor and glazing for three representative types of dwellings. It was found out that in order to achieve the maximum profitability from investment in insulation, the key factor for the semi-detached dwelling is the insulation of roof and floor while the insulation of wall and floor is crucial for a detached dwelling.

According to the research carried out by Kneifel [7], the cost-effective energy efficient improvements not only save money but also reduce a building's carbon footprint. A cost of carbon emissions is added to the building owner/operators energy costs based on the amount of energy use and type of fuel source.

One systematic and robust scientific method which was developed to conduct cost-optimal and nZEB energy performance levels calculations is the seven-step procedure by Kurnitski et al. [85] that can also be benefitted for national implementation of EPBD recast in other situations.

In the cool temperate climate of Melbourne, Morrissey [86] applied an integrated thermal modeling, life cycle costing approach to investigate life cycle costs. Their results suggested that the most cost-effective building design is always more energy efficient than the current energy code requirements, for the full time horizon considered. Again in the cold climate of Montreal, Canada, Leckner et al. [87] in their paper presented the life cycle cost and energy analysis of a NZEH, that has a combi-system with active solar technologies to provide for heating, domestic hot water and, a PV system for electricity.

Mostly in the literature a few reference buildings are chosen or defined based on a statistical analysis or experts judgments, and these are used to define energy consumption settings. In a new approach, Szalay et al. [52] in their study showed a methodology for defining the requirements for nZEB based on the analysis of a large, artificially generated sample of buildings with different geometric features and orientations to study effects of many parameters on energy balance due to this large number of combinations.

In turkey, Manioglu et al. [88] proposed an approach for determination of the most convenient building envelope and mechanical system operation period in relation to its life cycle cost and thermal comfort in temperate-humid climate of Istanbul. They examined a number of envelopes with different heat storage capacity combined with different heating schedules (all at least 8 hours a day) and compared variables in term of their life cycle cost to point out the most suitable variant. Their results showed that the minimum heat loss and maximum thermal comfort do not match economic situation.

In a study conducted by Yu et al. [89] optimum thickness for various insulation materials for the roof element in residential buildings -related to its life cycle cost- was determined for a climate zone in china with hot summer and cold winter.

In the context of Greece and a typical Mediterranean climate, economic analysis and evaluation of a number of energy saving measures on a domestic detached house were done; the measures like insulation types, upgrading of the heating system, use of thermal solar systems, upgrading of lighting, upgrading of electric appliances, and upgrading of the cooling system. It has been found that amongst the most effective energy saving methods are the upgrading of lighting, the insulation of the roof of the building and the installation of an automatic temperature control system [90].

The methodologies applied in the indicated studies with the objective of introduction of the optimum insulation type and thickness with a cost-effectiveness perspective, carried out in various countries and climates have been utilized in designing and performing the current research.

Chapter 3.

3 Phases, Materials, and Methods

In this chapter and in the subsection “Materials”, subjects of experimental and analytical studies which are prerequisites of investigations and analysis are described. Then, all applied methodologies whether in the scale of building components or the entire building are explained.

3.1 Operative phases

The entire study is articulated in the following phases:

Firstly, a comprehensive review of existing international and Italian scientific literature was presented regarding the main terms of the research topic in order to demonstrate relevant areas which have already been worked on as well as potential gaps that may emerge in the area of the knowledge. Literature study comprises different aspects to spotlight incomplete research areas and derives the specific subject of study.

Secondly, dwelling unit design was performed in line with necessities and requirements of emergency temporary houses based on lessons learnt in the literature review.

For the third phase, the considered insulation material ‘corrugated cardboard’ was put under experimental as well as environmental studies and its thermal characteristics was tested under steady-state in the laboratory.

As the next step, obtaining thermal properties of cardboard, the overall thermal behavior of stratified envelopes were calculated in accordance with relevant standards. To investigate energy performance of prefabricated units by using energy simulation techniques, building energy simulation was conducted using the simulation tools DesignBuilder and EnergyPlus.

In a parametric analysis, by variation in thermal transmittance level of the building envelope in the allowed range limit for Italian warm-temperate climates as suggested by Italian legislative, thermal energy loads of each variant were obtained.

Various solutions were compared in terms of energy performance and energy-related global cost to determine the cost-optimal solution in line with EPBD recast, Regulation (EU) No 244/2012, and EN 15459. The aim of this phase is to run an overall analysis on studied design variables in order to point out which design options could provide the most energy efficient, cost effective solutions.

3.2 Materials

3.2.1 Dwelling prototypes design

In order to implement the thermal, energetic and economic performance assessment of the temporary prefabricated homes, one or more prototypes must be available to become the basis of analysis. In the following, the concerns and procedures of their design are described.

3.2.1.1 Methodologies of generating reference building

According to Annex III of the EPBD recast, Reference Building (RB) is a building characterized by its functionality and representative of its geographic location. These buildings aim to represent the average building stock in terms of climatic conditions, functionality, typical energy performance for both building envelope and systems, and typical cost structure [71]. In a study by Corgnati et al. [91] a general methodology for the creation of reference buildings for the aim of cost-optimal solution determination is illustrated. According to them, for the purpose of creating RBs, the data could be collected into four main areas of investigation as Form, Envelope, System, and Operation. As it is specified and applied in project TABULA [92], three methodologies could be utilized to classify RBs: (1)Example reference building, (2)Real reference building, and (3)Theoretical reference building.

"Example building" method, which is considered for Reference Building classification in this study, roots in information from different sources and on the basis of experts' experience, assumptions and studies in accordance with handbooks, standards, references, and codes that are properly combined to provide building prototypes. These prototypes are supposed to prioritize architectural design improvement as the top issue and create the most probable of a building group.

3.2.1.2 Site characteristics

City of Ancona is considered as the base case site for the reference building. (Latitude: 43° 36'N; longitude 13° 27' E; Altitude: 26 m) characterized by warm temperate climate with 1688 heating degree days and is classified in climatic zone D. Summary of weather characteristics of Ancona e.g. Temperature, humidity, and wind which are influential in climatic architectural design is presented in figures 3.1 to 3.4, derived by weather data files provided by US Energy Department (DOE).

A research study [93] conducted to assess construction systems of temporary schools in different climate conditions gives general design guidelines suggested for temperate climates as follows; orientation of the building: main axis direction east-west, S/V: 0.63, Insulation material: wood wool and pressed cellulose, Window to wall ratio Nord façade: 30%, Window to wall ratio South façade: 50% in winter, 35% in summer, thermal mass Ms: 230kg,: periodical thermal transmittance (Yie): 0.10 W/m^{2}K.

Figure 3.1: Temperature profile, City of Ancona

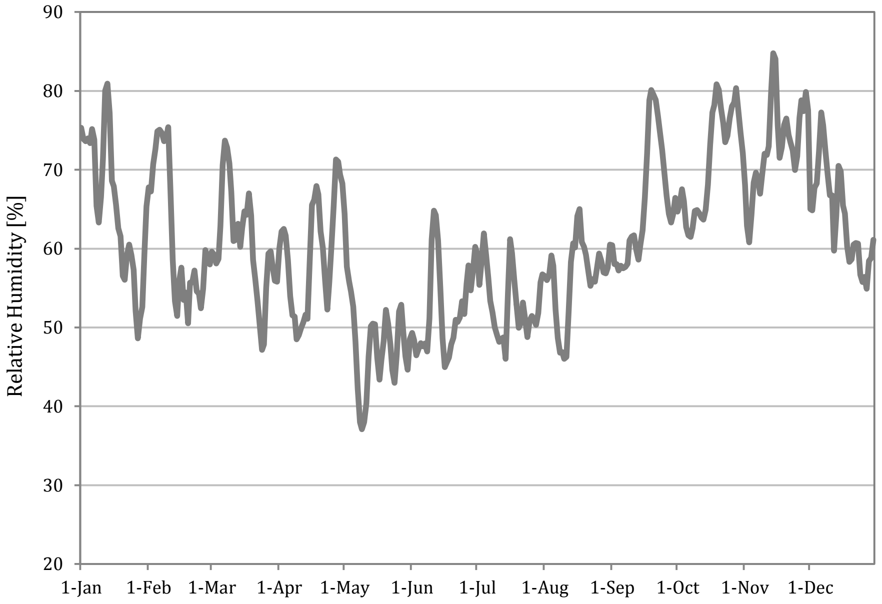


Figure 3.2: Relative Humidity profile, City of Ancona

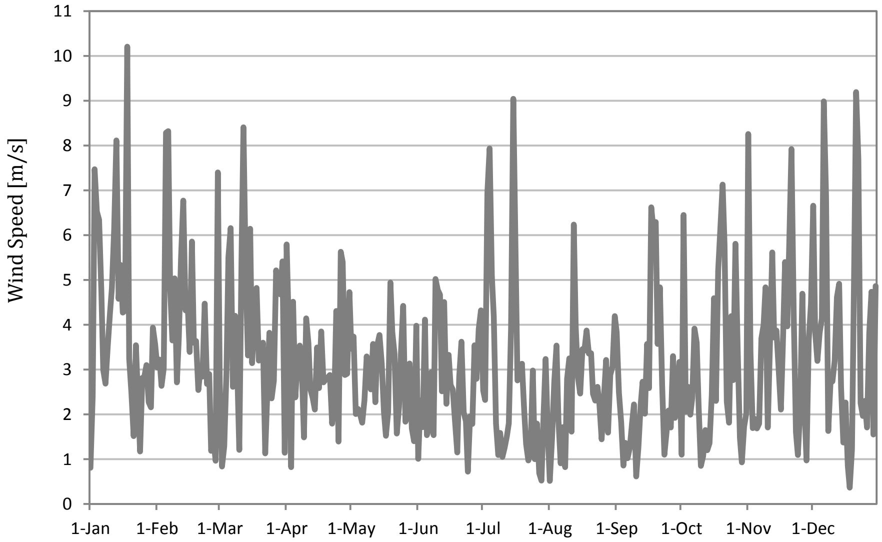


Figure 3.3: Wind Speed, City of Ancona

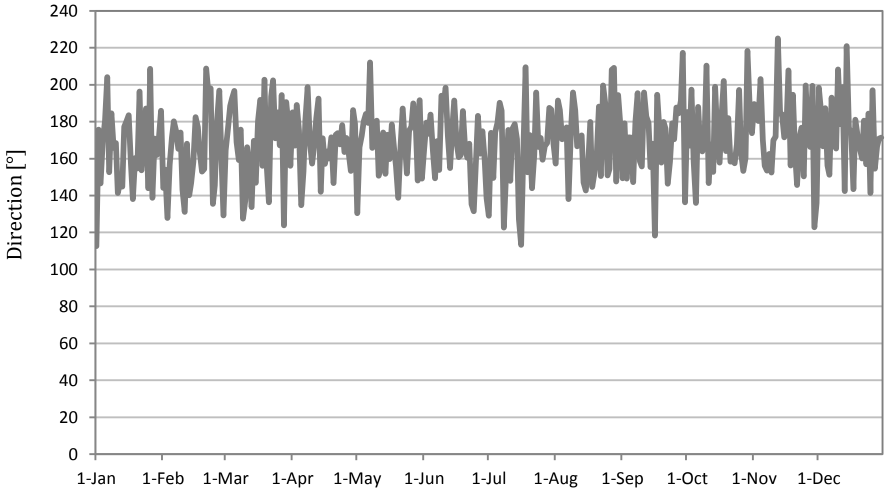


Figure 3.4: Wind direction, City of Ancona

3.2.1.3 Architectural design

Main features to be considered in units design for prefabrication purpose are: (1) Rapidity and simplicity of assembly; to execute buildings after disaster in a short time and by inexperienced staff; (2) Expandability and modifiability to create flexible solutions and facilitate required adaptations to reuse; (3) Use of natural and low environmental impact materials.

Post-occupancy studies showed that units design should provide the maximum degree of customization and high level of flexibility to satisfy customers through personalized products and deal effectively with diversity. In architectural point of view, it is intended to have a high performance in functional-spatial aspects.

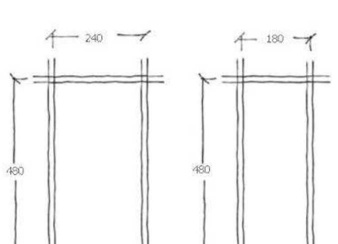
Requirements applicable to residential buildings by Italian regulations are also considered in many aspects which some of them are presented in Table 3.1. However, the exceptional functionality of emergency homes compensates some slight differences to normal dwellings particularly in term of occupancy rate which is higher than permanent houses.

The unit is completed by joining precast modules. Base modules are designed in two dimension sets as seen in Figure 3.5. Regarding functional aspects, one type of modules is specialized and equipped with bathroom, kitchen, and technical room and the second type is free and available for any functional attribution (Figure 3.6). To cover various family sizes and inhabitants needs, three typologies are presented as examples which have to potential to create more configurations with a larger surface area (Figure 3.7 a,b,c).

The living unit is articulated in two linking modules; a fixed block kitchen-bath and in a large multi-purpose space. The furniture is integrated with walls and the inner space is flexible and changeable. A reasonable level of customization for owners to alter their dwellings according to their needs must be considered to minimize inappropriate interventions undertaken by users.

Table3.1: Dimensional standard requirements

min Internal height	2.70 m
min Internal height (Corridors, Bathrooms, Closets, etc.)	2.40 m
min Area per resident	14 m^2
min single bedroom area	9 m^2
min living room area	14 m^2
min openable window area to floor area	1/8



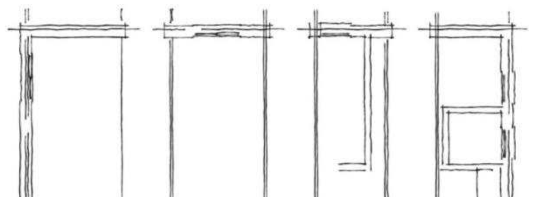


Figure 3.5(Left):Types of modules in term of dimention, **Figure 3.6**(Right):Types of modules in term of function

Wherever possible, passive building techniques are combined with low energy building principles. The longitudinal axis is considered to be oriented along East–West direction. However, the compact building shape is an important design factor for nZEBs, in very small one-story buildings, there are limitations that devour the design from its ideal form. Daylight Penetration is about 5–6 meters in the interior spaces at Central European latitude in the winter which guarantees natural light and solar gain for relatively all spaces in this narrow rectangular design.

The structural system of prefab homes composed of post and beam framing and Metal-based walls are considered for both external and internal walls. Open web studs through the walls facilitate installation of piping and cabling in the wall assemblage. Environmental assessment of materials has shown that the prefabricated steel system results in a significant reduction in the consumption of raw materials of up to 50.7% by weight[33]. Since studied units are supposed to be utilized in a temperate climate with rare possibility of snow and due to difficulties of sloped roofs to be modularized, flat roofs are taken into consideration.

The balance between opaque and transparent elements in the facade configurations affects the total energy efficiency of the building considerably. In warm climates, higher ratios can be acceptable as long as the windows are well shaded from the sun's heat [94]. Due to limited façade area and functional constraints of interior design in a minimal way, allocation of larger areas to glazing surfaces was not possible, however, larger areas could be beneficial in term of passive design principles.

The appropriate shadings are also needed to balance heat gains and losses. Movable shading is recommended since they could decrease cooling loads particularly while windows are located in east and west [94]. Besides, opening positioning and dimensioning are in a way to assure natural ventilation for all parts of the home in summer.

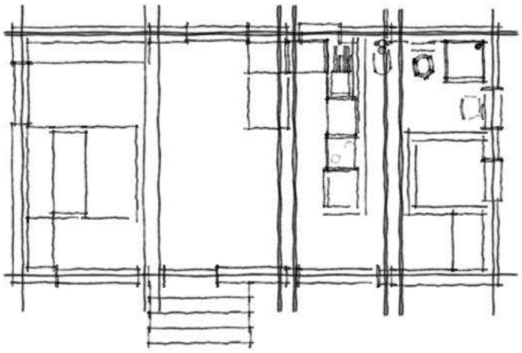


Figure 3.7(a): Small-sized unit

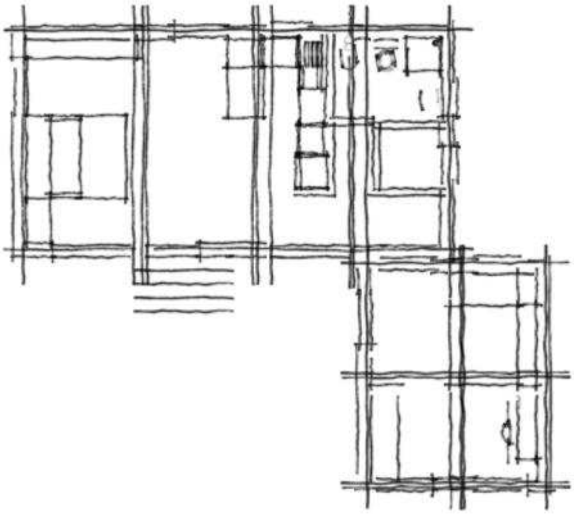


Figure 3.7(b): Medium-sized unit

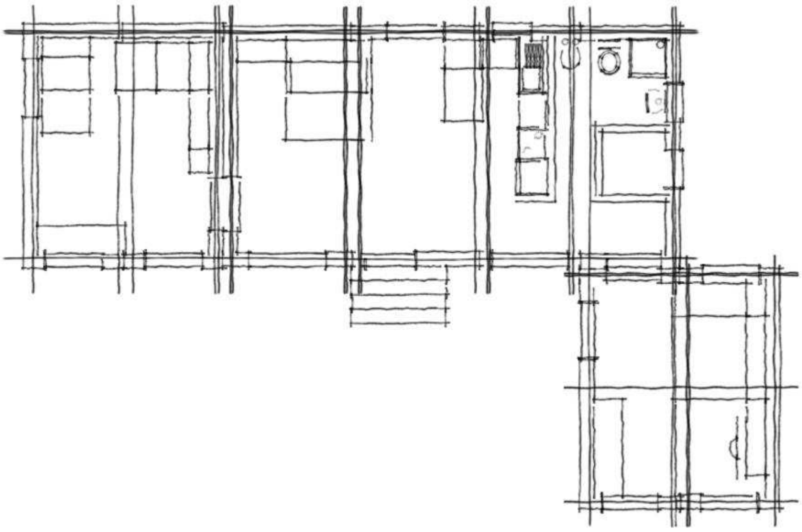


Figure 3.7(c): Large-sized unit

3.2.1.4 Assembly, disassembly, and transportation

The appropriate site which is selected for temporary dwellings is assumed to be provided with basic necessary infrastructure facilities as gas and electricity network, water supply, and drainage. Potential sites for installations could be close to the damaged property, in an open area in the neighborhood or in a planned site offered by the government. In many cases, it is considered inappropriate to rebuild the housing stock in the affected area; mostly because their permanent homes are under construction there. So decision-makers offer relocation to a new land and large plots of land must thus be identified [95]. This approach is called "Relocation to another place", and dwellers could be evacuated and relocated to another region when the housing sites were planned only for temporary uses in planning phase [19].

Building assembly starts when foundations are already finished. Figure 3.8 shows the preparation of foundation in a similar project [29]. Units can be placed on crawlspace or piers. They need to be attached directly to the foundation by getting anchored to steel plates embedded in the concrete slab to secure the house to the foundation.

Transportation of modular units also dictates some limitations, e.g. tight twists and turns must be avoided on the path of transportation and a sufficient open space near the construction site must be available for the crane to rest while it lifts the unit to its proper position with help from a crane and set crew.

Cold formed Light steel framing made of recycled material that is readily recoverable and recyclable after demolition is considered as units' structural system which is much lighter instead of traditional post and beam structures and facilitates its transportation. A major advantage of prefabricated steel and timber construction is that construction elements are able to be disassembled at the end of their useful life and reused in a new building [33].

After setting adjacent modules at their right place, the thin gap between them must be sealed against heat and moisture. As Tam [28] has indicated in his research, the main technological threat for the use of prefabrication is water leakage. Hence, joints must be carefully treated during the installation of façades to avoid water seep through the joints and consequent damages to internal finishing.

For this purpose, special foams impregnated with water-based acrylic are utilized for vertical joints of the walls and horizontal joints of the roofs as seen in Figure 3.9; in this way, a thermally insulated and water tight area is achieved. They are supplied pre-compressed to less than the joint size and are packaged with a self-adhesive on one side. After insertion, it expands to fill and seal the joint [96].

Due to difficulties to manage unused units after an emergency period as already discussed in 2.12, it is essential that a secondary life is planned for temporary units. The lack of disposal sites and limitation of natural sources cause minimization of waste in temporary housing projects. So in overall decisions regarding temporary housing design, minimizing demolition and dismantling is desired. Dry construction and other techniques that causes minimum loss occurs to materials during dismantling must be taken into account [97].

Figure 3.8: Preparation of foundation for Prefabricated houses [29]

Between two types of main “after-occupancy usage” plans - passive measure by implementing minimum intervention and active measures by applying a considerable level of demolition and dismantling interventions[98]- the former strategy is taken into account. In this way, units are being used all their lifetime and at the end, the houses would be available for possible reuse and recycling processes. If temporary houses be assumed to be reused and recycled with the same function, all facilities must remain inactive until a probable disaster happens and in this approach, rate of waste of energy and resource is relatively high. Alternatively, if temporary houses are used with a different, new function e.g. holiday camps, construction sites, weekend farm house during periods that no crisis necessity exists, resources embedded in buildings are saved.

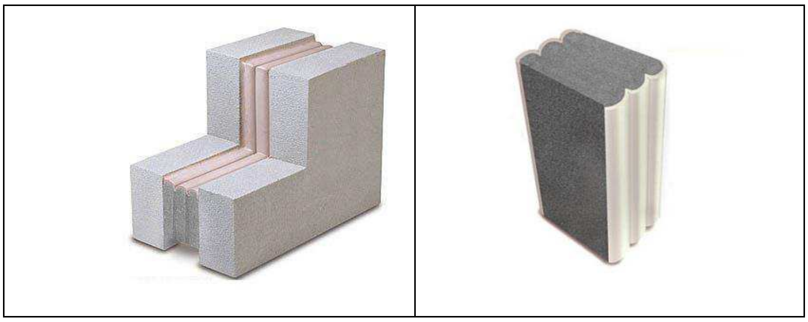


Figure 3.9: joint seal between adjacent prefabricated modules

3.2.1.5 Technical systems

The decree DPR59/09[99] , as the previous legislation, imposes renewable energy source utilization for generation of thermal energy and electricity.

Based on previous similar studies of renewable energy utilization in single-family houses, it is suggested that photovoltaic panels with 10 m^2 of effective area with a nominal power of 3 kW to be installed on the roof surface with a south orientation. Since the current study involves a kind of comparative analysis with the focus on the opaque envelope thermal transmittance, energy demand for domestic hot water –which is mostly dependent on the occupancy rate- does not affect the results. Therefore, the relevant plant facilities, renewable sources, and energy consumption are neglected in this part of study. More details of the HVAC system considerations are presented in 3.3.5.

3.2.2 Cardboard insulation specimen

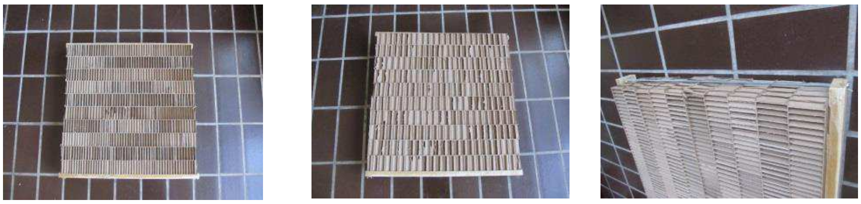
As previously described in 2.2.2, since thermal behavior of corrugated cardboard is highly dependent on corrugation size and portion of air within the material, definite thermal characteristics of cardboard in construction application have not been determined and most of the investigations look into its application in packaging industry. Therefore, an experimental study for the available product in the Italian market was carried out to obtain the actual thermal conductivity of material and assess its role as a thermal insulation in overall envelope energy efficiency.

For the experimental investigations of this project, a corrugated honeycomb cardboard product, produced in Italy [100] was used. The specimens were cut in a square of 50cm by 50cm – appropriate sizing to be used in hot plate test as is discussed in 3.3.1.- from commercially available panels of 110cm width, 305 cm length and 5cm thick. The honeycomb pieces are connected together with vegetable glue (starch). The corrugated and the straight paper layers are made of recyclable test-liner weighing about 140gr/m^2 having a caliper (thickness) of 0.15 mm and are not surface treated. The cell sizes are 11 mm with ±7% of tolerance. The average compressive strength of the product is 3.7 kg/cm^2 with ±10% of tolerance (product properties are according to manufacturer specifications sheets). Figure 3.10 and 3.11 illustrate surface and core of the material. Surface density or mass of material per unit area was measured in the laboratory which is 2.15 kg/m^2 and by knowing thickness of the specimen (50 mm) its density was calculated to be 43 kg/m^3.

Corrugated cardboard is an anisotropic material whose properties are directionally dependent and is not like isotropic materials whose properties are identical in all directions. Hence, investigation procedure of thermal properties of the specimen was repeated for perpendicular directions as well. As seen in the Figure 3.11, honeycomb core has different geometries in each direction. In order to investigate in-plane thermal conductivity of material, two samples were made by stack positioning of 5 cm bars of material, all placed together to make a square are of 50 cm by 50 cm (Figure 3.12).

Figure 3.10: Preparation of Corrugated Honycomb Cardboard Specimen

Figure 3.11: Geometry of honeycomb core of Cardboard in two directions



(a) (b) (c)

Figure 3.12: (a),(b) Specimens in two directions to measure in-plane thermal conductivity of material (c): placement of stack bars into the wooden frame to make a 50 by 50 cm square spesimen

3.2.3 Envelope detailed design

Basically, four main tasks are supposed to be satisfied by the opaque envelope stratification design: Supporting system, thermal protection, moisture protection, and both sides coatings. In developing units' envelope design, a number of guidelines were taken into account; (1) maximum energy efficiency of the building in line with nZEB requirements, (2) development of a solution able to accommodate running piping and wiring through modules, (3) maximum utilization of recycled recyclable materials with low environmental impact, (4) minimization of installation time and effort.

In the following sections, descriptions of the vertical and horizontal envelope elements are presented.

3.2.3.1 Wall

One key decision in the wall assemblage design is insulation layer positioning which can be placed in the inner side, outer side, or in the air cavity of central part. Material configuration can be effective on wall ability to regulate interior temperature. The optimum positioning of insulation in term of better energy efficiency achievement has been investigated in the preceding researches. According to [101], placing half of the insulation in the inner wall surface, half of the insulation in the outer wall surface result the best decrement factors. The best result for time lag (attainment of higher time lag) is for the case where two pieces of insulation are placed in a certain distance apart from each other in the wall (they are equally located from the inner and outer surfaces of the wall). Placing half of the insulation in the mid-center plane of the wall and the half of it in the outer surface of the wall gives very high time lags and low decrement factors. Another analysis of the winter energy consumption shows that a cavity wall with minimal existing insulation requires up to 63% less energy than an unfilled brick–block cavity wall [102].

The envelope materials composition (from the inside to the outside) is considered as the following:

- Gypsum board for interior finishing
- Cardboard panels as thermal insulation
- OSB panel which also performs as wall shear bracing
- Vapor barrier
  The synthetic membrane with three layers of polypropylene to restrain the mitigation of vapour through the envelope for its protection against moisture.
- Wall cavity
  containing a layer of cardboard, air gap, and cold-formed steel C-shaped studs at equal distances, OSB panel
- Air barrier
- Cardboard as external thermal insulation
- PVC slats for exterior finishing

3.2.3.2 Roof

According to sadineni et al. [61] who performed a review study on passive energy saving techniques of building envelopes, applying appropriate thermal insulation and using light-colored roof paints could be good solution for better energy performance of light-weight metal roofs. They showed that roof structure with polyurethane insulation and white painted top surface performed better and saved 53.8% of the peak cooling load compared to a dark painted roof with glass wool insulation.

The roof envelope materials composition (from the inside to the outside) is considered as the following:

- Gypsum board as false ceiling finishing including metal substrate
- Cavity
  including cold-formed steel C-shaped profiles placed
- Vapor barrier
- OSB panel
- Wood fiber
- OSB panel
- Water proof membranes
- Roof screed with 1% slope

3.2.3.3 Floor

Due to foundation consideration, a crawl space under the floor exists whose temperature is equal to the outdoor air temperature. Therefore, units' floor is treated as external floor.

External floor envelope materials composition (from the inside to the outside) is considered as the following:

- Timber flooring as interior finishing
- Plywood as substrate
- Vapor barrier
- OSB
- Wood fiber
- Air barrier
- OSB
- Cold-Formed Steel profiles

3.3 Methods

3.3.1 Experimental study of cardboard thermal behavior

Experimental measurements were carried out by method of guarded hot plate and heat flow meter according to EN ISO 12667[103]. This standard describes the fundamental characteristics of equipment and rules for evaluation the results and determination of the thermal conductivity and conductance, for the specimen having a thermal resistance of not less than 0.5m^2K/W. During experiments a detailed monitoring of heat flow is carried out to investigate thermal resistance of specimen. Based on this method, a temperature difference between the parallel faces of the specimen is generated by thermostatic baths. In this study the bath connected to the cold plate was set to 15°C and the other one to 25°C. Then the heat flow was measured by means of heat flow probes placed on hot and cold sides of the specimen. Each test lasted about 24 hours in order to meet steady state and surface temperatures as well as heat flux were recorded with the logging rate of one measure per minute by the acquisition system to be used as input values in the calculation of thermal conductivity of material.

Heat flow meters and temperature sensors were positioned in contact surface between the plates and measure the heat flow that crosses the surface where it is installed (Figure 3.14). Heat flow meters, As shown in Figure 3.15(a), to measure heat flux density (W/m^2) on the sample sides have a sensitivity of 50μV/Wm^2. As EN 1946-2 [104] indicates if the equipment meet the requirements stated within the EN 1946-2 and EN 1946-3[105], the accuracy of the measured thermal properties is within ±2%.

Then, by the relationship between the heat flow and the surface temperature difference, it's possible to calculate the thermal conductance of the tested sample according to Average method described in ISO 9869[106]. This standard describes the installation, the measurement procedures and the analysis of the data according to three different techniques: the average, the storage and the dynamic. The progressive average method requires measurements of internal/external surface temperature and heat flux at the internal side of the wall for a prolonged period in order to calculate the thermal conductance as eqtion below:

$$C=\frac{\sum_{j=1}^{n} Q_j}{\sum_{j=1}^{n} (Tsi_j - Tse_j)} \tag{3.1}$$

Where:

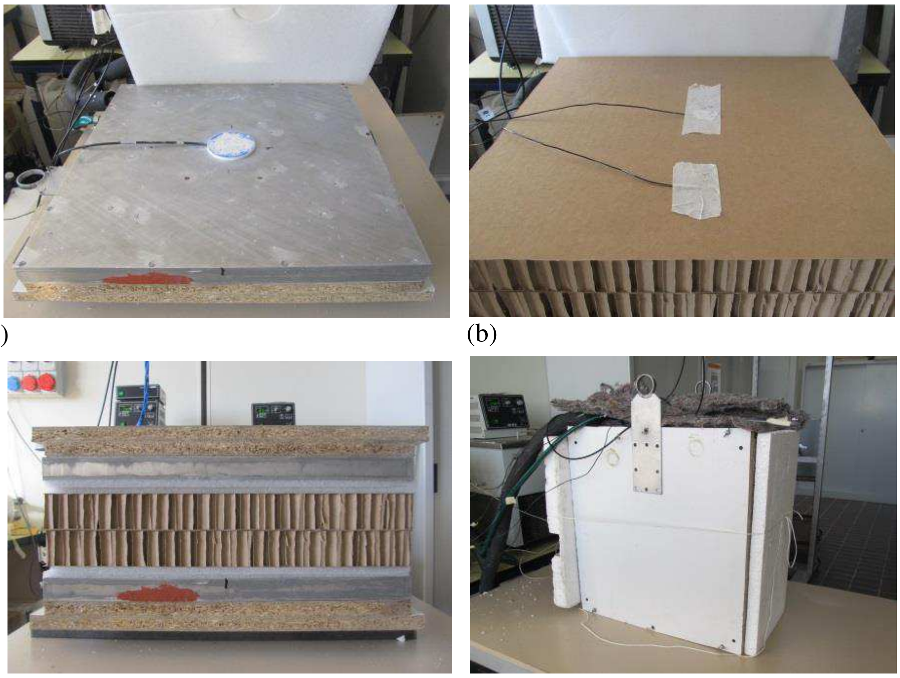
Q = Heat flow through the element

T_{si} = Internal surface temperature

T_{se} = External surface temperature

j = Individual measurements

Two thermostatic baths as illustrated in Figure 3.15 are needed to guarantee a constant and uniform density of heat flow rate through the specimen. One of them is connected to the hot plate, and the other connected to the cold plate. One of them is also connected to a PC for the purpose of data acquisition. They should be located at a level higher than the rest of the equipment, in particular with respect to the specimen. The apparatus also consists of two aluminum plates with a circuit inside in which hydraulic fluid is circulated, connecting to the thermostat baths. The connecting pipes (flow and return) which are between the thermostatic baths and the plates have been isolated thermally with flexible sheaths.


(a) (b)

(c) (d)

Figure 3.13: (a) Installation of heat flow meter, (b) Installation of Termocouples, (c) Placement of hot and cold plates on specimen sides, (d)Running the test

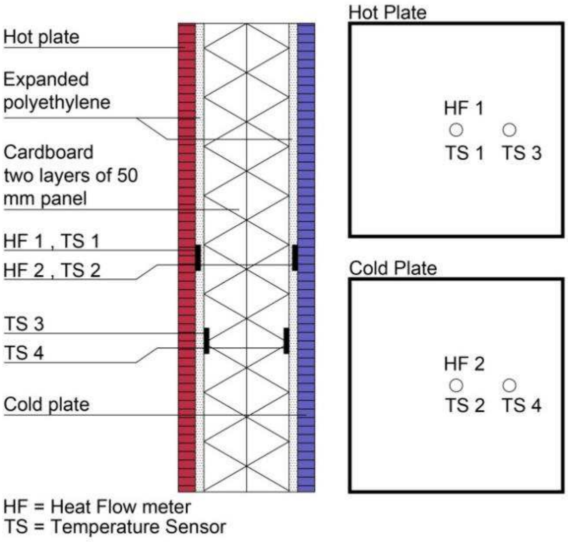


Figure 3.14: Placement of heat flow meters and temperature sensors in cross section

(a) (b) (c)

Figure 3.15: (a) Heat flow meters, (b) Thermostatic bath, (c) Aquisistion system

The desired temperature for each of the plates is possible to be set on the thermostatic bath and then the considered ΔT could be gained. It should be noted that because of some heat loss through the thermostatic bath and cold/hot plates, the temperature which is set is not necessarily equal to the actual temperature of the plates.

3.3.2 Environmental impact study of cardboard

Cardboard has been known in the material science as the recycled and recyclable product, however its application in the construction industry, particularly for insulating purposes have been very limited. It is desired that these sustainability potentials be compared to other insulation competitives in the market and current practice. Therefore, the aspect of "being recycled" has been tested in this phase of the study. Nevertheless, it is defined as a secondary task in this research and parallel to the thermal assessment process of cardboard.

Life cycle assessment (LCA) is a well-known method used to assess possible environmental impacts of products and services in their life time. This technique is also applicable to building elements as well as entire buildings to evaluate environmental aspects and potential environmental impacts. Several studies have utilized it either independently for a pure environmental assessment or within a multi-criteria analysis for a variety of building elements. The environmental analysis includes four fundamental sequential steps; Goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

In this study, energy and mass flows and preliminary environmental impacts of cardboard as a wall envelope element have been assessed from the production of raw materials to the manufacture of end-product. For this purpose, the software openLCA [107] was used for LCA analysis which is in agreement with EN ISO 14040 [108] and EN ISO 14044 [109]. Life cycle impact assessment, based on the inventory results, is qualified, quantified, and compared. In this research, ProBas and Ecoinvent are the data sources used for inventory study of materials and by means of two impact assessment methods, CML(baseline) and cumulative energy demand, following impact categories were assessed for cardboard and alternative insulations in openLCA; consumption of primary energy(MJ), GWP- Global Warming Potential(kg CO_2eq), acidification potential(kg SO_2eq), eutrophication(kg PO_4eq), and photochemical oxidation(kg C_2H_4eq).

"Cradle to gate" or pre-use phase study has been considered for this research including product stages A_1 to A_3; A_1: Raw material extraction and processing, processing of secondary material input, A_2: Transport to the manufacturer, A_3: Manufacturing [110].

Functional unit defines quantification of the identified functions of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related [108]. In this study, the functional unit (f.u.) is considered the mass of insulation material that provides U-value of 0.33 W/m^2K for the area of $1m^2$ of the wall. A similar procedure was repeated for six other insulation materials from three categories of Natural, Mineral, and Synthetic to recognize the situation of cardboard respect to its counterparts. Wood fiber and cellulose representative alternatives of natural products, glass wool and rock wool represents mineral insulations and Polyurethan as well as Expanded polystyrene belong to synthetic category of insulations.

3.3.3 Thermal performance study of Envelopes

Steady-state and periodic thermal transmittances of envelopes are calculated according to the method described in UNI EN ISO 6946 and UNI EN ISO 13786. For thermal conductivity values of materials UNI 10351and report IEA-Annex 24 are taken into account. Thermal resistance of horizontal and vertical air gaps with various thicknesses as well as interanl and external surface thermal resistance are presented in UNI EN ISO 6946 and considered in calculations [111].

Thermal resistance of each strate is calculated as the equation:

$$R = \frac{d}{\lambda} \tag{3.2}$$

Where

d: Material thickness of each state in the component

λ:Thermal conductivity of material

Total thermal resistance of the component is calculated by:

$$R_T= R_{si}+ R_1+R_2+\ldots+R_n+R_{se} \tag{3.3}$$

Where

R_{si}: Internal surface thermal resistance

R_1, R_2, …, R_n: Individual thermal resistance of layers

R_{se}: External surface thermal resistance

Total thermal transmittance (U-value) of the component is obtained by:

$$U = \frac{1}{R_T} \tag{3.4}$$

According to UNI EN ISO 13786[112], Periodic thermal transmittance (Yie) is the amplitude of density of heat flow rate on one side when the temperature amplitude on that side is zero and there is a unit temperature amplitude on the other side. Periodic thermal transmittance is calcutable by:

$$Y_{mn} = \hat{q}_m / \hat{\theta}_n \tag{3.5}$$

Where

$\hat{q}_m$: complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m

$\hat{\theta}_n$: complex amplitude of temperature in thermal zone n

Another influential parameter in periodic thermal behavior "decrement factor" is defined as the ratio of the periodic thermal transmittance to the steady-state thermal transmittance U as:

$$f = Y_{mn} / U \tag{3.6}$$

Definition and calculation methods of other auxiliary parameters (e.g. delay factor of decrement and thermal admittance) are described in UNI EN ISO 13786 in detail.

Values of periodic thermal transmittance (Yie) and linear thermal transmittance are set into requirements presented in DPR 59/09 and UNI EN ISO 14683, respectively. As indicated in DPR 59/09, for vertical opaque components Yie must be lower than 0.12 W/m^{2}K whereas for horizontal opaque components it is less than 0.2 W/m^{2}K.

Construction nodes are expected to thermally behave similarly to other parts of enclosure elements. However, due to different configuration and material adjacency in junctions, their thermal behavior would probably be distinguished from other continuous elements; In this regard, the parameter linear thermal transmittance (ψ) as an important indicator of thermal and energetic performance is introduced to evaluate thermal bridges which is possible to take

place in constructive joints through computer software operating in semi-stationary state. Hence, the ultimate aim of linear thermal transmittance study is to check that thermal function of the components do not get interrupted. The simplified methods for determining heat flows through linear thermal bridges are described in detail in EN 14683 [113]. The most likely locations for occurance of thermal bridge in buildings are introduced as external element junctions (corner of walls, wall to roof, wall to floor), internal wall/external wall junction, column spots in external walls, and around openings [113]. Therefore, by assessment of aforementioned locations, worst-case situations are studied to guarantee appropriate performance of the entire building.
According to UNI EN ISO 10211, linear thermal transmittance is calculated as

$$\psi = L_{2D} - \sum_{j=1}^{n} (Uj \times lj) \tag{3.7}$$

Where
L_{2D}: thermal coupling coefficient obtained from a 2D calculation
U: thermal transmittance obtained from a 1D calculation
l: length over which the value L_{2D} applies

Whereas L_{2D} is calculated as

$$L_{2D} = \frac{\varphi}{T_i - T_e} \tag{3.8}$$

Where
Φ: total heat flow rate
T_i: Internal air temperature
T_e: External air temperature

THERM 7 is two-dimensional heat-transfer analysis software provided by LBNL (Lawrence Berkeley National Laboratory) and freely available for download, based on the finite-element method which models the building geometries. This software was utilized in this study to obtain ψ -Psi value- of critical construction joints which are designed for the prefabricated units in order to check not to exceed recommended requirements. Geometry of construction element desired to be analyzed are defined possibly through dxf file; appropriate materials and the corresponding physical and thermal properties are assigned to layers of stratification. Then, boundary conditions e.g. temperature and film coefficient are attributed to the surrounding. Internal ambient value, external ambient value, and film coefficient were derived from UNI TS11300 [114], UNI EN 12831:2006, and UNI 6946 [111].

According to calculation code of software, U2D is obtained in the output and L2D is simply achievable by

$$L_{2D} = U \times l \tag{3.9}$$

U_{2D}: U-value of the connection node
l: length of construction detail

Additionally THERM provides users with Infrared and Isotherm visualization which gives ideas of temperature distribution through the component. Figure 3.16 illustrates modelling and material assignment in THERM enviroment.

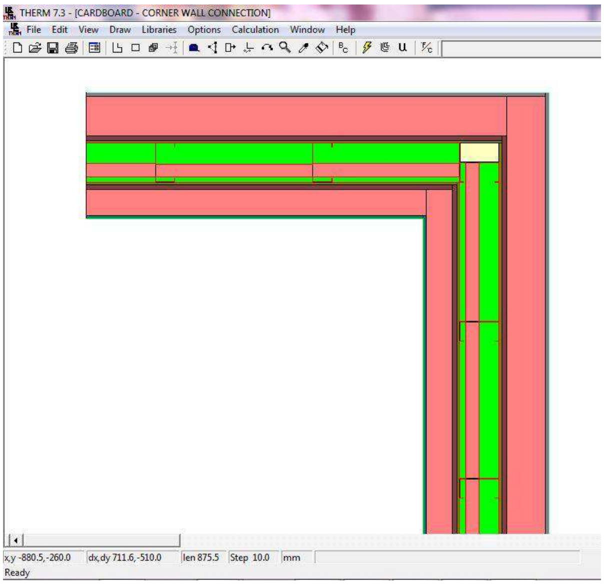


Figure 3.16: Material visualisation of wall corner in THERM

3.3.4 Whole building energy simulation

In this section, the procedure of attainment of thermal energy requirement for the prefabricated unit under study is presented.

The thermal energy demand (kWh/m^{2}yr) is the amount of energy estimated to meet the thermal needs associated with a standardized use of the building, including system losses and self-consumption of the system for space heating, cooling, and ventilation, from which the generated own-energy provided by photovoltaics, solar collectors or co-generation can be subtracted.

To have a numeric indicator of energy performance in the comparative study of cost-optimal level of minimum energy performance, the sum of the annual thermal energy requirements comprising heating and cooling consumptions (Q_h, Q_c) divided by conditioned floor area is obtained. Energy demands for domestic hot water, lighting, and electric appliances are excluded since they do not influence comaparive aim of study and are based on users' behavior and depend on occupancy assumptions.

3.3.4.1 Input data

Internal loads and Heating/cooling set point are set according to UNI/TS 11300-Part 1 which is considered 20°C for the heating season and 26°C for the cooling season.

Natural ventilation during summer season via window apertures according to UNI 10375 is assumed as well. Duration of heating season in different climatic zones under study: Climate zone D (as the base case climate): 1st November to 15th April, Climate zone C: 15th November to 31st March, Climate zone B: 1st December to 15th March. The small-sized unit with the area of 32 m^2 as the base case typology is considered to serve for a couple. Therefore, the occupancy density is set as 0.06 people/m^2.

A Good air tightness of the house is considered and rate of 0.3 ac/h is assumed for air change rate of residential buildings as recommended in UNI/TS 11300-Part 1. No external obstructions are considered in the modelling since all surrounding buildings are one-story units as well and allocated site for collective settlement of modular units – either in an emergency case or vacation purposes- do not possess tall shade plants. High reflective blinds are considered for windows in all directions and external shading for particular ones as described in 3.2.1.3.

3.3.4.2 Calculation method

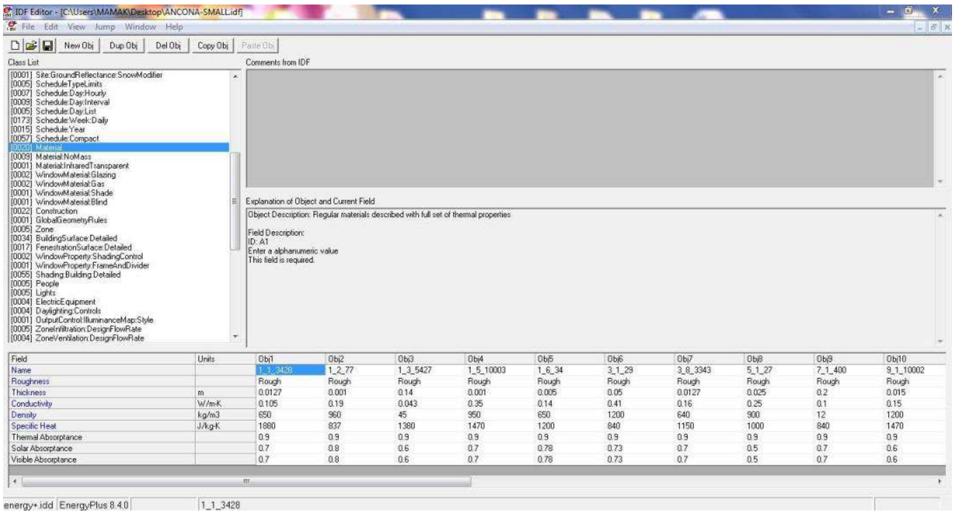
UNI EN 15603 is considered as the reference standard for calculation of energy consumption of buildings. By means of dynamic simulation method, thermo-physical parameters of envelopes, internal comfort conditions, and energy consumption are evaluated. Computer building energy simulation is an acceptable technique for assessing the dynamic interactions between the external climates and building energy load. Computational building performance modelling and simulation are normally based on numerical methods that aim to provide an approximate model of a realistic complexity in the real world with a reasonable computational effort.

To obtain building energy needs, the dynamic simulation software “Energy Plus” version 8.4.0 provided by the U.S. Department of Energy (DOE) [115] is used. This simulation program calculates whole-building final energy balance and heating and cooling loads necessary to maintain thermal control set points based on energy-related input parameters e.g. envelope thermal properties, orientation, glazing area, heating and ventilation systems, heat gains from lighting, appliances, human bodies and solar radiation, operation schedule, geographical location and outdoor climate (Figure 3.16).

The building unit was modelled with real geometrical dimensions and real properties of constructive elements. In addition, the actual occupancy relevant input data e.g. internal gain, ventilation schedules, and plant operation schedules were set into the software. Hourly heating and cooling energy requirement in a one-year period was calculated through local climate which are set through the weather file provided in the .epw format to be read in the program.

For comparative studies and long-term energy estimation, a yearly weather database representative of the prevailing climatic conditions is often used. As Lam et al. [116] describes weather data in building simulation software, weather data including 8760 hourly records representative of the prevailing weather conditions is a key element in building energy simulation. All energy simulation computer programs require weather data input to drive the thermal models within the simulation tools. The typical year approach can reduce the computational efforts in simulation and weather data handling by using one year instead of multiple years. Selection of typical weather months is based on four climatic parameters, namely dry bulb temperature, dew point temperature, wind speed and global solar radiation.

“DesignBuilder” was utilized as a graphical user interface (GUI) for 3D modeling and definition of building elements and technical plants. (Figure 3.18) The building was partitioned into multiple zones and building elements and envelope stratification as well as material characteristics were defined in the software to be exported into EnergyPlus and calculation of simulations in the dynamic state be run.



[0001] Site:GroundReflectance:SnowModifier
[0005] ScheduleTypeLimits
[0007] Schedule:Day:Hourly
[0009] Schedule:Day:Interval
[0005] Schedule:Day:List
[0173] Schedule:Week:Daily
[0015] Schedule:Year
[0057] Schedule:Compact
[0020] Material
[0009] Material:NoMass
[0001] Material:InfraredTransparent
[0002] WindowMaterial:Glazing
[0002] WindowMaterial:Gas
[0001] WindowMaterial:Shade
[0001] WindowMaterial:Blind
[0022] Construction
[0001] GlobalGeometryRules
[0005] Zone
[0034] BuildingSurface:Detailed
[0017] FenestrationSurface:Detailed
[0002] WindowProperty:ShadingControl
[0001] WindowProperty:FrameAndDivider
[0055] Shading:Building:Detailed
[0005] People
[0005] Lights
[0004] ElectricEquipment
[0004] Daylighting:Controls
[0001] OutputControl:IlluminanceMap:Style
[0005] ZoneInfiltration:DesignFlowRate
[0004] ZoneVentilation:DesignFlowRate

Object Description: Regular materials described with full set of thermal properties

Field Description:
ID: A1
Enter a alphanumeric value
This field is required.

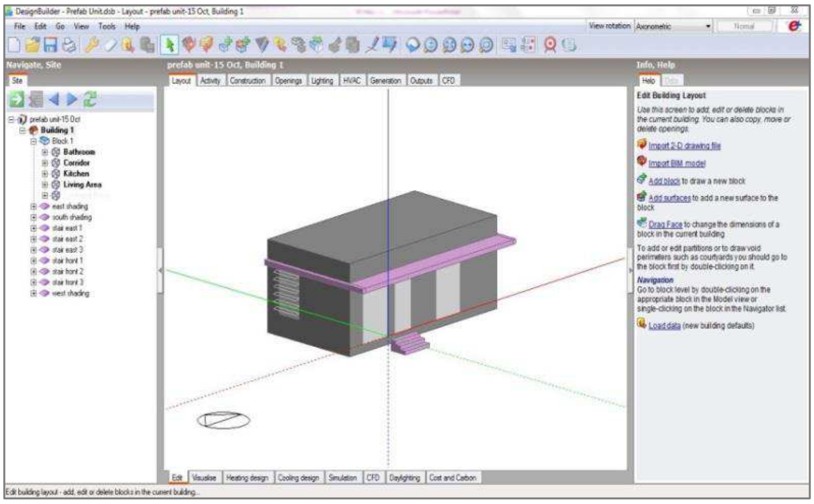
Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7	Obj8	Obj9	Obj10
Name		1_1_3428	1_2_77	1_3_5427	1_5_10003	1_6_34	3_1_29	3_8_3343	5_1_27	7_1_400	9_1_10002
Roughness		Rough	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Rough	Rough
Thickness	m	0.0127	0.001	0.14	0.001	0.005	0.05	0.0127	0.025	0.2	0.015
Conductivity	W/m-K	0.105	0.19	0.043	0.35	0.14	0.41	0.16	0.25	0.1	0.15
Density	kg/m3	650	960	45	950	650	1200	640	900	12	1200
Specific Heat	J/kg-K	1880	837	1380	1470	1200	840	1150	1000	840	1470
Thermal Absorptance		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Solar Absorptance		0.7	0.8	0.6	0.7	0.78	0.73	0.7	0.5	0.7	0.6
Visible Absorptance		0.7	0.8	0.6	0.7	0.78	0.73	0.7	0.5	0.7	0.6

energy+.idd EnergyPlus 8.4.0 1_1_3428

Figure 3.16: view of EnergyPlus IDF editor, field of object definition

The annual energy demand of a building for heating and cooling -called thermal energy demand- is taken as the energy indicator for comparative economic analysis. Zones in this field are kind of thermal concepts, not spatial term. Energyplus simulates models in such a way to maintain each zone at the specified requirements which are set for the model.

In this simulation, no particular HVAC system is assumed; instead, for the sake of simplicity, among the available system variables the option “Ideal Loads Air System” is used to study the performance of the building without modeling a full HVAC system.



Edit Building Layout

Use this screen to add, edit or delete blocks in the current building. You can also copy, move or delete openings.

Import 2-D drawing file

Import BIM model

Add block to draw a new block

Add surfaces to add a new surface to the block

Drag Face to change the dimensions of a block in the current building

To add or edit partitions or to draw void perimeters such as courtyards you should go to the block first by double-clicking on it.

Navigation

Go to block level by double-clicking on the appropriate block in the Model view or single-clicking on the block in the Navigator list.

Load data (new building defaults)

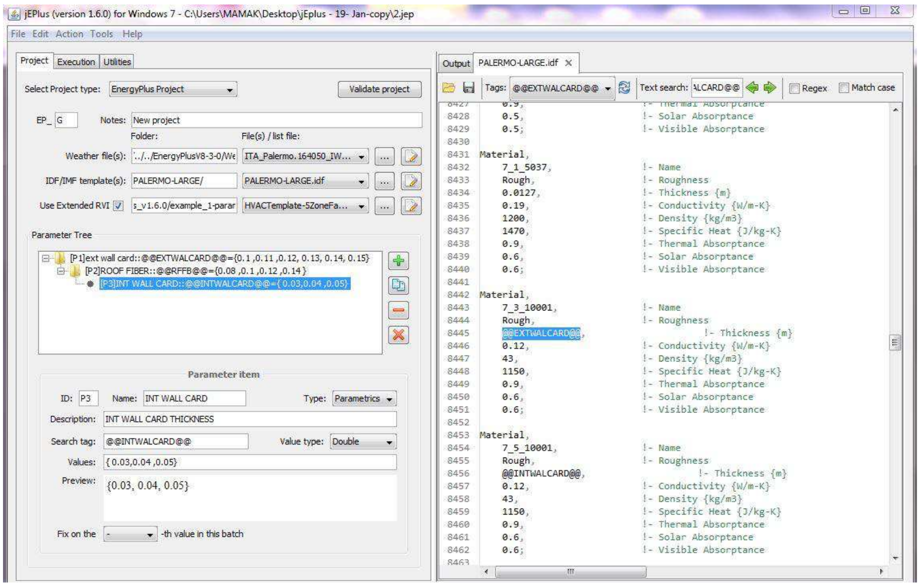
Edit building layout - add, edit or delete blocks in the current building.

Figure 3.17: view of simulation model in DesignBuilder

3.3.5 Parametric variation of Energy Efficiency Measures (EEM)

In order to compare the energy performance of the dwelling (heating and cooling energy needs) the building envelope insulation level was varied according to standards corresponding climatic zones. The parametric study is carried on by means of a number of discrete options, considering insulation level of building envelope elements (i.e. external walls, roof, floor). This last step is performed by jEPlus 1.6.0 (Figure 3.18), the parametric analysis software, where the IDF format output files are inserted as input data and a “parameter tree” created. Total numbers of solutions are in a manageable size which takes reasonable calculation effort. It provides a good balance of coverage of variation of variation while not letting the option numbers go very high.

In order to make sure that all further simulations are not affected by ventilation profiles or specific usage model of technical systems, the same assumptions regarding heating/cooling set points, internal gains, HVAC systems, and natural ventilation rate are taken into account in all cases.



jEPlus (version 1.6.0) for Windows 7 - C:\Users\MAMAK\Desktop\jEplus - 19- Jan-copy\2.jep

Select Project type: EnergyPlus Project

EP_ G Notes: New project

Weather file(s): Folder: '../../EnergyPlusV8-3-0/We File(s) / list file: ITA_Palermo.164050_IW...

IDF/IMF template(s): PALERMO-LARGE/ PALERMO-LARGE.idf

Use Extended RVI ☑ s_v1.6.0/example_1-parar HVACTemplate-5ZoneFa...

Parameter Tree

- [P1]ext wall card::@@EXTWALCARD@@={0.1 ,0.11 ,0.12, 0.13, 0.14, 0.15}
  - [P2]ROOF FIBER::@@RFFB@@={0.08 ,0.1 ,0.12 ,0.14 }
    - [P3]INT WALL CARD::@@INTWALCARD@@={ 0.03,0.04 ,0.05}

Parameter item

ID: P3 Name: INT WALL CARD Type: Parametrics

Description: INT WALL CARD THICKNESS

Search tag: @@INTWALCARD@@ Value type: Double

Values: { 0.03,0.04 ,0.05}

Preview: {0.03, 0.04, 0.05}

Fix on the - -th value in this batch

PALERMO-LARGE.idf

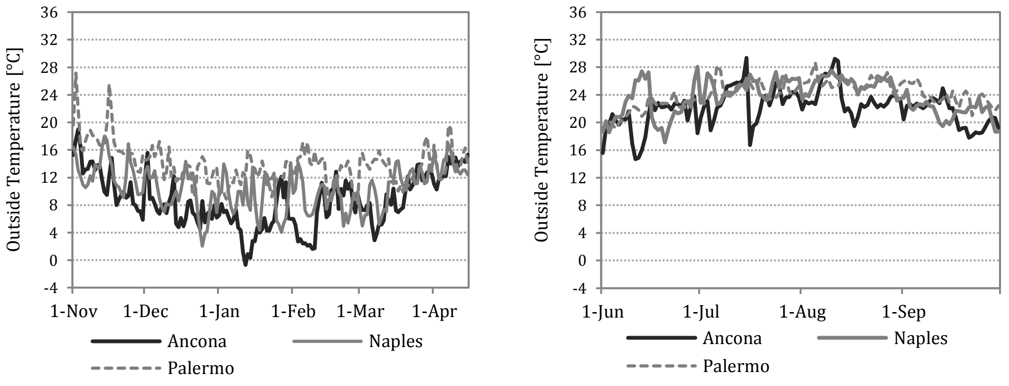
Tags: @@EXTWALCARD@@ Text search: ALCARD@@

```
    0.5,                        !- Solar Absorptance
    0.5;                        !- Visible Absorptance

Material,
    7_1_5037,                   !- Name
    Rough,                      !- Roughness
    0.0127,                     !- Thickness {m}
    0.19,                       !- Conductivity {W/m-K}
    1200,                       !- Density {kg/m3}
    1470,                       !- Specific Heat {J/kg-K}
    0.9,                        !- Thermal Absorptance
    0.6,                        !- Solar Absorptance
    0.6;                        !- Visible Absorptance

Material,
    7_3_10001,                  !- Name
    Rough,                      !- Roughness
    @@EXTWALCARD@@,                        !- Thickness {m}
    0.12,                       !- Conductivity {W/m-K}
    43,                         !- Density {kg/m3}
    1150,                       !- Specific Heat {J/kg-K}
    0.9,                        !- Thermal Absorptance
    0.6,                        !- Solar Absorptance
    0.6;                        !- Visible Absorptance

Material,
    7_5_10001,                  !- Name
    Rough,                      !- Roughness
    @@INTWALCARD@@,                       !- Thickness {m}
    0.12,                       !- Conductivity {W/m-K}
    43,                         !- Density {kg/m3}
    1150,                       !- Specific Heat {J/kg-K}
    0.9,                        !- Thermal Absorptance
    0.6,                        !- Solar Absorptance
    0.6;                        !- Visible Absorptance
```

Figure 3.18: graphical interface of parametric analysis software “jEPlus”

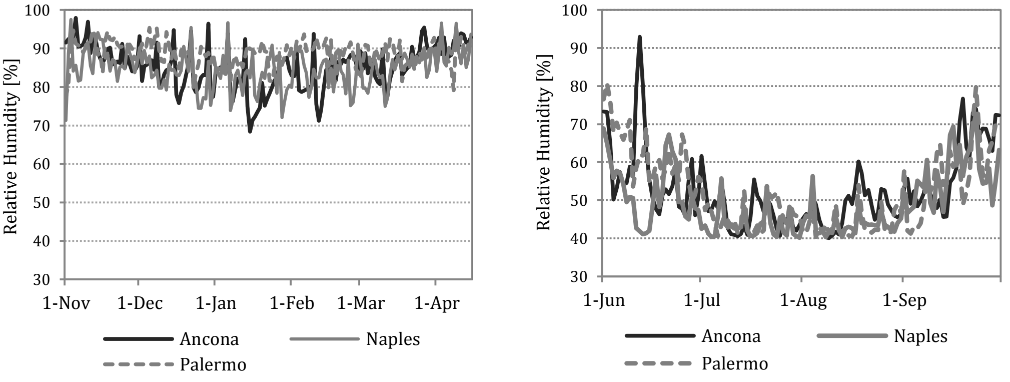
3.3.5.1 Climatic zones and selection of cities

Insulating building envelope over a certain thickness is not usually an effective practice but it considerably relates to local climate that dictates heating and cooling needs of the building. In term of climatic conditions, Italy is a country with diverse climatic zones including mild climate regions as well as cold alpine areas. In order to study this threshold in a variety of Italian climatic conditions, three cities belonging to warmer regions of Italy were selected. The base case model which was designed according to required limits for climatic zona D was investigated with a higher thermal transmittance of its envelopes to reach lower limits requested for warmer climates of C and B in southern regions of Italy. The diversity of temperature, relative humidity level, and solar irradiation in summer and winter seasons is illustrated in Figures 3.19, 3.20, and 3.21. Variation range of each design variable is discretized; this is achieved by reduction of insulation layer thickness (dX) in any iteration with a practical step as the product availability in the market; which is 1 cm for cardboard panels and 2 cm for wood fiber boards which is considered. Three fixed levels of thermal transmittance are considered for Glazing in external walls as seen in Table 3.2.



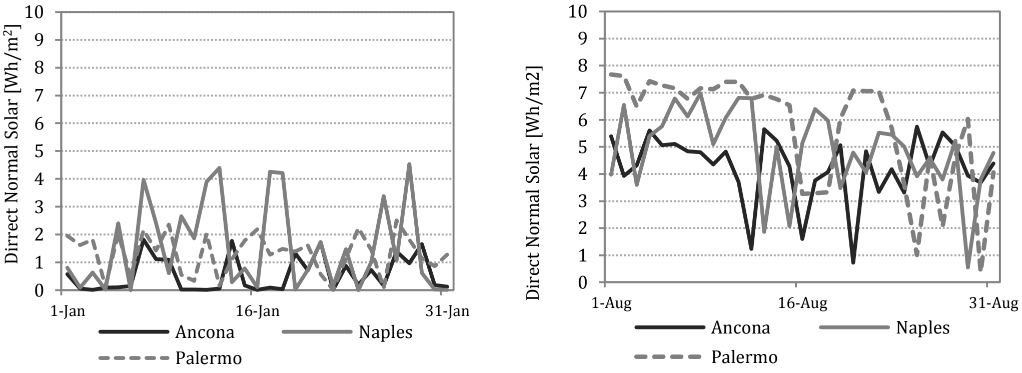
(a) (b)

Figure 3.19: Dry-bulb temperature profile, (a) Winter season (b) Summer season



(a) (b)

Figure 3.20: Relative humidity profile, (a) Winter season (b) Summer season



(a) (b)

Figure 3.21: Solar Irradiation, (a)Winter study(January)(b) Summer study (August)

Table 3.2: value variation for parametric analysis

Building Element	Variable Parameter	Parametric Values		
		Upper Limit [cm]	**Lower Limit [cm]**	**Step [cm]**
Wall	External Insulation Cardboard Thickness	15	10	1
	In-cavity Insulation Cardboard Thickness	5	3	1
Roof	Wood fiber Thickness	14	8	2
Floor	Wood fiber Thickness	14	8	2
		Constant U-value		
		Zone D	Zone C	Zone B
Window		1.77	2.28	2.8

(1) Double LowE (e_2=1) 6 mm/13 mm Air
(2) Double LowE (e_2=4) 3mm/13 mm Air
(3) Double LowE (e_2=4) 3 mm/6 mm Air

3.3.5.2 Thermal parameters requirements

Generally, in line with wall insulation increase, heating and cooling loads and consequently energy cost decreases; while life time cost trend behaves differently as illustrated in Figure 3.22 [117].

Table 3.3 describes required thermal transmittance of building envelope elements in corresponding zones in two different time horizon. In this study, the highlighted values in second column which respects future limitations and force stricter insulation levels are taken into account.

Each scenario (including transmittance of wall, roof, floor envelopes and glazing area creates specific investment cost and energy cost to run a comparative analysis among scenarios and make a trade-off to identify optimal ranges. As Audenaert et al. [84] have demonstrated in their study, a combination of insulation investment for wall, roof, floor and glazing lead to better energy savings than investments in the insulation of individual constructional element.

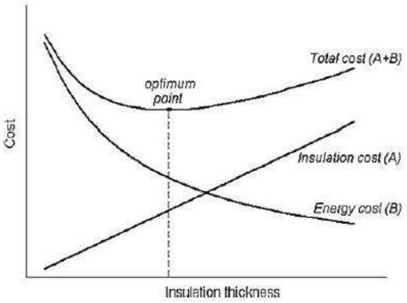


Figure 3.22: correlation of insulation thickness and Total cost [117]

Table 3.3: Required thermal transmittance of building envelopes

Thermal Transmittance	**Zone D**		**Zone C**		**Zone B**	
	2015 (1)	2019 (2)	2015 (1)	2019 (2)	2015 (1)	2019 (2)
	U [W/m^{2}K]					
External wall Vertical Opaque elements	0.34	0.29	0.38	0.34	0.45	0.43
Roof Horizontal and Inclined Opaque elements	0.30	0.26	0.36	0.33	0.38	0.35
External Floor Horizontal Opaque elements	0.32	0.29	0.40	0.38	0.46	0.44
Transparent/Opaque elements of Opening/Glazing	2.00	1.80	2.40	2.20	3.20	3.00

(1) from 1st July 2015 applicable for all buildings

(2) from 1st January 2019 for public buildings and from 1st January 2015 for all other buildings

3.3.6 Economic evaluation: LCC analysis

As previously described in section 2.5, EPBD recast requested that minimum requirements for the energy performance of buildings and building elements should be set with a view to achieve the cost-optimal balance between the investments and the saved energy costs during the lifecycle of the building. For this purpose, the Commission laid down a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements.

The following steps suggested by comparative methodology framework of European commission are carried out to identify cost-optimal level from energy efficiency standpoint:

These phases are already performed in previous stages: (1) Definition of reference buildings as a representative of their functionality and geographic location, (2) Definition of energy efficiency measures (as for a whole building or for individual building elements) to be assessed for the reference buildings. (3) Assessment of thermal energy needs of the reference buildings with defined EEMs. In the current phase, global costs of energy efficiency measures during the predicted economic lifecycle for the reference buildings were calculated by applying the comparative methodology framework principles [71] and comprared with in order to point out the optimal range of solutions in terms of cost and energy (Figure 3.23). In paragraph 4.3 of regulation EU no 244/2012, method of global cost calculation for financial evaluations is described. In addition, EN 15459 provides a calculation method for the economic issues of energy systems that are involved in the energy consumption of the building [118]. A detailed description of the method is further provided in 3.3.7.6.

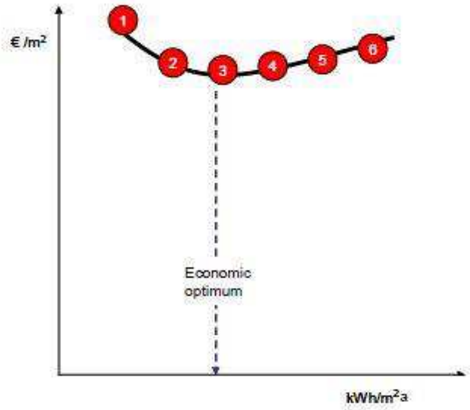


Figure 3.23: Cost-optimal range of solutions [119]

3.3.6.1 Time horizon

As [7] indicated, the study period length is important in determining which design alternative is the most cost-effective extension of lifetime of products and buildings can reduce possible damages to the natural environment [120]. According to [18], specific attention must be paid to extend the utilization period of the houses in order to minimize temporary houses cost. Different life spans of a building influence the equivalent present value of operation and maintenance, replacement and demolition costs. As the energy system components have similar life times, a shorter life time of the building results that the equipment does not need to be replaced with a new one [121].

In cost-optimal calculation study of conventional residential buildings, a service life of 30 years is considered. In this study, life-cycle costing is conducted over six time horizons: 5, 10, 15, 20, 25, and 30 years to realize that the suggested energy efficient building units are most cost-effective for longer or shorter time horizons.

Time horizon has been taken as a variable parameter in previous studies. In an investigation carried out by Morrissey [86], life cycle costing is conducted over four time horizons: 5 years, 10 years, 25 years, and 40 years. As Kneifel [7] states, no predictions are included beyond 2050 and longer study periods increase uncertainty in the accuracy of the life cycle cost estimates due to assumptions made about costs and occupant behavior decades into the future. Research results have suggested that the most cost-effective building design is always more energy efficient for the full time horizon considered and for longer time horizons. With a longer time horizon and greater energy savings, higher thermal performance scenarios become more cost effective. In this study, a similar analysis is carried out to observe whether equal results are approved for temporary prefabricated buildings.

3.3.6.2 Global cost method

The financial calculation was carried out according to the Global Cost method described in the European Standard EN 15459 through a calculation Excel spreadsheet which catches determined values e.g. economic data, building measures, various types of costs, etc. and runs the calculations for every single case (Figure 3.24). This standard permits that only components and systems which influence the energy performance of the building are considered and others could be assumed constants and not be applied in the calculations. Global cost means the sum of the present value of the initial investment costs, the sum of running costs, and replacement costs (referred to the starting year), as well as disposal costs if applicable. Its equation can be written as [118]:

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i) \right) - V_{f,\tau}(j) \right] \qquad (3.7)$$

Where

τ: calculation period

C_g (τ): global cost referred to the starting year τ_0

C_I: initial investment cost

$C_{a,\,i}$ (j): annual cost for component or system *j* at the year *i*

R_d (i): discount factor for the year *i*

$V_{f\,,\,\tau}$(j): final value of component *j* at the end of calculation period

The running costs comprising maintenance costs, operational costs, energy costs and added costs is multipled by “Present value factor” which is derived from interest and inflation rates and utilized in global cost calculations, as [118]:

$$f_{\text{pv}}(\text{n}) = \frac{(1+\text{d})^{\text{n}} - 1}{\text{d}(1+\text{d})^{\text{n}}} \qquad (3.7)$$

Present value factor particularly considered for energy costs by taking into account rate of development of the price for energy [122]:

$$f_{\text{pv, e}}(\text{n}) = \frac{(1+Re)}{d-Re} \left[1 - \left(\frac{1+Re}{1+d} \right)^{n} \right] \qquad (3.8)$$

Where

d: discount rate

n: number of years

Re: Rate of development of the price for energy

If the lifespan of component from the starting year or after the replacement exceeds calculation period, its final value is aslo included in the calculations. Detailed descriptions are provided in EN 15459 paragraph 5.2.

3.3.6.3 Economic input parameters

Utilization of the accurate financial rates is crucial in obtaining precise global cost outcome. In a Master thesis carried out by Massi [123] , historical data from ISTAT (Italian national institute of statistics) and ECB (European Central Bank), and AEEG (Authority of electricity and gas) were investigated through econometric analyses and the following rates in Table 3.4 were suggested which was also taken as input values in this study as well.

Table 3.4: Rate values of input economic input parameters

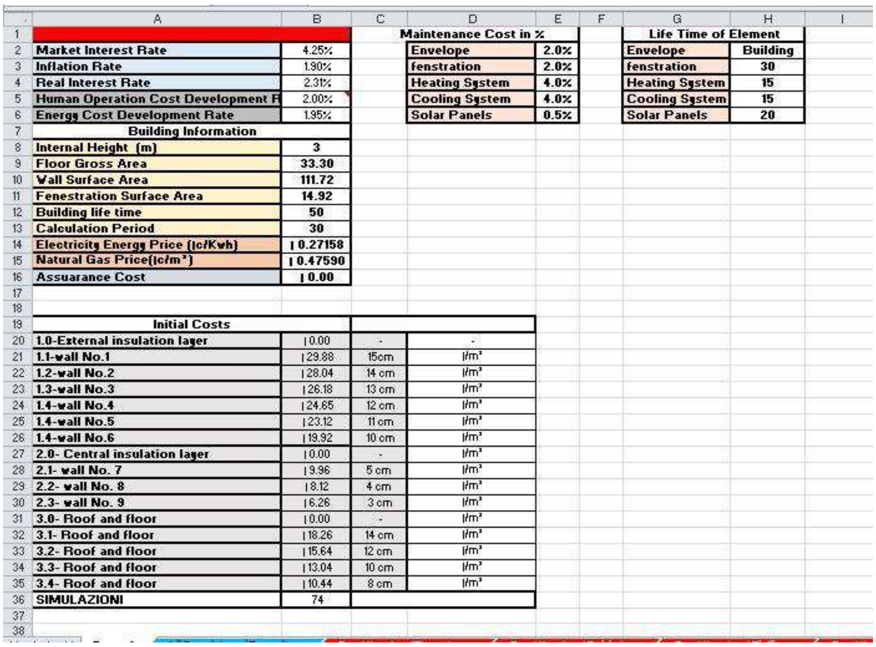
Input Parameter	
Starting year	2015
Market interest rate (R)	4.25%
Inflation rate (R_i)	1.90%
Rate of development of the price for energy (R_e)	1.95%
Rate of development of the price for human operation (R_o)	2.00%

3.3.6.4 Investment costs

Initial capital costs must be realistic and market-based. However, EU no 244/2012 has recommended that constant costs which are equal in all design measures could be omitted and solely investment costs for systems related to energy are considered e.g. investments related to the efficiency of the building envelope. In order to sum up initial construction costs, the national/local price of required items was collected (Figure 3.24).

Modules are supposed to be manufactured in the factory and assembled on site. Mantling/dismantling and transportation costs are equal in all design variables; besides, for cost calculation of unit area of envelopes, non-energy related layers e.g. coatings, metal studs, etc. were omitted since they are repetetive in all variables.

Regarding renewable energy sources, flat-plate solar collectors found out in preceding studies [87] as the best financial option -regardless of how many collectors are installed- and have been considered for installation.



	A	B	C	D	E	F	G	H	I
1				Maintenance Cost in %			Life Time of Element		
2	Market Interest Rate	4.25%		Envelope	2.0%		Envelope	Building	
3	Inflation Rate	1.90%		fenstration	2.0%		fenstration	30	
4	Real Interest Rate	2.31%		Heating System	4.0%		Heating System	15	
5	Human Operation Cost Development R	2.00%		Cooling System	4.0%		Cooling System	15	
6	Energy Cost Development Rate	1.95%		Solar Panels	0.5%		Solar Panels	20	
7	Building Information								
8	Internal Height (m)	3							
9	Floor Gross Area	33.30							
10	Wall Surface Area	111.72							
11	Fenestration Surface Area	14.92							
12	Building life time	50							
13	Calculation Period	30							
14	Electricity Energy Price (|c/Kwh)	| 0.27158							
15	Natural Gas Price(|c/m³)	| 0.47590							
16	Assuarance Cost	| 0.00							
17									
18									
19	Initial Costs								
20	1.0-External insulation layer	| 0.00	-	-					
21	1.1-wall No.1	| 29.88	15cm	|/m³					
22	1.2-wall No.2	| 28.04	14 cm	|/m³					
23	1.3-wall No.3	| 26.18	13 cm	|/m³					
24	1.4-wall No.4	| 24.65	12 cm	|/m³					
25	1.4-wall No.5	| 23.12	11 cm	|/m³					
26	1.4-wall No.6	| 19.92	10 cm	|/m³					
27	2.0- Central insulation layer	| 0.00	-	|/m³					
28	2.1- wall No. 7	| 9.96	5 cm	|/m³					
29	2.2- wall No. 8	| 8.12	4 cm	|/m³					
30	2.3- wall No. 9	| 6.26	3 cm	|/m³					
31	3.0- Roof and floor	| 0.00	-	|/m³					
32	3.1- Roof and floor	| 18.26	14 cm	|/m³					
33	3.2- Roof and floor	| 15.64	12 cm	|/m³					
34	3.3- Roof and floor	| 13.04	10 cm	|/m³					
35	3.4- Roof and floor	| 10.44	8 cm	|/m³					
36	SIMULAZIONI	74							
37									
38									

Figure 3.24: Input spreadsheet for global cost calculation

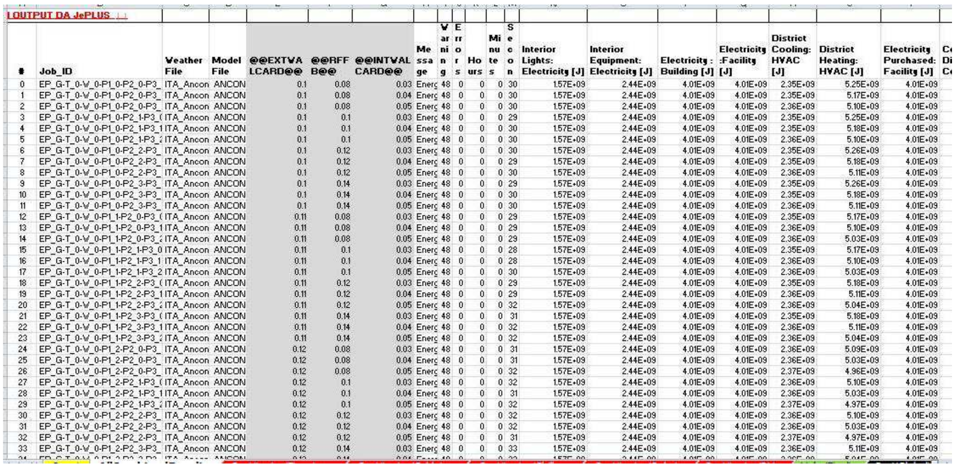
3.3.6.5 Maintenance, repair, and replacement costs

Replacement costs address those components or systems which last less than building life time while maintenance costs are calculated as a percentage of the initial costs for almost all items as indicated in Annex A of EN 15459.

Replacement costs are quantified considering lifespan of the components and systems with respect to calculation period. Product costs are maltiplied by the discount rate of the corresponding year and add up to obtain the total actualized value of replacement.

3.3.6.6 Energy costs

The annual energy consumptions derived from jEPlus parametric analysis are summed up in the calculation spreadsheet as shown in Figure 3.25. Then, energy costs are obtained through the energy tariffs provided by AEEG (Authority of electricity and gas) and are updated every three months. According to AEEG databank updated on December 2014, electricity and gas prices are considered to be 0.2716 €/Kwh +VAT (10%) + excise costs and 0.4759 €/m^3 + VAT (22%), respectively. It must be noted that in this study illumination related costs as well as energy consumption of household devices are not considered.



LOUTPUT DA JePLUS

#	Job_ID	Weather File	Model File	@@EXTWALCARD@@	@@RFFB@@	@@INTWALCARD@@	Message	Warning	Errors	Hours	Minutes	Secon	Interior Lights: Electricity [J]	Interior Equipment: Electricity [J]	Electricity : Building [J]	Electricity :Facility [J]	District Cooling: HVAC [J]	District Heating: HVAC [J]	Electricity Purchased: Facility [J]
0	EP_G-T_0-W_0-P1_0-P2_0-P3_	ITA_Ancon	ANCON	0.1	0.08	0.03	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.25E+09	4.01E+09
1	EP_G-T_0-W_0-P1_0-P2_0-P3_	ITA_Ancon	ANCON	0.1	0.08	0.04	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.17E+09	4.01E+09
2	EP_G-T_0-W_0-P1_0-P2_0-P3_	ITA_Ancon	ANCON	0.1	0.08	0.05	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.10E+09	4.01E+09
3	EP_G-T_0-W_0-P1_0-P2_1-P3_(	ITA_Ancon	ANCON	0.1	0.1	0.03	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.25E+09	4.01E+09
4	EP_G-T_0-W_0-P1_0-P2_1-P3_1	ITA_Ancon	ANCON	0.1	0.1	0.04	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.18E+09	4.01E+09
5	EP_G-T_0-W_0-P1_0-P2_1-P3_2	ITA_Ancon	ANCON	0.1	0.1	0.05	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.10E+09	4.01E+09
6	EP_G-T_0-W_0-P1_0-P2_2-P3_	ITA_Ancon	ANCON	0.1	0.12	0.03	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.26E+09	4.01E+09
7	EP_G-T_0-W_0-P1_0-P2_2-P3_	ITA_Ancon	ANCON	0.1	0.12	0.04	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.18E+09	4.01E+09
8	EP_G-T_0-W_0-P1_0-P2_2-P3_	ITA_Ancon	ANCON	0.1	0.12	0.05	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.11E+09	4.01E+09
9	EP_G-T_0-W_0-P1_0-P2_3-P3_	ITA_Ancon	ANCON	0.1	0.14	0.03	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.26E+09	4.01E+09
10	EP_G-T_0-W_0-P1_0-P2_3-P3_	ITA_Ancon	ANCON	0.1	0.14	0.04	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.18E+09	4.01E+09
11	EP_G-T_0-W_0-P1_0-P2_3-P3_	ITA_Ancon	ANCON	0.1	0.14	0.05	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.11E+09	4.01E+09
12	EP_G-T_0-W_0-P1_1-P2_0-P3_(	ITA_Ancon	ANCON	0.11	0.08	0.03	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.17E+09	4.01E+09
13	EP_G-T_0-W_0-P1_1-P2_0-P3_1	ITA_Ancon	ANCON	0.11	0.08	0.04	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.10E+09	4.01E+09
14	EP_G-T_0-W_0-P1_1-P2_0-P3_2	ITA_Ancon	ANCON	0.11	0.08	0.05	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.03E+09	4.01E+09
15	EP_G-T_0-W_0-P1_1-P2_1-P3_0	ITA_Ancon	ANCON	0.11	0.1	0.03	Energ	48	0	0	0	28	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.17E+09	4.01E+09
16	EP_G-T_0-W_0-P1_1-P2_1-P3_1	ITA_Ancon	ANCON	0.11	0.1	0.04	Energ	48	0	0	0	28	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.10E+09	4.01E+09
17	EP_G-T_0-W_0-P1_1-P2_1-P3_2	ITA_Ancon	ANCON	0.11	0.1	0.05	Energ	48	0	0	0	30	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.03E+09	4.01E+09
18	EP_G-T_0-W_0-P1_1-P2_2-P3_(	ITA_Ancon	ANCON	0.11	0.12	0.03	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.18E+09	4.01E+09
19	EP_G-T_0-W_0-P1_1-P2_2-P3_1	ITA_Ancon	ANCON	0.11	0.12	0.04	Energ	48	0	0	0	29	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.11E+09	4.01E+09
20	EP_G-T_0-W_0-P1_1-P2_2-P3_2	ITA_Ancon	ANCON	0.11	0.12	0.05	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.04E+09	4.01E+09
21	EP_G-T_0-W_0-P1_1-P2_3-P3_(	ITA_Ancon	ANCON	0.11	0.14	0.03	Energ	48	0	0	0	31	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.35E+09	5.18E+09	4.01E+09
22	EP_G-T_0-W_0-P1_1-P2_3-P3_1	ITA_Ancon	ANCON	0.11	0.14	0.04	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.11E+09	4.01E+09
23	EP_G-T_0-W_0-P1_1-P2_3-P3_2	ITA_Ancon	ANCON	0.11	0.14	0.05	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.04E+09	4.01E+09
24	EP_G-T_0-W_0-P1_2-P2_0-P3_	ITA_Ancon	ANCON	0.12	0.08	0.03	Energ	48	0	0	0	31	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.09E+09	4.01E+09
25	EP_G-T_0-W_0-P1_2-P2_0-P3_	ITA_Ancon	ANCON	0.12	0.08	0.04	Energ	48	0	0	0	31	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.03E+09	4.01E+09
26	EP_G-T_0-W_0-P1_2-P2_0-P3_	ITA_Ancon	ANCON	0.12	0.08	0.05	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.37E+09	4.96E+09	4.01E+09
27	EP_G-T_0-W_0-P1_2-P2_1-P3_(	ITA_Ancon	ANCON	0.12	0.1	0.03	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.10E+09	4.01E+09
28	EP_G-T_0-W_0-P1_2-P2_1-P3_1	ITA_Ancon	ANCON	0.12	0.1	0.04	Energ	48	0	0	0	31	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.03E+09	4.01E+09
29	EP_G-T_0-W_0-P1_2-P2_1-P3_2	ITA_Ancon	ANCON	0.12	0.1	0.05	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.37E+09	4.97E+09	4.01E+09
30	EP_G-T_0-W_0-P1_2-P2_2-P3_	ITA_Ancon	ANCON	0.12	0.12	0.03	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.10E+09	4.01E+09
31	EP_G-T_0-W_0-P1_2-P2_2-P3_	ITA_Ancon	ANCON	0.12	0.12	0.04	Energ	48	0	0	0	32	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.03E+09	4.01E+09
32	EP_G-T_0-W_0-P1_2-P2_2-P3_	ITA_Ancon	ANCON	0.12	0.12	0.05	Energ	48	0	0	0	31	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.37E+09	4.97E+09	4.01E+09
33	EP_G-T_0-W_0-P1_2-P2_3-P3_	ITA_Ancon	ANCON	0.12	0.14	0.03	Energ	48	0	0	0	33	1.57E+09	2.44E+09	4.01E+09	4.01E+09	2.36E+09	5.11E+09	4.01E+09

Figure 3.25: jEPlus output data as the input in energy consumption

Chapter 4.

4 Results

4.1 Dwelling reference buildings

As the main design features were previously discussed in 3.2.1.3, preliminary design of basic modules and examples of their configurations are presented in Figures 4.1, 4.2, and 4.3. Also, three-dimensional views of conceptual exterior design are presented in Figure 4.4.

Two types of main grids are used for the structural frame(240 cm × 480 cm and 180 cm × 480 cm). Firstly, to satisfy the allowed width in Italian road transportation (2.50m) and secondly to meet different functional residential needs. Cold-formed steel (CFS) profiles were assumed as the structural post and beam elements [124]. Vertical studs along continuous walls are placed at 60 cm distances and double-profiles are considered for grid intersections. According to nature of prefabricated portable buildings which could be placed in any location, no certain geotechnical data or wind design load is available; therefore, the supporting system must be designed in such a way to satisfy the worst cases in considered regions.

For resistance against lateral loads e.g. wind and seismic forces, a sheathing-braced approach is considered. In this method, instead of X-braces, the boards are attached to flanges of studs to reinforce the wall. This system is recommended as the stud-bracing system for low-rise buildings. Additionally, the bridging technique could assist the structure to behave properly in case of minor axial bending and wind loads to prohibit studs from axial rotations. More detailed structural design of CFS profiles is out of the scope of this study.

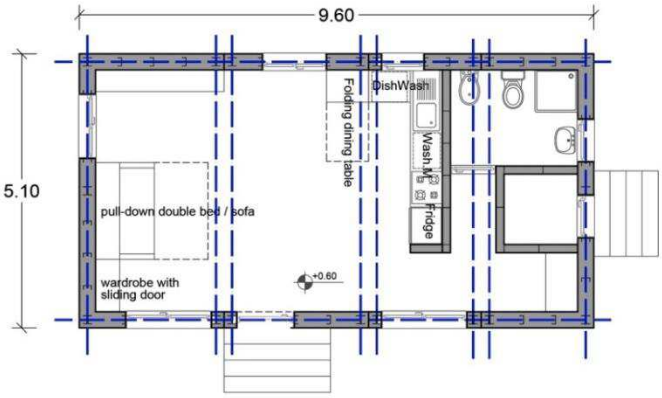


Figure 4.1: Small-sized unit, comprised of 4 modules

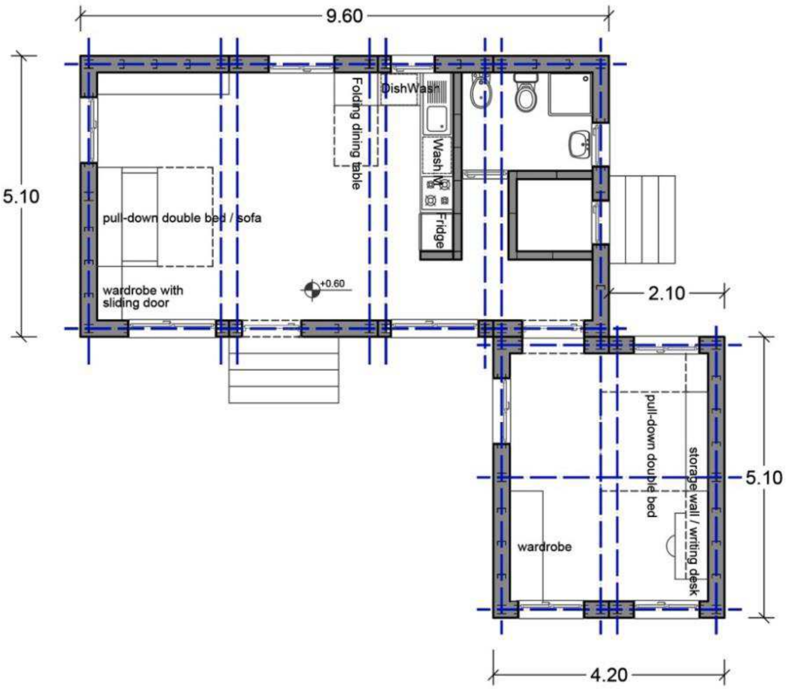


Figure 4.2: Medium-sized unit, comprised of 6 modules

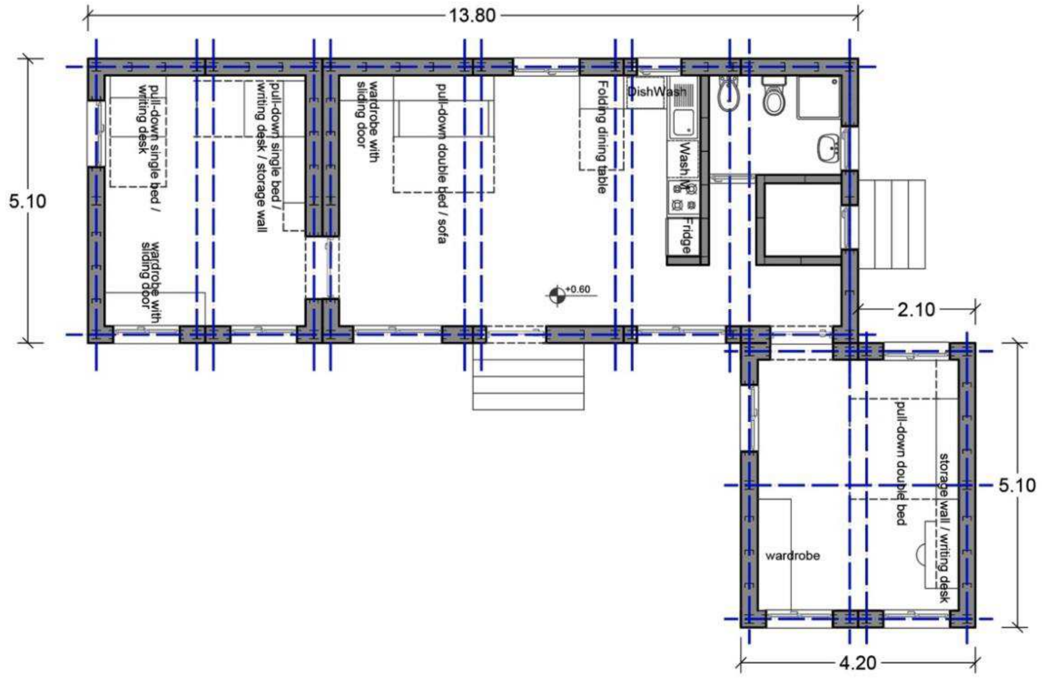
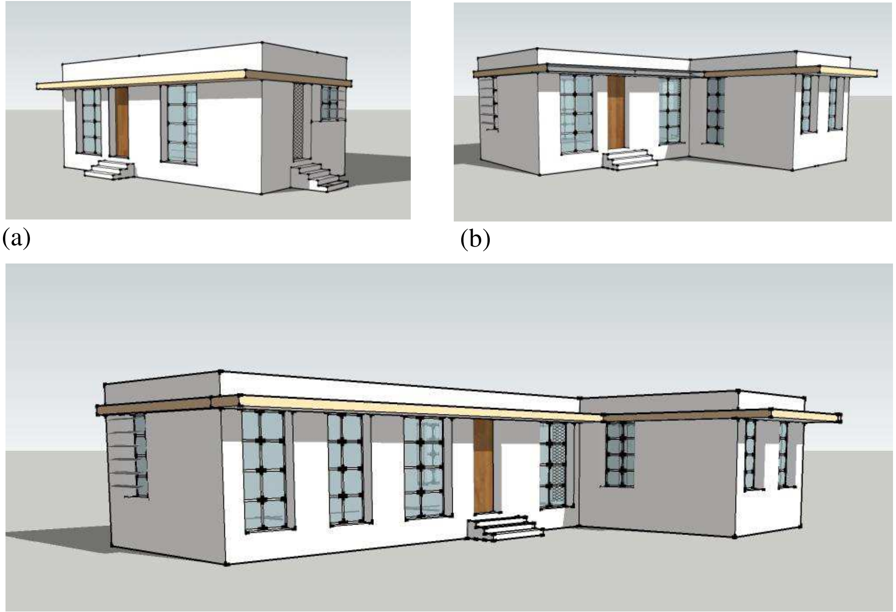


Figure 4.3: Large-sized unit, comprised of 8 modules



(a) (b)

(c)

Figure 4.4: 3D views of dwelling buildings (a) small-sized, (b) medium-sized, (c) large-sized

Table 4.1: Summary of architectural design data

Design Parameter		Small-sized	Medium-sized	Large-sized
Living zone [m^2]		-	19.4	19.4
Bedroom [m^2]		-	16.2	32.4
Night/day zone [m^2]		19.4	-	-
Cooking zone [m^2]		7	7	7
Wet zone [m^2]		4.2	4.2	4.2
Circulation zone [m^2]		6.4	6.4	6.4
Technical zone [m^2]		1.8	1.8	1.8
Total gross floor area [m^2]		50.0	71.4	91.8
Window-Wall Ratio [%]	South	21.8	30.6	33.3
	North	12.9	16.4	12.6
	East	10.0	3.4	3.4
	West	11.8	14.3	12.8
	Total	15.0	17.1	17.5

Particularly in smaller units, utilization of multi-purpose folding furniture [125] is desired to provide an appropriate night/day zone for multiple functions. All spaces except for technical room- which is separated from the residential area and directly accessible from outdoor- are air-conditioned.

4.2 Experimental results of cardboard thermal performance

For the purpose of thermal performance assessment of wall envelope stratification, determination of thermal properties of honeycomb cardboard is crucial. To this end, the output of thermal sensors installed for the cardboard specimen were studied and the measurements were investigated in order to prepare appropriate input for calculation of its thermal conductivity (λ). Obtained results are presented in the following sections.

4.2.1 Heat flux

In the following, monitoring output of outgoing/incoming heat flow density for the cardboard specimen in the standard (parallel) position is illustrated. It is possible to observe that the curve drops steeply and reaches steady state. The absolute value regardless of positive/negative signs is demonstrated. Similar studies were performed for two other directions as discussed in 3.3.1. Dark and light curves show measured values from hot side and cold side of the specimen, showing +7.5 W/m^2 and -8.5 W/m^2, respectively.

4.2.2 Surface Temperature

Surface temperature measurements for the parallel-oriented specimen are reported in Figure 4.5. However the cold thermostatic bath was set to 15°C and the hot one to 25°C, sensors show values about 16°C and 22°C, respectively which is due to heat transfer along pipes and the actual ΔT is about 6°C.

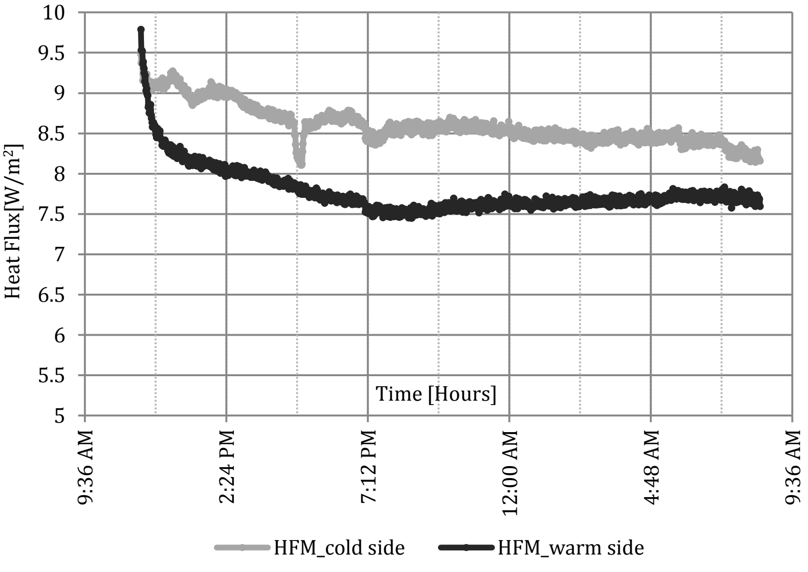


Figure 4.5: Heat flow measurement on cardboard specimen hot/cold sides

The tests were carried out during the last week of February 2015 in a laboratory with heating system off. TC_ambient represents temperature values obtained from one of the thermoresistances left in the open air next to the system.

On the hot side of the specimen, the thermoresistances show more consistent values (±2% of deviation) than the cold side (±3% of deviation). Besides, temperature difference trends between sensors installed on the center and on the edge are almost equal; on the hot side, there is a temperature drop on the edge whereas on the cold side, it rises with an equal amount (both ±4%). In addition, the temperature difference (T_{HOT} - T_{COLD}) which is directly involved in thermal conductivity calculations do not deviate more than ±4% (Figure 4.6).

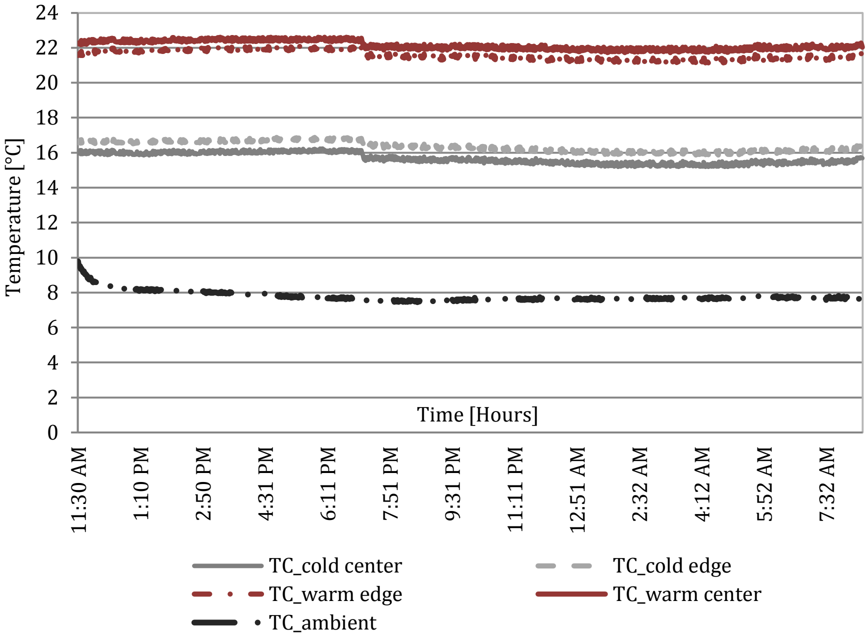


Figure 4.6: Temperature profile of installed thermoresistances on cardboard specimen hot/cold side

4.2.3 Obtained Thermal Conductivity

Figure 4.7 represents the trend of specimen's conductivity. The light-colored curve indicates the instant conductivity which is calculated based on individual parameter values at any single moments. It could be observed that even though the trend of instant conductivity follows the conductivity which is calculated based on the progressive average method (dark-colored curve), there is about 0.3 W/m^2K of difference between obtained values. Thermal conductivity of 0.123 W/m^2K was considered for cardboard material layer in wall envelope thermal performance analysis.

Since honeycomb cardboard is a heterogeneous material with a non-uniform structure, heat transfers differently in two other directions. As seen from Figure 4.8, a similar behavior was also recorded by two other specimens composed of stacked layers for conductivity measurement in other directions, however, lower conductivity is achieved in two other orientations (0.075 W/m^{2}K and 0.895 W/m^{2}K). Hereby, it could be guaranteed that by applying λ=0.123 W/m^{2}K (obtained value for parallel orientation) in calculations, no underestimation in material thermal resistance occurs.

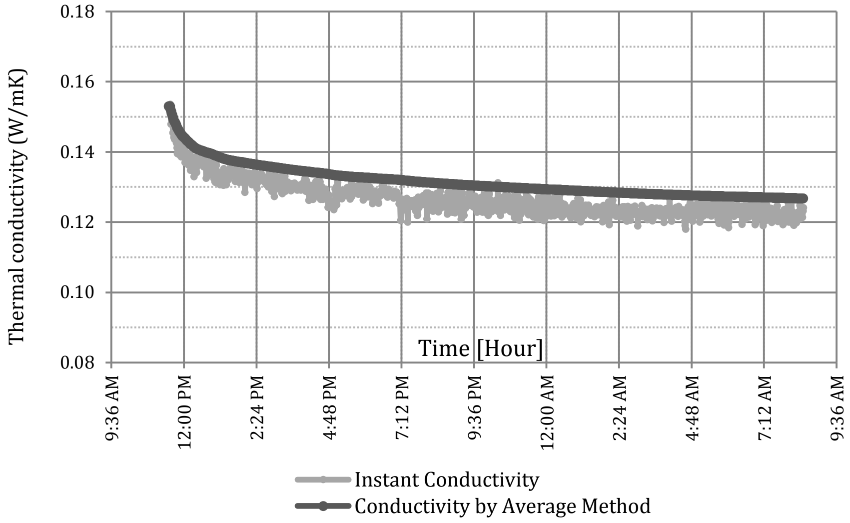
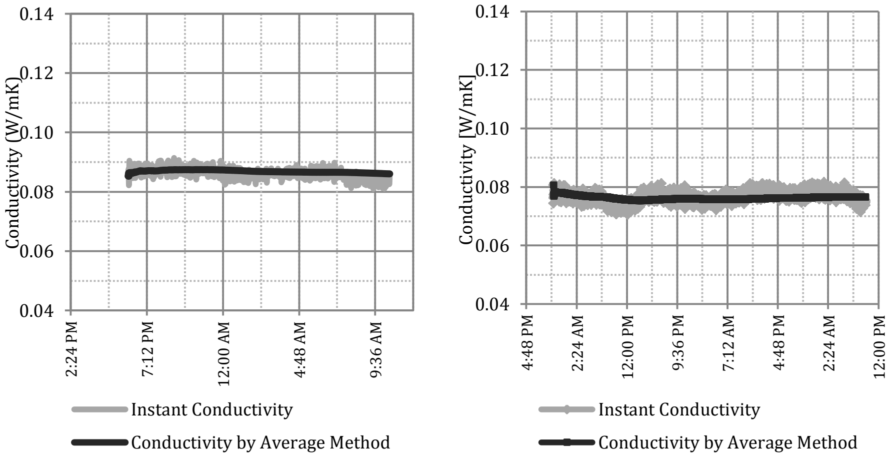


Figure 4.7: trend of calculated thermal conductivity (parallel orientation)



(a) (b)

Figure 4.8: trend of calculated thermal conductivity (a) perpendicular orientation 1, (b) perpendicular orientation 2

4.3 Life cycle Environmental impact assessment (LCIA) of cardboard

Results of Life Cycle Environmental Impact (LCIA) assessment of cardboard in production stage (pre-use phase) and its comparison with other insulation counterparts are presented in this chapter.

As shown in Figure 4.9, in "Cumulative Energy Demand" method although the contribution of cardboard in total energy consumption compared to other insulations is high and ranked as the second one, the share of non-renewable energy goes to the fifth place among seven alternatives. In other words, usage of non-renewable energy in the production phase of cardboard is lower than wood fiber, EPS, polyurethan, and glass wool. Therefore, in term of non-renewable energy, it can compete with common insulations.

Additionally, in Figure 4.10, indicators of CML(baseline) method are illustrated. Results per f.u. are organized in a relative percentage format; all indicators of cardboard material are set to 100% and other alternatives are presented as a percentage respect to the performance of cardboard. For instance, performance of cardboard compared to EPS could be percieved as: 14% lower in GWP (Global Warming Potential), 21% higher in Acidification, 13% lower in Acidification, and 65% higher in Photochemical oxidation.

In GWP (Global Warming Potential), cardboard is rather at the level of synthetic insulations such as polyurethane and EPS. In categories of Eutrophication, Acidification, and Photochemical oxidation, cardboard is placed as the third and fourth alternative, respectively.

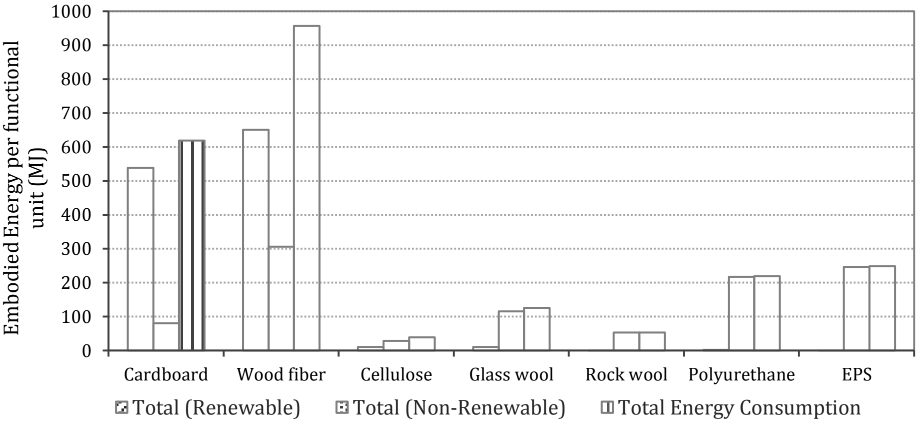


Figure 4.9: LCA results for cardboard and insulation alternatives in *"Cumulative Energy Demand"* method

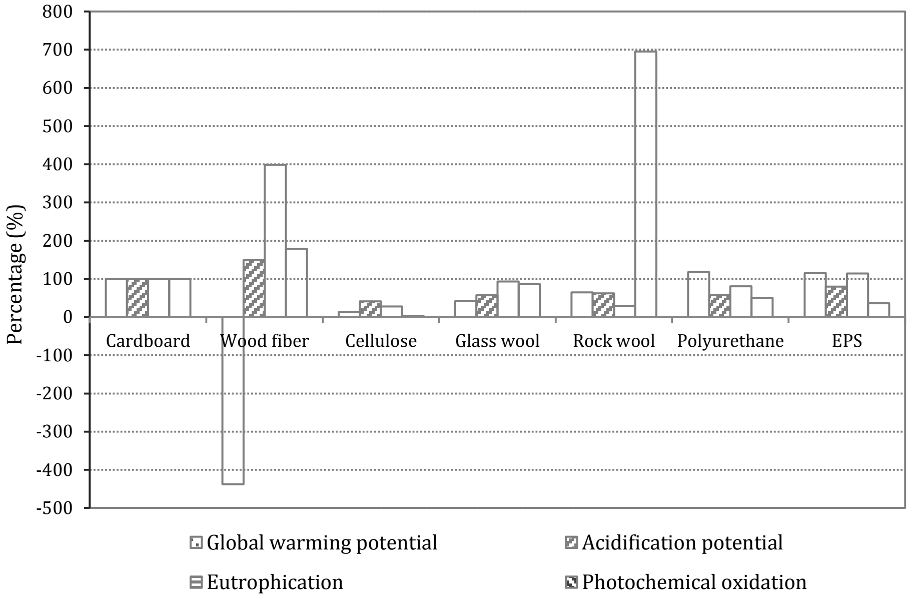


Figure 4.10: LCA results for cardboard and insulation alternatives in *CML(baseline)"* method

Results of the pre-use phase environmental study demonstrate that in term of non-renewable energy consumption, cardboard is preferable to other insulations while in other investigated impact categories has not any notable superiority over other insulation alternatives.

4.4 Thermal performance analysis of envelope

According to the expectations from a building envelope to meet the requirements both in term of prefabrication and energy efficiency, appropriate materials and thicknesses were chosen for the fundamental elements in the stratification (as previously described in 3.2.3). Thus, the overall stratification of wall, floor, and roof were designed, modified, and optimized through trial and error process to satisfy the requested architectural/structural functions and energy performance limits (Figures 4.11, 4.12, 4.13).

4.4.1 Steady State Thermal Transmittance

The following tables (4.2, 4.3, and 4.4) report the stratification composition and overall thermal resistance/transmittance of building envelopes in stationary regime. The thickness values address requirements for climatic zone D and in further steps of this study (4.6.1) they are varied to fit requested values of climates B and C.

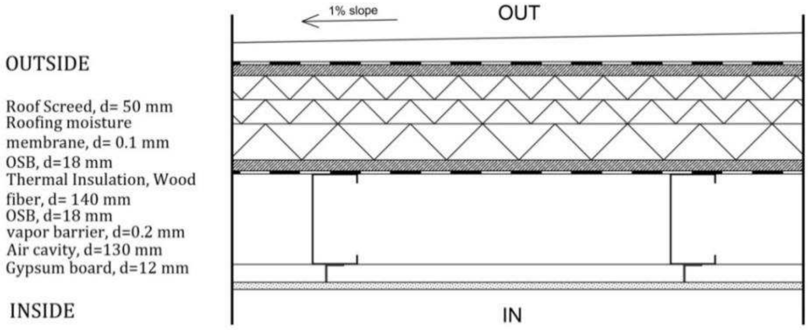


Figure 4.11: Roof envelope design

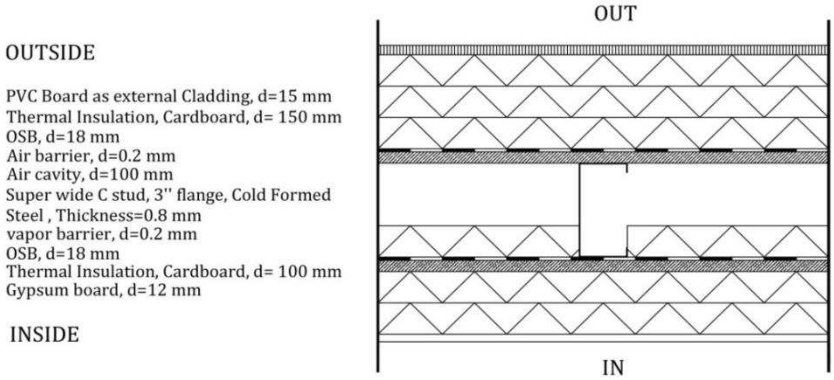


Figure 4.12: Wall envelope design

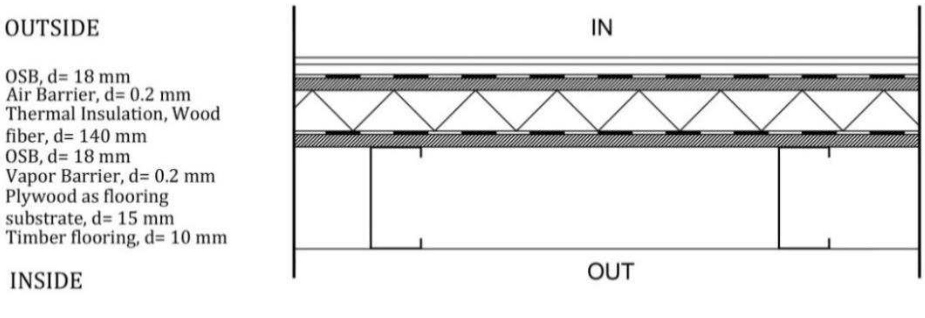


Figure 4.13: Floor envelope design

Table 4.2: Calculation of Total thermal resistance of wall envelope

Description of the layers		Thickness [m]	Thermal Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m^3]	Thermal Resistance [m^{2}K/W]
Rsi	**Inner Strate**					**0.130**
1	Gypsum Board	0.012	0.16	1150	640	0.075
2	Cardboard	0.1	0.12	1336	43	0.833
3	OSB	0.018	0.105	1880	650	0.171
4	Vapor Barrier	0.002	0.35	1470	950	0.006
5	Cardboard	0.05	0.12	1336	43	0.417
6	Air Gap	0.1				0.180
7	OSB	0.018	0.105	1880	650	0.171
8	Air Barrier	0.002	0.35	1470	950	0.006
9	Cardboard	0.15	0.12	1336	43	1.250
10	PVC tile	0.015	0.15	1470	1200	0.100
Rse	**Outer Strate**					**0.040**
Component Total Thickness [cm]		**46.7**		**Total Thermal Resistance [m^{2}K/W]**		**3.379**

Table 4.3: Calculation of Total thermal resistance of roof envelope

Description of the layers		Thickness [m]	Thermal Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m^3]	Thermal Resistance [m^{2}K/W]
Rsi	**Inner Strate**					**0.170**
1	Gypsum Board	0.012	0.16	1150	640	0.075
2	Air Gap	0.13				0.180
3	Vapor Barrier	0.002	0.35	1470	950	0.006
4	OSB	0.018	0.105	1880	650	0.171
5	Wood fiber	0.14	0.043	1380	45	3.256
6	OSB	0.018	0.105	1880	650	0.171
7	Roofing Membrane	0.001	0.19	837	960	0.005
8	Roof Screed	0.05	0.41	840	1200	0.122
Rse	**Outer Strate**					**0.040**
Component Total Thickness [cm]		**37.1**		**Total Thermal Resistance [m^{2}K/W]**		**4.197**

Table 4.4: Calculation of Total thermal resistance of floor envelope

	Description of the layers	Thickness [m]	Thermal Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m^3]	Thermal Resistance [m^{2}K/W]
Rsi	**Inner Strate**					**0.170**
1	Timber Flooring	0.01	0.14	1200	650	0.071
2	Plywood	0.015	0.19	1470	1200	0.079
3	Vapor Barrier	0.002	0.35	1470	950	0.006
4	OSB	0.018	0.105	1880	650	0.171
5	Wood fiber	0.14	0.043	1380	45	3.256
6	Moisture Membrabe	0.001	0.19	837	960	0.005
8	OSB	0.018	0.105	1880	650	0.171
Rse	**Outer Strate**					**0.040**
Component Total Thickness [cm]		**20.400**		**Total Thermal Resistance [m^{2}K/W]**		**3.900**

Table 4.5: Results of thermal properties in Stationary Regime

Parameter	Unit	Wall Envelope	Roof Envelope	Floor Envelope
Total Thermal Ressistance	Rt [m^{2}K/W]	3.379	4.197	3.900
Transmittance	U[W/m^{2}K]	0.296	0.238	0.256
Conductance	C [W/m^{2}K]	0.312	0.251	0.266
Heat Capacity per unit area	Cta [kJ/m^{2}K]	102.104	115.515	64.083
Time Constant	τ [h]	95.844	134.658	69.423

4.4.2 Periodic Thermal Transmittance

Thermal properties of horizontal and vertical envelopes in periodic situations which are representative of summer-time building performance is reported in Table 4.6. It is thus possible to affirm that obtained values are in an acceptable agreement with mandatory requirements.

Table 4.6: Results in Periodic Regime

Parameter	Unit	Wall Envelope	Roof Envelope	Floor Envelope
Decrement Factor (Attenuation)	fd [-]	0.300	0.600	0.867
Delay Factor of Decrement	φ [h]	8.965	7.425	4.256
Periodic Thermal Transmittance	$\vert Yie \vert$ [W/m^{2}K]	0.089	0.143	0.222
Thermal admittance (Inner Side)	Yii [W/m^{2}K]	1.203	1.739	2.169
Thermal admittance (Outer Side)	Yee [W/m^{2}K]	2.214	4.497	1.777
Periodic Thermal Capacity (Inner Side)	k_1 [kJ/m^{2}K]	17.764	25.730	31.581
Periodic Thermal Capacity (Outer Side)	k_2 [kJ/m^{2}K]	31.610	63.771	26.630

4.4.3 Linear Thermal Transmittance

Figure 4.14 presents schematic junctions and their heat flux density modeling by means of infrared and Isotherm visualizations in THERM. As seen in Figure 4.15, typical wall structure is far from major anomalies because steel studs are so frequent in the wall that their effects are not accounted individually. Also, other building elements e.g. roof, floor, and opening were designed in accordance with traditional construction methods. Values of ψ_e and ψ_i in Table 4.7 are accounted for external and internal dimension of joining elements as described in EN 14683[113]. As seen in 4.15, the use of cardboard does not cause any noticeable difference in linear thermal transmittance in junctions.

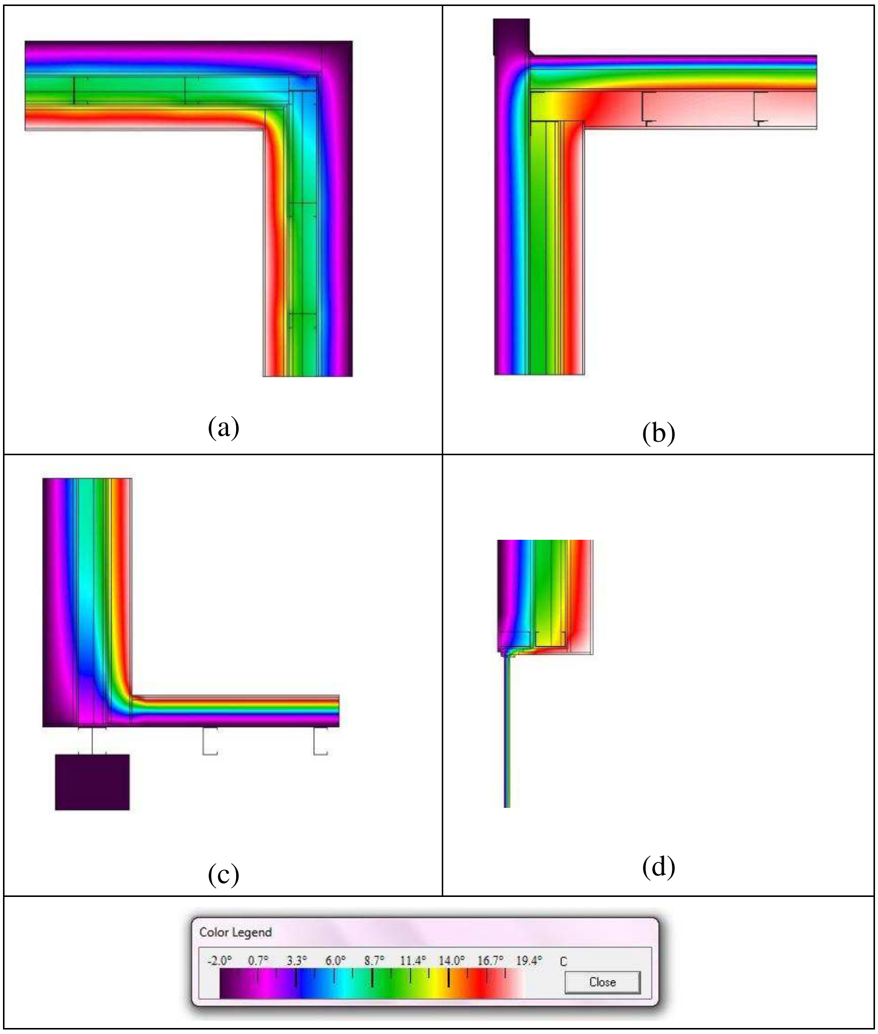


Figure 4.14: Infrared visualizaton of major construction joints; (a) wall corner connection, (b) wall-roof connection, (c) wall-floor connection, (d) wall-opening connection

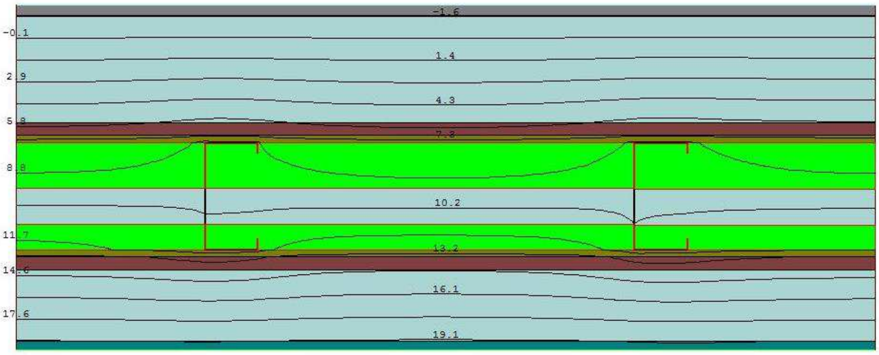


Figure 4.15: Isotherm visualizaton of continuous wall

Table. 4.7: Psi-value of construction junctions for insulation choices

Periodic transmittance (W/m^2K)	ψ_i	ψ_e
Wall to Wall	0.105	- 0.165
Wall to Floor	0.183	- 0.008
Wall to Roof	0.220	-0.003
Wall to Opening	0.16	0.16

4.5 Building energy performance analysis of “Base Case” models

In this part, simulation outcome of the software EnergyPlus with the aim of thermal energy demand estimation for the base-case unit building is presented. Acronyms presented in Table 4.8 are utilized in the following comparative graphs for the sake of brevity.

Table 4.8: Abbreviation of alternatives

City	Size	
Ancona	Small-sized	AN-S
	Medium-sized	AN-M
	Large-sized	AN-L
Napoli	Small-sized	NA-S
	Medium-sized	NA-M
	Large-sized	NA-L
Palermo	Small-sized	PA-S
	Medium-sized	PA-M
	Large-sized	PA-L

4.5.1 Heat Gain/Loss

Figure 4.1 displays overall fabric and ventilation heat gain/loss for three cities. It includes internal gain e.g. equipment, artificial lighting, people occupancy, and HVAC energy delivery as well as external loads e.g. heat transfer through surface envelope and glazing elements and moving air via infiltration and ventilation. Since a number of setting defaults are equal for three cases, e.g. occupancy, lighting and equipment schedules no significant difference is observed in these categories. Alternatively, in external loads it is possible to underline a noticable difference in solar heat gain values; They are rather twice in Napoli and Palermo compared to Ancona. However, undesired heat loss tendency which especially takes place in winter is quite similar in three cases. Regarding opaque envelopes, Palermo shows lower amount of heat discrepencies thanks to lower difference between outdoor and indoor temperatures.

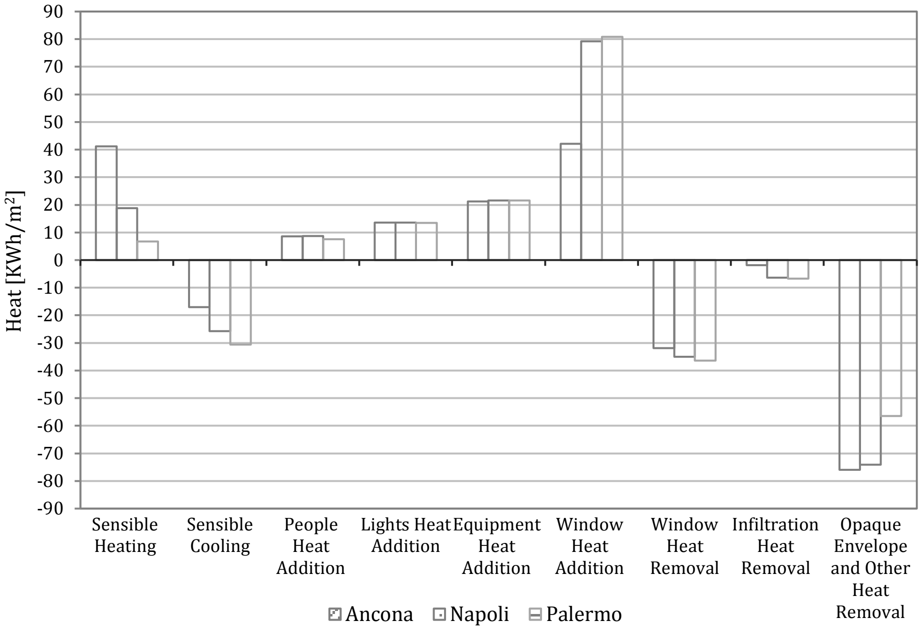


Figure 4.16: Comparative heat gain/loss in three climates

4.5.2 Energy consumption breakdown

Comparative Energy consumption percentage graph reveals some results in terms of building size and climate effect of its context. The base-case building in Ancona (climate D) consumes 33% of its total energy consumption for heating purposes. This amount drops to 17% and 7% for Napoli (climate C) and Palermo (Climate B). Alternatively, cooling consumption shares make an opposite image and is 16%, 26%, and 37% for Ancona, Napoli, and Palermo.

As building size increases from small to medium and large in heating-dominated climates like Ancona, there is a significant heating consumption rise from 33% to 43% and 46%, respectively. This effect is less noticale in two ther climates (11% and 6% in Napoli and Palermo, respectively). However, in cooling-dominated climates building size is less effective on cooling consumption share compared to other portions. This phenomenon indicates that heating consumption of the building gets affected more than other items when building size increases.

Since building size increase has marginal impact on energy demand for interior lighting and domestic hot water, (respect to conditioning energy demand), their portions are smaller in larger building sizes.

4.5.3 Annual energy consumption

In all the three climates, the middle–size building displays the highest amount of consumption per square meter; in other words, thermal energy consumption increases along building area increase in the first step (medium-sized), but the values drop for the second step of size increase (large-sized). This trend holds true for individual cooling/heating consumption as well except for cooling energy consumption in Ancona. This difference is easier to be distinguished in cooling-dominated climates like Napoli and Palermo while in Ancona the obtained values differ slightly and the trend is more linearly which implies that building geometry contributes to a very small extent in the thermal energy consumption. Thereby, it is possible to infer that influence of surface/volume ratio and building shape on energy consumption rate are greater in warmer climates and it is more essential to find the most optimum area and S/V ratio in design stage to attain the best energy performance.

It should also be outlined that by designing according to required thermal transmittance in national mandatory regulations, it is easier to achieve low energy buildings in warmer zones than in milder central zones; for instance, thermal energy consumption for small-sized alternative in Palermo is about 33% less respect to Ancona (envelope thermal transmittance is based on requirements for the corresponding climate).

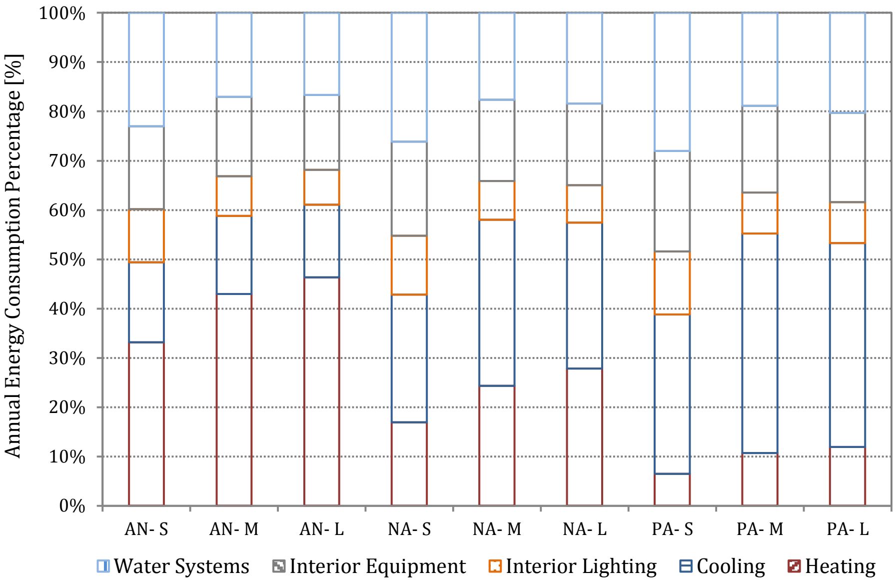


Figure 4.17: Comparative energy consumption breakdown in three climates

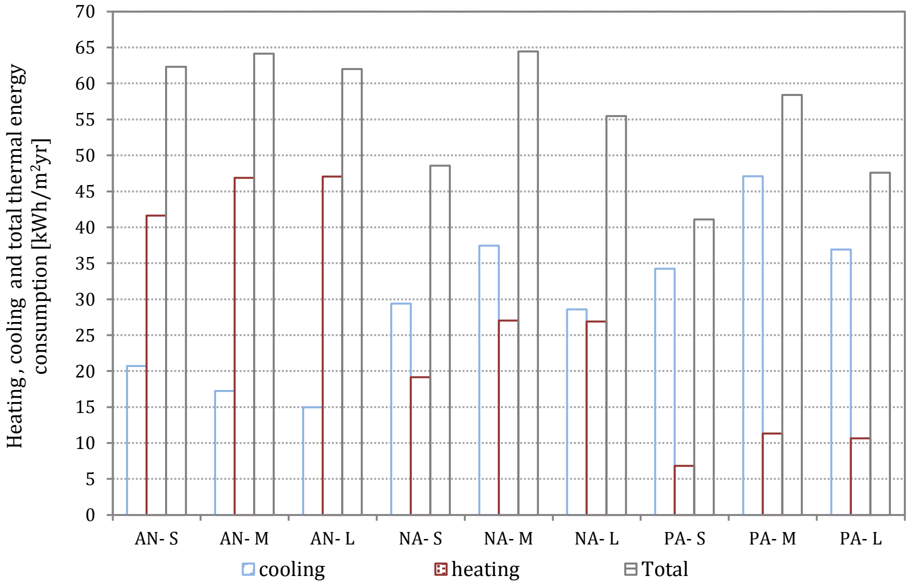


Figure 4.18: Comparative thermal energy consumption in three sizes and three climates

4.5.4 Summer time behavior

Building thermal analysis in order to assess its summer-time behavior (as shown in figure 4.19, 4.20, 4.21) covers the period 27th July to 3rd August for all three representative cities. Ambient and surface temperatures in the south-face wall of the living room in small-sized units were compared. In Ancona, outdoor temperature almost fluctuates daily between 19°C and 27°C while this range for Napoli and Palermo varies between 20°C-31°C and 22°C-29°C, respectively. Internal temperature follows cooling set points and their trends are relatively similar in three cities. Although the wall envelope stratification has a light weight and low mass, internal surface temperature variation ranges are acceptable. In all cases, the internal surface reaches the peak temperatures in the early night (about 6 hours later than the maximum external surface temperature) which is rather close to room air temperature (about 1°C higher in milder climates and 2°C in warmer climate zones).

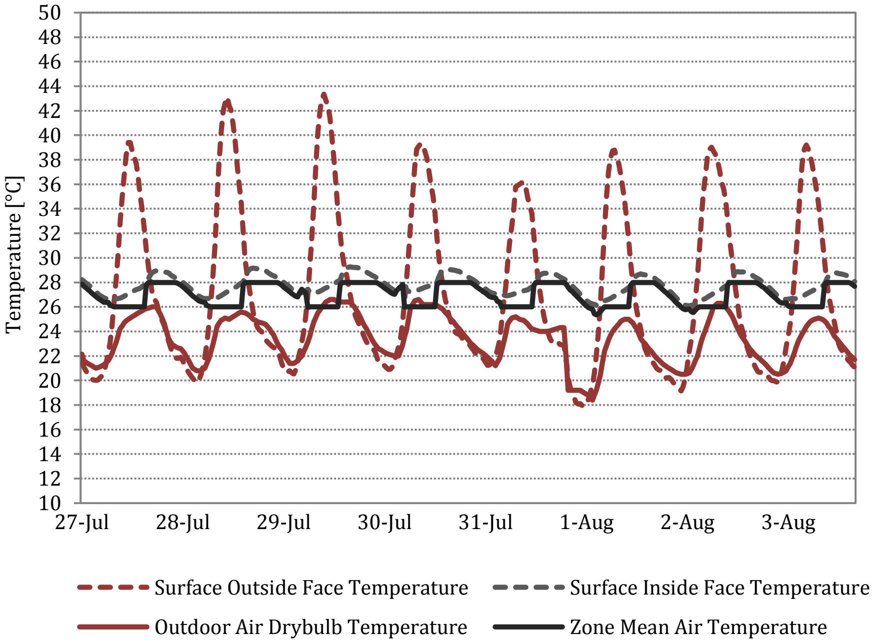


Figure 4.19: Air and surface temperature, summer-time, south wall, Ancona

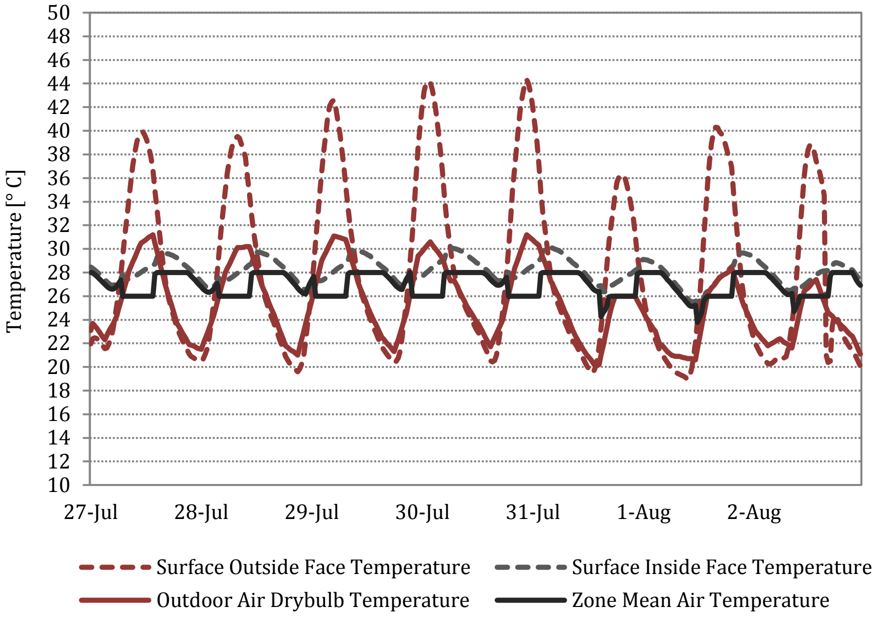


Figure 4.20: Air and surface temperature, summer-time, south wall, Napoli

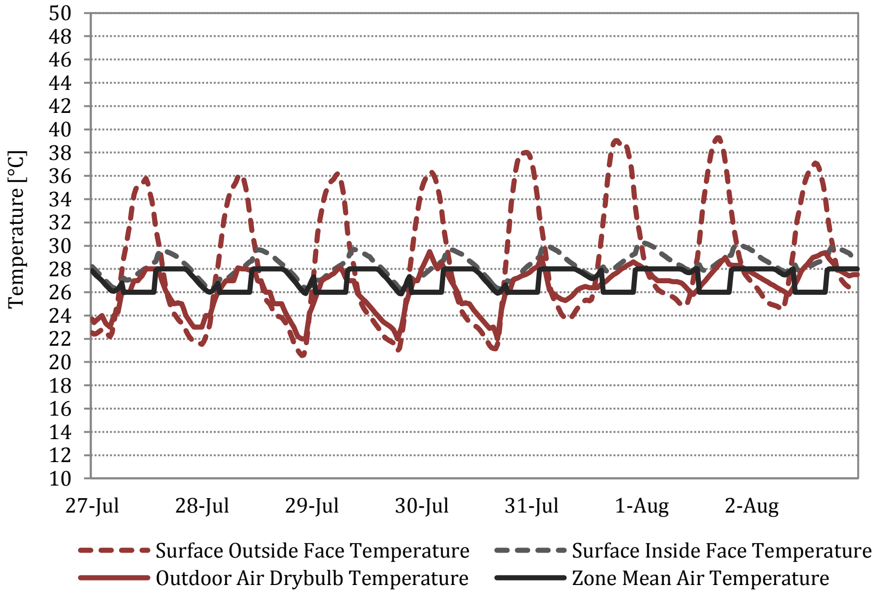


Figure 4.21: Air and surface temperature, summer-time, south wall, Palermo

4.5.5 Winter time behavior

Results of thermal comfort for a winter week from 1st to 7th December are shown in Figures 4.21, 4.22, and 4.23. As seen in the dark red-colored curve, three cities experience very different environmental conditions; for instance in Ancona, the temperature gets down to 5°C while in Palermo outside temperature does not go lower than 12°C in the considered period and reaches 21°C. As one can easily see, in sunny days higher level of solar radiation result in considerably high external surface temperatures which in turn affect the inside air temperature. Similarly to summer thermal behavior, internal surface temperature trend moves very close to the inside ambient air temperature. In Ancona, this difference is averagely 2°C and in two other climates quite 4°C.

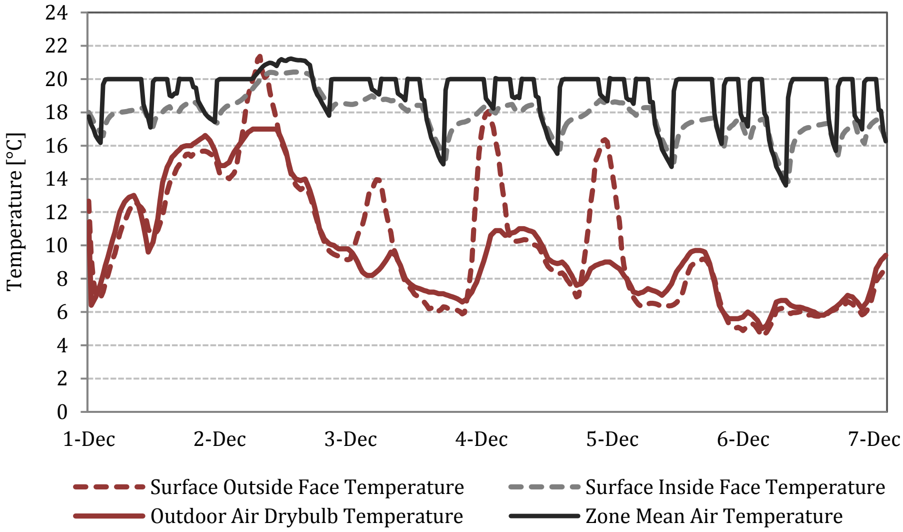


Figure 4.22: Air and surface temperature, winter-time, south wall, Ancona

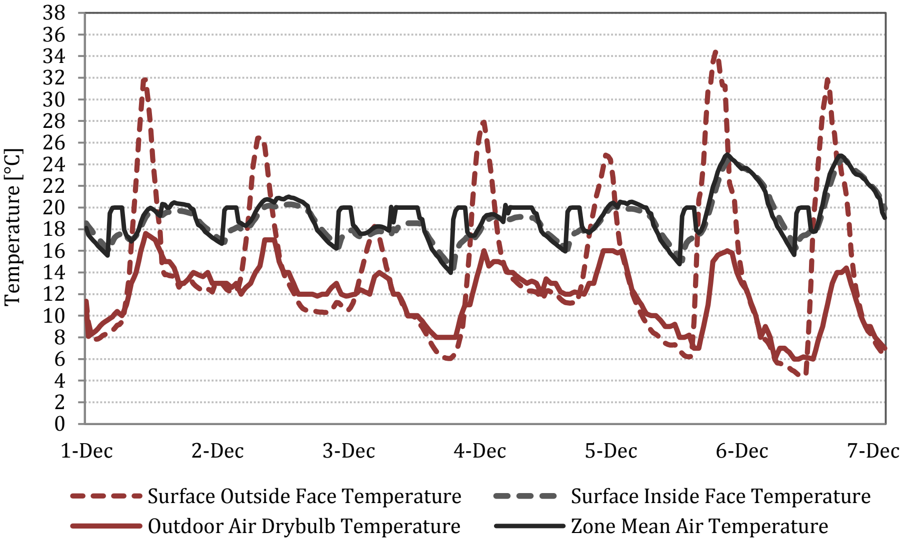


Figure 4.23: Air and surface temperature, winter-time, south wall, Napoli

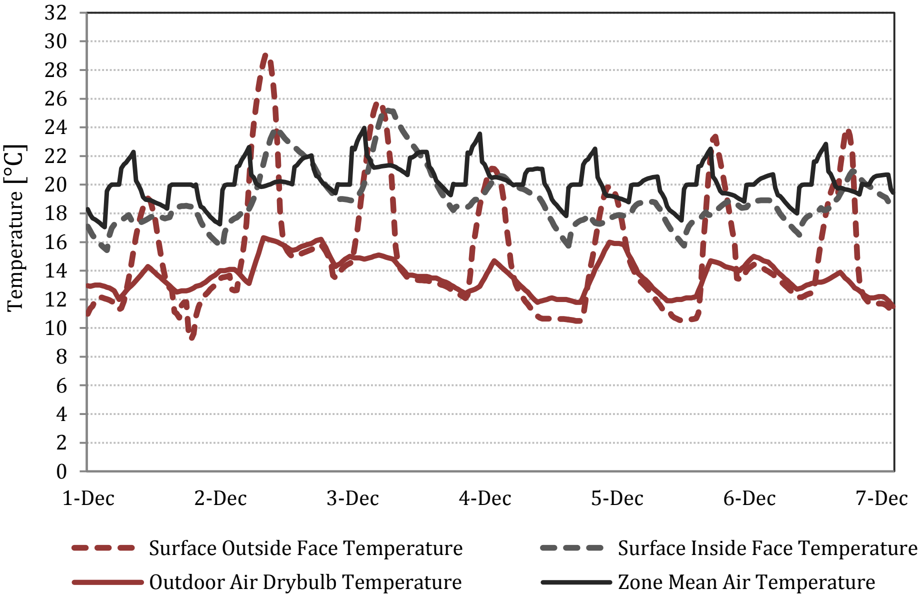


Figure 4.24: Air and surface temperature, winter-time, south wall, Palermo

4.6 Cost efficiency analysis of variants

This section of study concerns the monetary performance of different envelope variables to make a trade-off between building global cost and energy efficiency as already mentioned in 3.3.7. The derived results of cost-benefit analysis regarding building thermal energy consumption are presented.

4.6.1 Effects of variation in envelope thermal transmittance

Figures 4.25, 4.26, and 4.27 illustrate the graphical representation of energy-related global cost (€/m^2) versus energy consumption of building for heating/cooling purposes (Q_h+Q_c) for a number of variables in term of insulation thickness and configuration. Similar graphs are prepared to correspond cities of Ancona, Napoli, and Palermo, respectively to observe the possible effect of climate on energy-cost correlation of the reference building.

In the first glance, it is possible to notice that the most optimal solution from energy viewpoint does not coincide with the economic optimum solution. In figure 4.25, the point indicated as “base case” has the suggested insulation thickness to meet allowed U-value for zone D (comprising 15 cm of cardboard for external layer, 5 cm for in-cavity layer, 10 cm for internal layer, and 14 cm of wood fiber for floor/roof insulation); whilst the optimum case showing the lowest cost and meanwhile a reasonable energy consumption amount, suggests a different insulation configuration; comprising 10 cm of cardboard for external layer, 4 cm for in-cavity layer, 10 cm for internal layer, and 8 cm of woodfiber for floor/roof insulation. The economically optimum solution has 5% higher energy consumption and 14% lower cost compared to the base case solution.

In Napoli, energy consumption is 2.5% higher and the global cost is 4% lower in the optimum point rather than the suggested base case. Here, the base case solution includes 12 cm external cardboard, 4cm in-cavity cardboard, and 10 cm wood fiber for floor/roof insulation; while the optimum point offers 10 cm cardboard for the external layer, 3 cm cardboard for in-cavity and no difference in thickness of wood fiber.

The most similarity between optimum and base case solutions is observed in Zone B (city of Palermo). The cardboard thickness could be kept as suggested (10 cm external cardboard and 3 cm in-cavity cardboard) and wood fiber thickness is increased to 10 cm instead of 8 cm. By aforementioned change, energy efficiency will be improved by 6% with almost zero difference in cost level (Figure 4.27).

Among three investigated climate zones, the most attention must be paid to climate D in which the difference between base case and economically efficient solutions is relatively considerable. Besides, in the warmest climate (climate B), even by increasing floor/roof insulation thickness by 2 cm, the obtained solution will be closer to the cost-optimal energy efficient point.

4.6.2 Effect of building size

The optimum insulation thickness in medium and large-sized reference buildings were also analyzed as seen in the following figures. In climate D (city of Ancona), as building size increases, lower level of isulation thickness is sufficient to meet cost-optimal energy efficient solution, e.g. in large-sized building, 4 cm thinner wood fiber for floor/roof and 2 cm less cardboard for in-cavity cardboard are required (Figure 4.28). In zones B and C, building size does not affect the optimum solution and the corresponding insulation thicknesses to a great extent (Figure 4.29 and Figure 4.30).

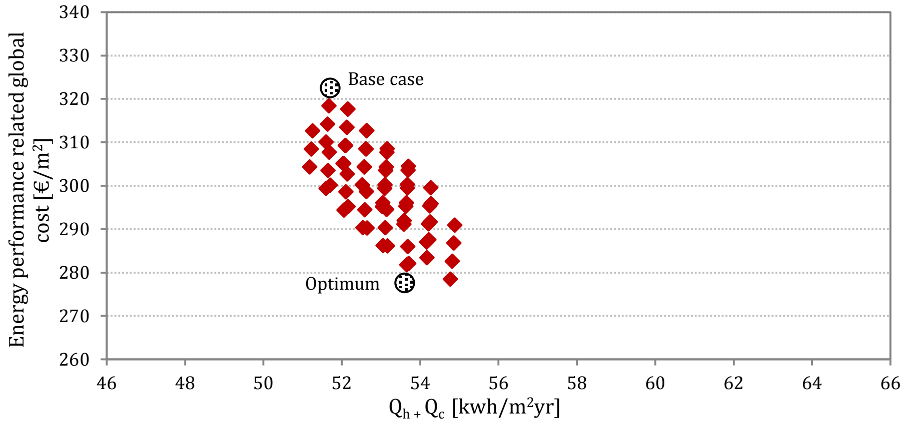


Figure 4.25: Cost-energy diagram of 72 design variables, Base case building, Ancona

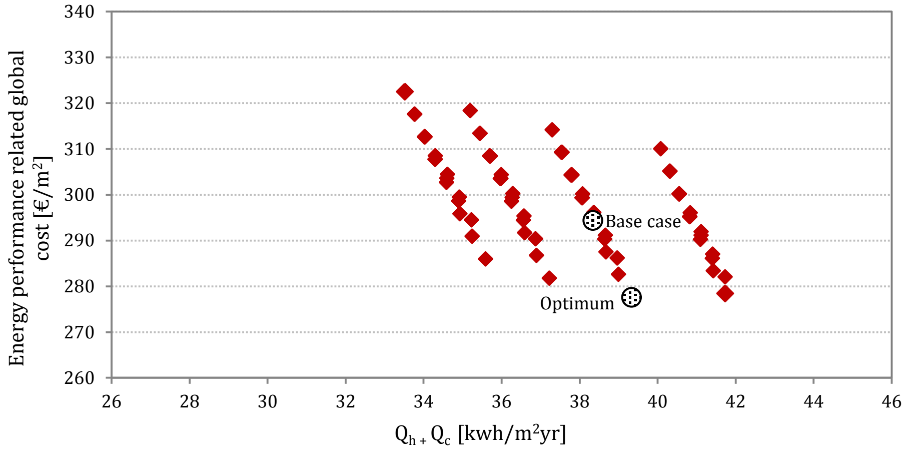


Figure 4.26: Cost-energy diagram of 72 design variables, Base case building, Napoli

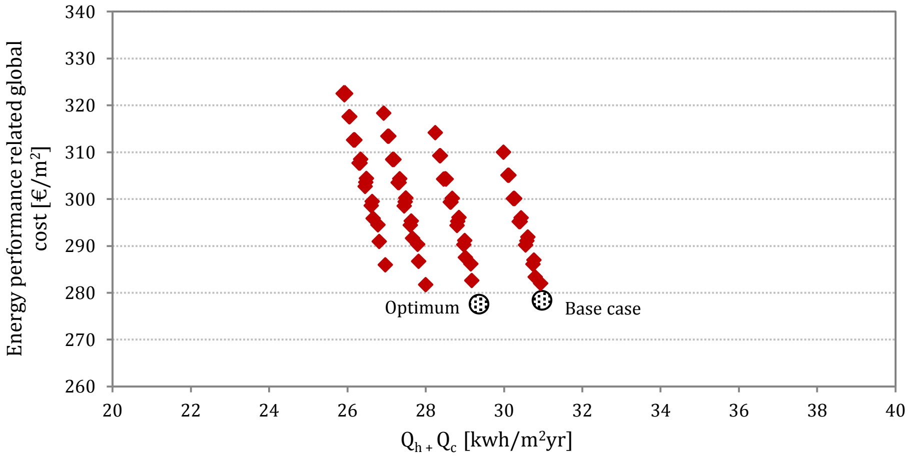


Figure 4.27: Cost-energy diagram of 72 design variables, Base case building, Palermo

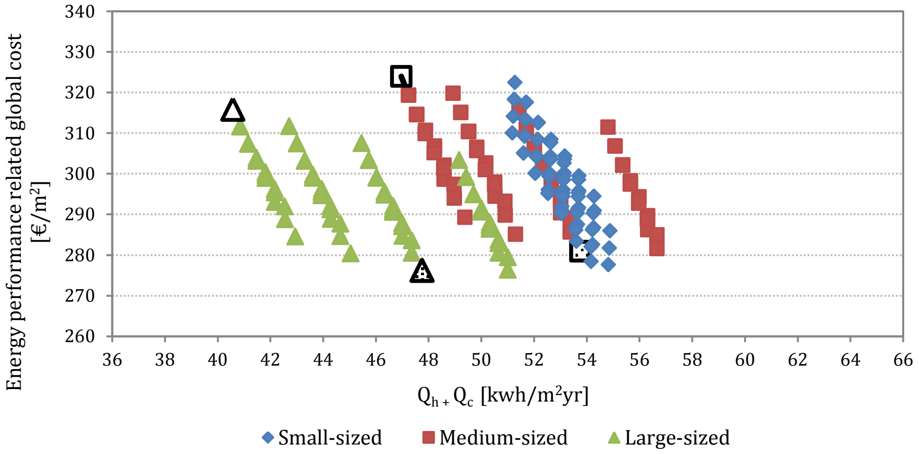


Figure 4.28: Summary diagram of 72 variables for 3 building sizes, Ancona

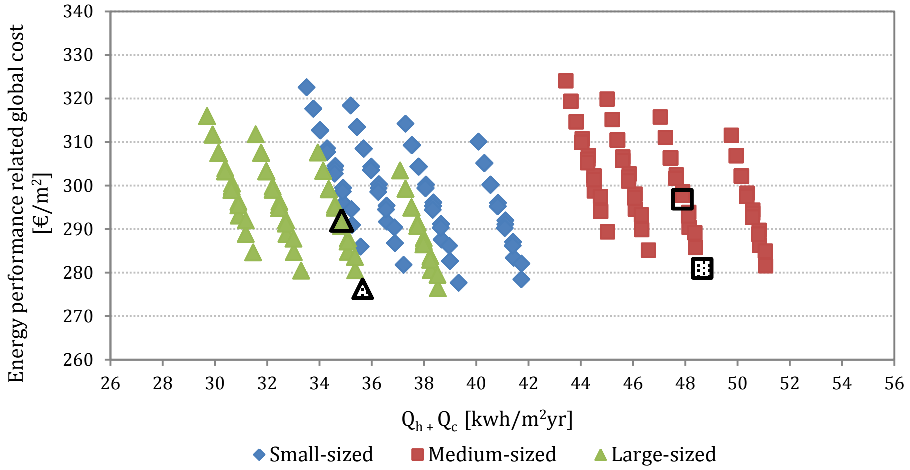


Figure 4.29: Summary diagram of 72 variables for 3 building sizes, Napoli

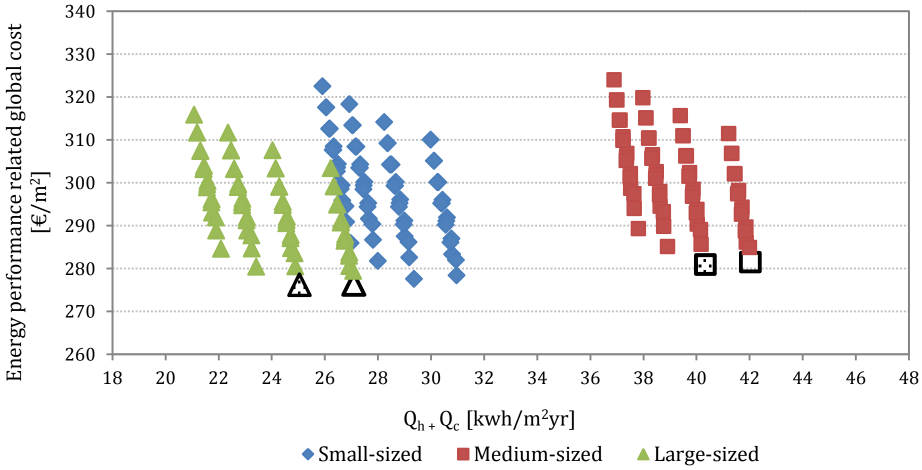


Figure 4.30: Summary diagram of 72 variable for 3 building sizes, Palermo

4.6.3 Effects of time horizon

Since time period plays a role in the cost-benefit analysis and regarding discussions in 3.2.1.4 in term of "second life" of prefabricated buildings, the effect of different calculation time was studied to investigate the most convenient time horizon for prefabricated buildings.

Economic assessment of base case building in climate D with 5-year intervals illustrated in Figure 4.31. As seen in the figure, the cost value drops for the first to fourth scenarios. It is more profitable to apply 15-year scenario instead of 10-year or 5-year. The 20-year scenario displays the lowest cost and the optimum point and then the curve rises again. This situation can be explained given that on the 20th year, the renewable source devices e.g. solar and PV panels have to be replaced. The optimum life time for prefabricated units is strongly influenced by the greatest capital cost items and their life time which determine the replacement year.

On the basis of aforesaid issues, it is advisable that a sensitivity study to be carried out for determination of the optimum economic life time which is mostly dependent on the prevailing replacement costs.

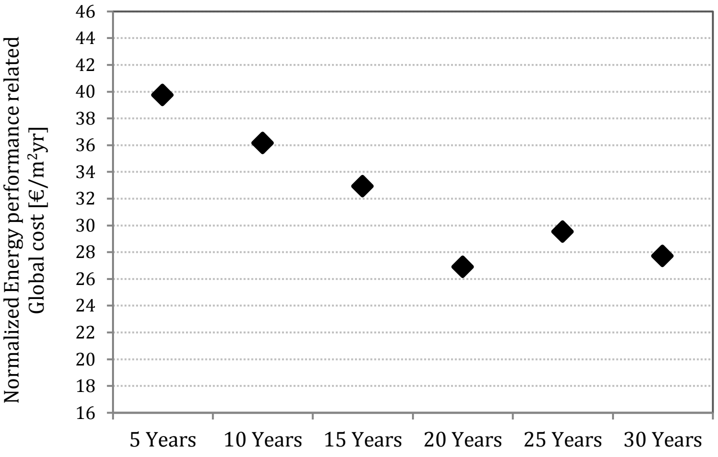


Figure 4.31: Comparative time horizon scenarios for prefabricated building

As a secondary result, it can be seen in Figure 4.32 that with smaller time horizons, the range of variation of global cost for examined design variables decreases. In this reference building (small-sized unit in Ancona) the variation range differs from 12 €/m^2 for 5-year time horizon to 45 €/m^2 for 30-year time horizon. In other words, choice of appropriate insulation thickness is more influential in the cost effectiveness of the building when greater time horizons are considered.

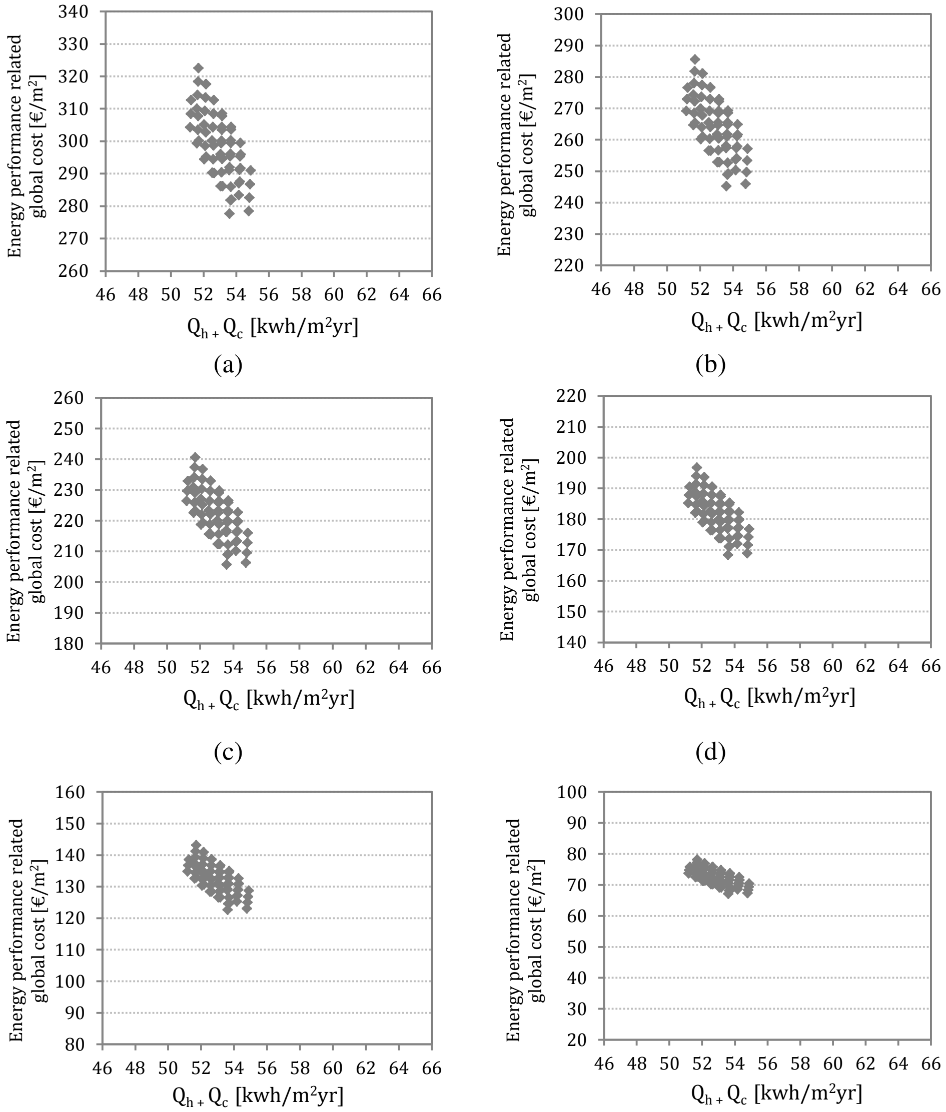

(a) (b) (c) (d) (e) (f)

Figure 4.32: global cost variation range in different time horizons (a) 30 years, (b) 25 years, (c) 20 years, (d) 15 years, (e) 10 years, (f) 5 years

4.7 Technical design characteristics of optimal solutions

Based on the obtained results through analyzing the reference prefabricated building in three size categories and three climate categories, the most recommended envelope solutions could be introduced.

Among the investigated climates (zones B, C, and D), in the milder climate of Ancona, by 30% reduction in thickness of extrnal insulation, 20% reduction in in-cavity insulation in wall envelope, and 30% reduction in floor/roof insulation thickness, the cost optimal energy efficient solution is achieved. However, wall envelope and roof/floor U-value of this solution is 20% greater than the limit values considered limit (0.29 W/m^{2}K for zone D). In warmer climate of Napoli with 15% reduction in wall external and 25% reduction in in-cavity insulation, the optimum point is reached. Nevertheless, the thermal resistance of the new configuration is 15% less than the required value in the regulations.

Conversely, in the warmest climate of Palermo, the floor/roof insulation thickness is suggested to increase by 25% to attain the more cost-effective energy efficient variable.

Chapter 5.

5 Conclusion

The present dissertation is dedicated to the cost-effective and energy efficient design of emergency temporary homes which represent a reasonable thermal performance suitable for Italian context with a focus on regions with warm temperate climate. Since, in the majority of preceding temporary prefabricated buildings, energy concerns have been underestimated, this study was carried out with the main aim of prioritizing energy efficiency issues in these building types.

By review of the most recent and the advanced prefabricated projects, their common advantageous features were extracted and a representative building was created as the reference building for the further steps of the study. The noticeable achievements of the design were to adopt physical demands of various users, to be simple, executable, and light-weight, to be modularized in order to be shaped in different combinations, and to be compatible with the climatic design and environmentally low impact.

Design of the horizontal and vertical opaque envelope as the determining factor in the energy performance of buildings was set out for in-detail investigations. Accordingly, the appropriate dry composition adaptive with portable temporary characteristics were suggested, referring to the allowed thermal transmittance limits for corresponding climate zones in Italian regulations. Apart from steady state U-value, the periodic thermal transmittance was controlled to be within permitted range and the linear thermal transmittance was also checked in critical construction joints to avoid thermal bridges.

In parallel, the innovative material of corrugated honeycomb cardboard as the recycled environmental product was considered for the wall thermal insulation. Experimental findings showed that the thermal conductivity of 0.123 W/mK in parallel and 0.08 W/mK in perpendicular directions make it suitable for insulation purposes. Additionally, environmental assessment of its production stage revealed that in non-renewable cumulative energy demand compared to other insulation counterparts, it shows a considerable superiority over other insulations. In other main categories of CML (baseline), the cardboard behaviour is close to the synthetic insulations. Although its demolition phase was not put under comparative study, it is not surprising that thanks to the recyclability features, the cardboard alternative acts in a relatively similar manner. After all, the aforesaid studies affirmed the sufficiency of cardboard application for the insulation purposes.

Examination of the dwelling in three cities with different climatic conditions showed that if transmittance level of envelopes is designed according to the national limits, heat removal through opaque envelope components is more critical in milder climates (In Ancona it is 30% higher than the warmer climate of Palermo). The level of space heating /cooling energy demand also confirms this finding. Therefore, to achieve a reasonable thermal performance in envelopes and low energy building in milder climates, it is not sufficient to design based on allowed limits in regulations and extra considerations must be taken into account.

Not surprisingly, the pattern of cooling/heating consumptions is drastically different in diverse climates; but size variation affects dissimilarly in three climates. In warmer climates, thermal energy consumption per unit area is more vulnerable to the building size and their correlation is not linear; therefore, it is of great importance to optimize building area and geometry from energy efficiency perspective.

In the cost-efficiency assessment, it was found out that the variable compatible with allowed thermal transmittance level does not match the cost-optimal energy efficient variable. In milder climate of Ancona, 30% reduction in wall envelope thickness and 40% reduction in roof/floor insulation thickness lead to a solution 14% lower global cost and 5% higher thermal energy consumption. The same trend holds true with a slighter rate of reduction in climate B; however, in Palermo, a 25% increase in wall envelope insulation thickness was suggested to arrive at the cost-optimal energy efficient solution. In larger dwelling size, the differentiation between national limit-based design and cost-optimal one is less.

Regarding the most convenient life time to be considered for temporary dwellings, analysis of the base case unit in climate D reported that with the longer time horizon for the building, the lower energy-related global cost is achieved. This value reaches its lowest point at 20th year – which is the replacement time for renewable energy sources- and then rises again. Therefore, to plan a profitable second life and third life for the temporary buildings, major replacement costs such as HVAC facilities and reneawable energy sources and their life time must be considered to reach the maximum savings.

There are a number of limitations in the scope as well as the precision of this analysis that could be addressed in future works. First, societal aspects of temporary dwellings are excluded in this research since it is another extensive area of study. It would be an interesting field to be integrated with architectural, energetic, environmental, and economical dimensions of this type of homes. Second, more energy-related design items can be added to the last part of analysis; e.g. fenestration design, glazing transmittance as well as facility choices like technical systems and renewable energy technologies to investigate the effects of the design aspects on efficiency of temporary prefabricated buildings.

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