Dissertation zur Erlangung des akademischen Grades

einer Doktor-Ingenieurin (Dr.-Ing.)

am Fachbereich Architektur

der Technischen Universität Darmstadt

Vorgelegt von:

Dipl.-Ing. Ifigeneia Theodoridou

geboren am 21. August 1981

Serres, Griechenland

Re-Polis \ retrofitting Polykatoikia

The case of Mediterranean urban housing typology;
measures to increase energy efficiency and comfort,
exemplified for the Thessaloniki urban area, Greece.

Referenten:

Erstreferent: Prof. Dipl.-Ing. M. Sc. Econ. Manfred Hegger

Korreferent: Prof. Dr.-Ing. Agis M. Papadopoulos

Drittgutachter: Prof. Dr.-Ing. Annette Rudolph-Cleff

Tag der Einreichung: 19.12.2011

Tag des Prüfungstermins: 27.02.2012

Darmstadt 2012

D17

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"The path of writing is crooked and straight"

Heraclitus

Deutsche Zusammenfassung

1. Einführung

Das Thema der Energieversorgung ist ein globales Problem. In Zusammenhang mit dem Aspekt des Umweltschutzes, werden neue Maßstäbe bezüglich der Energiepolitik gesetzt. Die Tatsache, dass der Energieverbrauch steigt, während die Energievorräte sinken, wird zwangsläufig zu einer neuen Form von Energiekrise führen. Infolgedessen werden Energieeinsparungsmaßnahmen bezüglich des Gebäudebestands geplant, besonders für Wohngebäude, welche 63% des gesamten Endenergieverbrauchs entsprechen. Die 160 Millionen Gebäude in der Europäischen Union sind für mehr als 40 % des europäischen Primär-Energieverbrauchs verantwortlich. Darüber hinaus sind sie eine wichtige Quelle von CO_2-Emissionen und auf lange Sicht eine Gefahr für die Sicherheit der Energieversorgung.

Dementsprechend, um eine Kehrtwende im energetischen Verhalten der Gebäude einzuleiten, reicht es nicht nur von jetzt an energieeffiziente Gebäude zu bauen. Man muss auch im Bestand eingreifen und zwar mit integrierten, ausgedachten Konzepten, realistischen Ideen und innovativen Technologien. Unter diesem Aspekt bilden städtische Räume den Kern dieser Problematik. Deren Verwaltung und Energieeffizienz basiert auf die Entwicklung strategischer Konzepte für die Senkung der Energieverluste im Gebäudesektor. Demnach sind bestehende Gebäude nicht nur als Gebäudeeinzelheiten zu betrachten, sondern auch als ein Teil eines lebendigen Organismus, der Stadt.

2. Methodologie

Ziel dieser Forschungsarbeit war es also, Energieeinsparungsmaßnahmen vorzuschlagen, die in einem größeren Maßstab umgesetzt werden können. Dadurch wird nicht nur Energieeffizienz unterstützt, die Erhöhung des Lebensniveaus in den Städten gesichert sowie die architektonische Regeneration urbaner Räume geprägt, sondern auch der Umweltschutz und der soziale Zusammenhalt gestärkt und die Wirtschaft angetrieben.

Gegenstand dieser Arbeit war den Zusammenhang zwischen Stadt und Gebäudebestand zu identifizieren und entsprechende Instandsetzungskonzepte vorzuschlagen. Diese Beziehung ist ein Thema was mehrere Forscher betrifft. Die Auseinandersetzung mit der Nachhaltigkeit in städtischen Räumen und die Vielfältigkeit dieser Problematik ist nämlich eine schwierige Aufgabe.

Um sich mit dieser Problematik auseinanderzusetzen musste als erstes der Basisansatz festgesetzt werden. In der Literatur werden zwei Ansätze verwendet bezüglich der Entwicklung nationaler Energieeinsparungspolitik, nämlich der „bottom-up" und „top-down" Ansatz. Im ersten Fall werden die Maßnahmen nach dem eigentlichen Energieeinsparpotential im Gebäudebestand festgesetzt. Für den zweiten Fall gilt genau das Gegenteil. Genauer betrachtet, im Fall des „bottom-up" Ansatzes wurde als erstes eine bauphysikalische und-oder statistische Analyse des Bestands durchgeführt. Im Fall des „Top-down" Ansatzes spielen volkswirtschaftliche Werte eine wichtigere Rolle. Es wird natürlich klar, dass im Fall des „bottom-up" Ansatzes die Resultate der Analyse viel sicherer sind, da sie das reale Potential in Senkung der Energieverluste reflektieren. Im Rahmen dieser Dissertation wurde der „bottom-up" Ansatz gewählt.

Die Methodologie ist folgenderweise aufgebaut: Als erstes wird eine strukturelle Bestandsanalyse durchgeführt. Bezüglich politischer, sozialer, historischer und typologischer Kriterien werden die Gebäude in bestimmten Baualtersklassen kategorisiert. Demzufolge werden die untersuchenden Stadträume analysiert und typische Gebäude bestimmt. Diese werden anhand von realen Daten und Simulationen energetisch untersucht. Damit wird ihr energetisches Profil festgestellt und die angemessenen Sanierungsmaßnahmen bestimmt, bezüglich der Klimazone und der Gebäudeklasse. Danach kann der gesamte Gebäudebestand zu diesen typischen Gebäuden gekoppelt werden um eine klare Aussage bezüglich der Planung von Maßnahmen zu erzeugen. Letztlich folgt eine Multikriterienanalyse zur Auswertung der Ergebnisse aus der Sicht der Energieeffizienz, der Wirtschaftlichkeit, der Umweltverträglichkeit sowie der Architektur, um zu den optimalsten Sanierungsmaßnahmen geleitet zu werden.

3. Fallstudie - Gebäudeeinheit

Im Fall der griechischen Städte werden zum größten Teil Mehrfamilienhäuser saniert, denn mit 90% Anteil an ausschließliche und gemischte Wohnnutzung sind sie das dominierende Element. Diese Gebäudetypologie der griechischen Mehrfamilienhäuser wird Polykatoikia genannt. Es handelt sich um eine Kombination von Hoch- und Mehrfamilienhaus. Mehrere berühmte Architekten, wie Kenneth Frampton, haben die Fortschrittlichkeit und Besonderheit dieser architektonischen Typologie anerkannt. Richard Woditsch unterstreicht in seiner Dissertation die Originalität der Polykatoikia Typologie. Mehrere Architekten wie Geipel, Christiaanse, Sarkis sowie viele griechische Architekten waren von diesem besonderen, architektonischen Akzent fasziniert. Obwohl also die Polykatoikia als eher typische Gebäudetypologie mit sich wiederholenden Eigenschaften gilt, kann es zu starken Differenzierung kommen. In diesem Rahmen, ist es schwierig "einen gemeinsamen Nenner" zu finden. Deswegen, um die Planung der effizienter Eingriffsszenarien zu sichern, war es nötig eine Gebäudeklassifizierung vorzuschlagen. Dies erlaubt die Gruppierung von Gebäudetypologien mit ähnlichen Charakteristika und demzufolge die einfachere Festlegung von gezielten Energieeinsparmaßnahmen. Auf der Basis der statistischen Analyse sowie der typologischen Charakteristika wurden bezüglich der Baujahreszeit fünf Bualtersklassen formuliert. Wichtig ist der Drehpunkt ab 1980, wo die erste WSchV in Kraft gesetzt wurde. Als Standort der Fallstudie wurde die Stadt Thessaloniki gewählt. Die zwei größten Stadtbezirke wurden ausgewählt, Thessaloniki und Kalamaria. Was die klimatischen Bedingungen der Stadt betrifft, so liegt Thessaloniki in der zweitkältesten Klimazone Griechenlands im Bereich des mediterranen Klimas und weist auf ähnliche klimatische Eigenschaften wie Marseille in Frankreich und Triest in Italien. Auf der Basis der Gebäudebestandsanalyse wurden vier typische Polykatoikia ausgewählt entsprechend der drei wichtigsten Baualtersklassen B2, C und D als repräsentatives Beispiel der Studie.

4. Fallstudie - Stadtmaßstab

Ziel der GIS Studie war es einen Zusammenhang zwischen typischen Typologien und dem städtischen Gebäudebestand zu finden. Das wichtigste bei diesem Unternehmen war es, eine bestimmte Methodologie zu entwickeln, die das energetische Verhalten von größeren urbanen Räumen festsetzten kann. In diesem Rahmen wurden drei Hauptaspekte betrachtet:

1. erneubare Energien
2. die Gebäudehülle und deren Sanierung
3. die geschätzte CO_2 Emissionen

Insbesondere wurden übliche Eingriffe in der Hinsicht von nationalen Sanierungsmaßnahmen größeren Maßstabs vorgesehen, wie Solarthermie, Photovoltaik, Gründachsysteme und Wärmedämmung. Letztlich wurden die CO_2 Emissionen für den Fallstudie-Standort festgelegt, bezüglich des energetischen Verhaltens der Polykatoikia.

Näher betrachtet, basierte die GIS Studie auf die offiziellen Landkarten der untersuchenden Stadtbezirke in digitaler Form. Diese wurden mit den offiziellen statistischen Daten verbunden, bezüglich der Höhe, des Baujahrs und der Nutzung der Gebäude. Da die Software Vektorgrößen ablesen kann, war die Bestimmung von Bauteilflächen und verfügbare Dachflächen möglich. Um die optimale Kopplung der typischen Gebäude mit dem Bestand zu schaffen, wurde deren energetisches Verhalten für mehrere Bebauungssysteme untersucht. Die Kopplung hat bewiesen, dass die ausgewählten typischen Gebäude die überwältigende Mehrheit des untersuchenden Baubestands umfassen. Auf der Basis dieser Beziehung wurde eine Abschätzung der entsprechenden CO_2 Emissionen durchgeführt.

Interessant sind noch die Ergebnisse bezüglich der Kostenanalyse von Energieeinsparmaßnahmen wie z.B. nachträgliche Wärmedämmung. Die Fläche der Gebäudehüllen wurden kalkuliert für Polykatoikia die vor 1980 gebaut wurden. Für die Implementierung eines typischen Wärmedämmverbundsystems und einer Flachdachdämmung, allein für das Stadtgebiet Thessaloniki reichen die Gesamtkosten fast 375 Millionen Euro und für das ganze Untersuchungsgebiet 460 Millionen Euro. Diese Zahlen sind wichtig in der Hinsicht nationaler Förderprogramme. Auf diese Art und Weise kann man nämlich eine grobe Abschätzung der Eingriffsmaßnahmenkosten erzielen, welche dann mit den entsprechenden positiven Einflüssen verglichen und dementsprechend evaluiert werden muss. Dieses Verfahren erlaubt eine sicherere Investition, da man die erwarteten positiven Ergebnisse genauer berechnen kann. Das war einer der Gründe, weshalb der „bottom-up" Verfahren verwendet wurde.

5. Sanierungskonzepte

Energieeffizienzmaßnahmen für den Gebäudesektor sind ein Gegenstand der Forschung seit mehreren Jahrzehnten, insbesondere in Bezug auf Wohngebäude. In letzter Zeit zusätzlich zur Optimierung der Energieeinsparrung und der Minimierung der CO_2-Emissionen ist die gesamte Umweltvertraglichkeitsstudie solcher Eingriffe von entscheidender Bedeutung. In Bezug auf den griechischen Wohnungsbestand ist eine solche integrierte Auswertung typischer Maßnahmen zur Energieeinsparung von hoher Bedeutung, im Hinblick auf ihrer wirtschaftlichen, energetischen und ökologischen Machbarkeit. Der Parameter Architektur, und der Einfluss solcher Eingriffe auf das ganze Stadtbild sollte nicht vernachlässigt werden.

Die Frage ist, welche sind die optimalen Szenarien für die energetische Sanierung des Gebäudebestands? Es gibt eigentlich keine direkte Antwort zu dieser Frage. Um genaue Schlussfolgerungen ziehen zu können, wurde ein mehrdimensionaler Auswertungsprozess entwickelt, deren Ergebnisse stark von den Bewertungskriterien sowie den jeweiligen Strategien abhängig sind.

Die erste Achse dieser Methodologie bezieht sich auf die Bewertungskriterien, nämlich:

a. Die Mindestanforderung, die von der Gesetzgebung festgelegt sind. Das heißt, dass alle zu untersuchenden Eingriffe diese Anforderungen erfüllen müssen.
b. Das Energieeinsparpotential, das für jede Sanierungsmaßnahme variiert.
c. Die Machbarkeit, nämlich der Grad des Durchführbarkeitspotential bezüglich der Wirtschaftlichkeit.
d. Umweltaspekte bezüglich des Einflusses der energetischen Sanierungsmaßnahmen.

Die zweite Achse beschreibt den Einfluss der jeweiligen Strategien auf die Bewertung der Eingriffsszenarien. Es wird klar, dass es dadurch starke Differenzierungen geben kann; eine „Minimale – Investitionskosten“ Strategie setzt andere Prioritäten, während das Thema des technischen Aufwands und spezifischer Anforderungen eine völlig andere Perspektive im Hinblick der Ergebnisevaluation setzt.

Demzufolge, wurde das mehrdimensionale Auswertungsschema in drei Schritten aufgeteilt. Als erstes werden die vorgeschlagenen Eingriffe einzeln bewertet. Für jeden Eingriff gibt es verschiedene Variationen, die miteinander verglichen werden, bezüglich der verschiedenen Bewertungskriterien und den drei strategischen Vorgehensweisen. Folglich werden mehrere Kombinationen geprüft und auf derselben Basis untersucht um letztlich zu den optimalen Eingriffen pro Gebäudetypologie zu kommen. Für die Darstellung der zweidimensionalen Auswertung, wurde eine spezifische Tabelle entwickelt. Auf der Basis der analytischen LCA Ergebnissen, werden in einer Tabelle deren qualitative Auswertungen dargestellt.

6. Ergebnisse

Insgesamt, können die wichtigsten Ergebnisse der Evaluation wie folgt zusammengefasst werden:

- Das Bebauungssystem hat einen starken Einfluss auf die Auswertung typischer Eingriffe
- Unabhängig von der Gebäudetypologie sind Verbesserungsmaßnahmen bezüglich der Anlagensysteme immer positiv bewertet.
- Das beste Szenario, aus architektonischer Sicht, ist nicht immer die wirtschaftlich vorteilhafteste Lösung.

Es ist jedoch wichtig zu betrachten, wie sich die Ergebnisse der Auswertung formulieren im Hinblick des architektonischen Akzents. Die Mehrheit der Gebäudehülle-bezogenen Szenarien wird positiv beurteilt, vorausgesetzt sie werden richtig implementiert. Die Anlagentechnik-relevante Eingriffe werden eher negativ evaluiert, wegen der oft willkürlichen Wandmontierung, die zu der Verformung der Fassade führt. Insgesamt sollte man aber unterstreichen, dass der Parameter Architektur, nicht einfach bewertet werden kann. Er muss aber mit Energieeinsparmaßnahmen, die für größere Maßstäbe geplant sind, kombiniert werden, um eine gesamte positive Auswirkung zu erreichen, nicht nur für die Gebäudeeinheit sondern für den ganzen städtischen Raum.

In diesem Sinne kann die Applikation von WDVS Schäden an den Außenwänden beseitigen. Weiterhin sollen spezifische Mindestanforderungen eingehalten werden bezüglich der Fensteraustauschmaßnahmen, um einen harmonischen Fassadenbild zu gewährleisten. Dasselbe gilt für den Sonnenschutz, wo Markisen oft nicht für die ganze Fassade vorhanden sind, und Rollladen willkürlich installiert werden, entweder aus Holz oder Kunststoff. Ein einheitliches Sonnenschutzsystem könnte in diesem Sinne dem Gebäude einen klaren architektonischen Akzent vergeben und gleichzeitig für Energieeffizienz sorgen. Außerdem weisen Gründachsysteme eine unmittelbar drastische Lösung für den Betonüberfluss und die extrem dichte Städte. Die Flachdachfreiflächen der griechischen Städten, die zum größten Teil ungenutzt bleiben, könnten jetzt eine Art von neuer Stadt über der Stadt bilden, das Mikroklima und das energetische Verhalten der Gebäude verbessern. Schließlich für die Anlagentechnik müssen erfinderische, architektonische Ideen implementiert werden, sodass die Polykatoikia-Fassaden intakt bleiben. Architektur ist also extrem wichtig beim Planen von Energieeinsparmaßnahmen.

7. Ausblick der Dissertation

Weiterhin sind wichtigsten Schlussfolgerungen bezüglich des Ausblicks der Dissertation:

- Der Auswertungsprozess selbst ist von gleicher Bedeutung wie die daraus resultierenden Ergebnisse.
- Die Bewertungskriterien haben einen starken Einfluss sowohl auf den Auswertungsprozess, als auch auf die Ergebnisse.
- Die vorgeschlagene Methodologie ist in diesem Sinne sehr flexibel (mehrere Bewertungskriterien).
- Polykatoikia sollte nicht als eine Gebäudeeinheit betrachtet werden. Sie muss eher als ein Teil der urbanen Landschaft behandelt werden.
- Eine ganzheitliche Energieeinsparungsstrategie sollte eindeutig auf die effizientere Lösung für jeden einzelnen Gebäudetypus basieren.
- Wie erwartet, wurde bestätigt, dass die Ergebnisse von den klimatischen Bedingungen beeinflusst werden.

In diesem Rahmen ergibt sich starke Notwendigkeit für:

- In Kraft-Setzung von Förderprogrammen von der Seite des Staates
- Strenge Mindestanforderungen, welche nicht nur die richtige Implementierung der Maßnahmen sichern werden, sondern auch den architektonischen Akzent der städtischen Polykatoikia
- Energieeffiziente Maßnahmen eine ästhetisch akzeptable Umsetzung gewährleisten
- In diesem Sinne, sollten für jede Klimazone und jede Gebäudetypologie, die entsprechenden Bewertungskriterien sorgfältig festgelegt werden

Es wurde gezeigt, dass wenn Energieeinsparmaßnahmen gründlich geplant werden und für einen größeren Maßstab, einen positiven Einfluss nicht nur auf die Energieeffizienz der Gebäude haben sondern auch auf die Wirtschaft, die Umwelt, die Lebensqualität und die ästhetische Qualität der Städte. Weiterhin, hat es sich erwiesen, dass das Bebauungssystem und die Morphologie der Städte sehr stark das energetische Verhalten der Gebäude beeinflussen und deswegen muss die Beziehung zwischen urbanen Gebäuden und Städten im Epizentrum dieser Betrachtung bleiben. Folglich erweist sich die Architektur an sich als ein leistungsfähiges Werkzeug, welches das Verknüpfen von energetischen Sanierungsstrategien mit der nachhaltigen Stadtentwicklung ermöglicht.

Bezüglich der innovativen Merkmale dieser Dissertation musste betont werden, dass die hier vorgeschlagene Methodologie für fast jede europäische Stadt angewendet werden. Ihre flexible Strukturierung ermöglicht die Anpassung an den jeweiligen klimatischen Bedingungen und typologischen Merkmalen für mehrere urbane Räume.

Weiterhin, während die meisten Studien bis jetzt Energieeinsparmaßnahmen nur aus der Seite der Gebäudeeinheit geplant wurden, bietet diese Methodologie ein breites mehrdimensionales Bewertungsschema, welches mehrere Faktoren, wie Wirtschafts-, Energie-, Umwelt- und Lebenszyklusaspekte, sowie technische Fragen und Angelegenheiten architektonischer Qualität berücksichtigt.

In dieser Hinsicht kann dieses Werkzeug von Ingenieuren in der Forschung und in der Praxis benutzt werden, sowie auch von Behörden, um die Untersuchung und Förderung von Energieeffizienzmaßnahmen im städtischen Raum effektiv zu realisieren. Dementsprechend kann es kann die Basis für weiterführende Forschung bilden durch die:

- Umsetzung der vorgeschlagenen Methodologie für weitere Gebäudetypologien
- Optimierung von Energieeinsparmaßnahmen nach klimatischen Bedingungen
- Den Einbau der methodologischen Schritte in ein Software-Tool
- Projektion der Resultate auf Stadtebene

Abstract

This thesis deals with the issue of Greek urban residential buildings, by means of their energy behaviour. Since Greek cities are characterised by multi-family buildings, the assessment of their energy performance is practically synonymous to the energy behaviour of multifamily residential buildings, the so called *Polykatoikia*.

Apart from sustainability, the need of revival and redefinition of the Greek urban environment played a key role to the formation of this bottom-up methodology; hence, several parameters have been taken into account, based on the complexity and the versatility of Greek *Polykatoikies*.

In this line of thought, a methodological approach is being proposed and applied to the city of Thessaloniki, a typical example of the Greek urban environment. The scope of this scheme is to create an integrated and flexible assessment tool, which will support the implementation of large scale retrofit policies. Consequently, the proposed methodology was designed in order to obtain the energy performance of urban environments, design intervention measures and evaluate their feasibility in regard to their environmental, economic and energy influence, both in a building unit scale and a city scale.

Acknowledgments

It is commonly said, that the journey is more important than the destination. For me, this journey started early in 1999 when I first left Greece to study in Germany at the age of 18; this thesis is my Ithaca, the final destination of a long voyage between two different worlds.

Besides my joy, I feel the need to express my deep gratitude for all those who believed in me and supported me throughout these years. Firstly, Professor Manfred Hegger who has instilled in me the love for sustainable architecture, along with the belief that energy efficient design is a powerful tool in the hands of an architect. His inspiring teaching filled me with an optimistic view as regards retrofitting strategies for Greek buildings, which was a fertile ground for research and the development of new ideas. I am grateful for the opportunity he gave me and the confidence he showed in me for this dissertation thesis.

I am deeply indebted to Professor Papadopoulos, my second supervisor and mentor; he believed in me, supported me and my ideas. Working by his side was an invaluable experience that determined me to great extents. I am thankful for his constant guidance and most importantly his moral support.

Moreover, I would like to express my deep appreciation to Professor Annette Rudolph-Cleff, for honouring me by being a member of supervising committee.

I would also like to thank my colleagues and friends at the Laboratory for Heat Transfer and Environmental Engineering. Firstly, Dr. Simos Oxizidis who introduced me to energy building simulation. In addition I would like to thank Dr. Dimitrios Anastaselos, a colleague and a dear friend, for his priceless support concerning the environmental assessment of my proposed intervention scenarios. Dr. Efrosini Giama, for her valuable collaboration and friendship. Dr. Natalia Boemi, for our long cooperation. Dipl. Ing. Stella Chadiarakou for her great help in the early beginnings of my Thesis. Dipl. Eng. Christina Konstantinidou, Dipl. Eng. Katerina Christodoulou and Dipl. Eng. Konstantina Leonidaki for their bright smiles, their support and their valuable friendship.

Moreover, I am thankful to Dr. Lora Slini, who always enlightened me with her knowledge on statistics. Furthermore, my appreciation to Dr. George Mallinis, a valuable colleague as regards Geographic Information Systems.

Dipl. Eng. Anna Psefteli, for her spontaneous and unstinting assistance concerning the English editing of this Dissertation.

I would also like to express my deep appreciation to all homeowners who helped me with my field research, Mr. Banioras, Mrs. Kountoura and Mr. Mamounis.

My dear, long time friends, who always gave me strength.

My very good friend and business partner Andreas Mermigkas for his support and patience.

My partner Marinos Karteris and his family. I was blessed with their love and support.

My family; my grandfather and my uncle whom I love deeply.

Above all my beloved parents; I cannot find the words to express my endless love, admiration and gratitude. I only wish I have made them proud and my experiences, which I owe to them, will one day make me a parent worthy as they have been.

It is an honour for me to end this educational circle in Darmstadt, at the TU Darmstadt, the place that defined me as a person and an architect, my Alma Mater. I am determined to carry on.

Table of Contents

1 Introduction

1.1 State of the art

The latest developments in the field of energy supply, along with the major issue of environment protection, set new priorities and yardsticks concerning the energy policies implemented worldwide. The fact that the sovereign models for the energy consumption are mainly based on the oil consumption, in combination with the reduction of the fossil oil production, could lead in time to a new form of energy crisis. In Europe 27, the final energy consumption is constantly rising, whilst the total production of primary energy is dropping (Fig. 1.1).

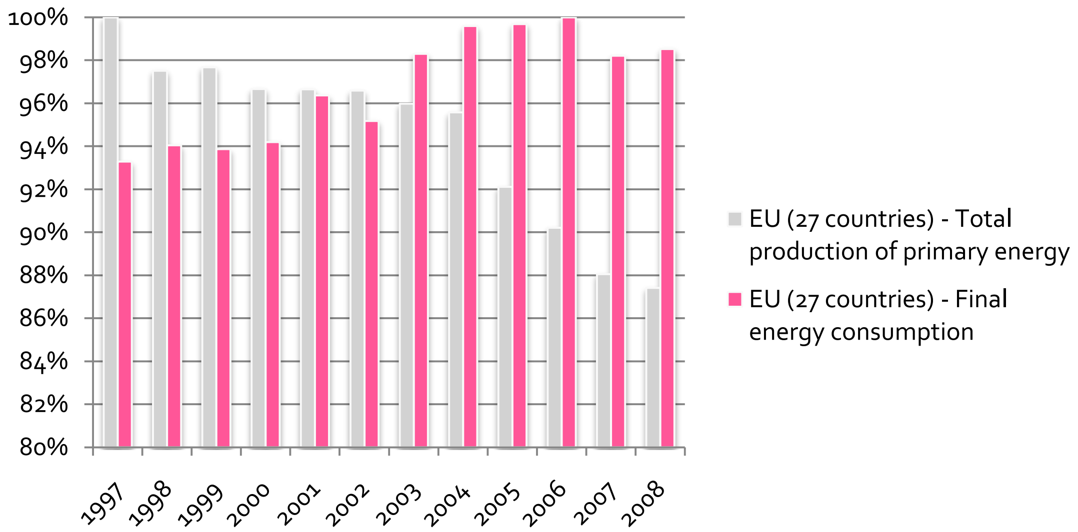


Fig. 1.1 Total production of primary energy and final energy consumption in EU 27 since 1997 (1)

The relation between these factors can also be described by the "energy dependency factor". Energy dependency shows the extent to which an economy relies upon imports in order to meet its energy needs, whilst the indicator is calculated as net imports divided by the sum of gross inland energy consumption plus bunkers (Fig. 1.2). Fig. 1.2 describes the respective tendency in EU-27 and various Member States, indicating an upward trend. Moreover, Greece is one of the most energy depended countries in EU-27 with an average dependency of 69.9% and a rather constant performance over the past 3 years.

The development and implementation of effective energy conservation policies has been a target of the European Union ever since the days when it was still called European Economic Community. In this framework, and despite the successes already monitored, the need for further energy conservation in the building sector is both an aim and a tool. Emphasis is being placed on the residential building stock and the improvement of its energy performance. Greece has been one of the last countries to adopt the Directive on the Energy Performance of Buildings. A thorough research regarding the nature of the Greek residential building stock helps in highlighting the problems associated with this delay, but also the perspectives for catching up with the other EU member states and achieving the aims set for the coming years.

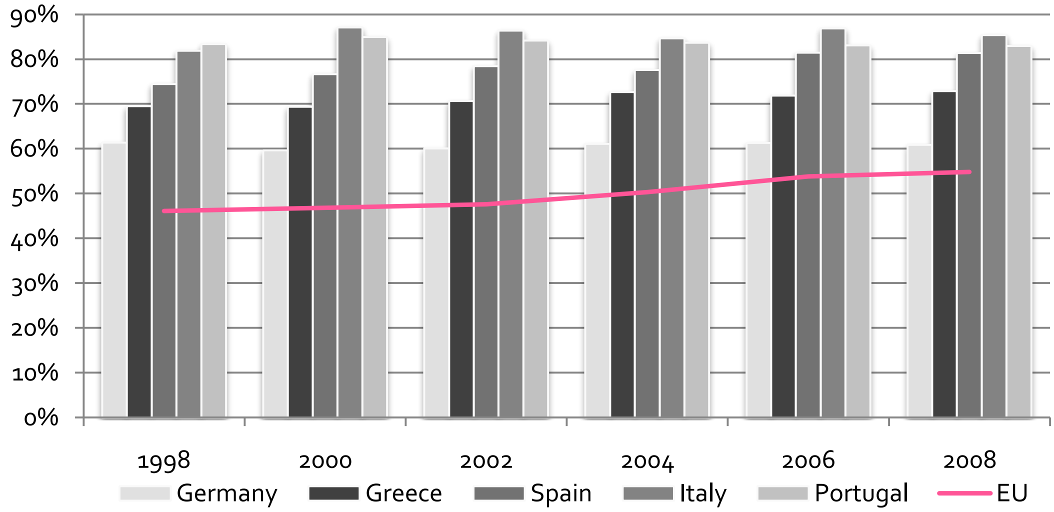


Fig. 1.2 Energy dependency in % for various Member States (2)

Assuredly, the energy crisis influences the global economic and political proceedings as well as environmental issues, which should govern the motivations for energy saving policies. Researchers agree on the fact that the GHGs emissions affect the eco balance leading to the greenhouse effect, the ozone hole and acid rain. An international collaboration is of great importance, in order to counter this phenomenon, thus on the 9th May 1992 the United Nations Framework Convention on Climate Change took place. The Kyoto Protocol was signed at the third congress (3) binding 141 countries to the minimisation of the GHGs emission by 8% in a four year time frame starting from 2008.

1.1.1 Energy and buildings

According to European Environment Agency (E.E.A.), greenhouse gas emissions in the EU-27 represent 11 to 12% of global greenhouse gas emissions (4). In addition to this each EU citizen is responsible for 10.2 t CO_2 equivalent emissions annually (4). In 2007, the EU-15 accounted for 80% of all EU-27 emissions. Moreover, among the five EU-15 Member States emitting the most greenhouse gases is Germany followed by the United Kingdom, Italy, France and Spain. On the other hand, Germany is the only Member State that has reached, and even exceeded its 2010 target and is progressing well towards its 2020 target (4).

Additionally, the European building sector is responsible for approximately 40% of the world's total primary energy consumption (5), whereas buildings in Europe account for one third of the total energy related CO_2 emissions (6). Furthermore, an 8.2% increase in CO_2 emissions from Households and Services was recorded during the period 2007-2008 (7). More specifically, in 2005 the European residential sector accounted for 26.6% of the final energy consumption, while the per capita household energy consumption increased during the period 1990-2005 in the majority of the Member States (EU-27) by 11.6%, whilst only five Member States managed to decrease their per capita energy consumption (8). More importantly, space heating is the largest component of energy use in virtually all Member States, accounting for 67 % at the level of the EU-15, followed by water heating and appliances/lighting (8).

In Germany, one of the largest potential in energy conservation lies in the existing building sector, as they consume three times more energy for space heating than new buildings. Thus, 87% of the total energy consumption in the residential sector is used for space heating and domestic hot water (9). More specifically, as regards the German housing building stock, there are 16,583,053 residential buildings with 40,183,563 households (10), the majority of which were built during the period 1949–1978. Only 27% of the residential building stock was constructed after the implementation of the first Thermal Insulation Regulation (Wärmeschutzverordnung) in 1977, and more importantly 61% of them are single-family houses (11).

It becomes clear that there is a great potential for improving the energy behaviour of existing residential buildings. Germany made great efforts in this direction by implementing respective regulations since 1977. More specifically, three Thermal Insulation Regulations were established in 1977, 1982 and 1994 respectively, and were combined with the Heating Systems Regulation (Heizungsanlagenverordnung) in 2002, in order to create the German Directive for Energy Conservation in Buildings - EnEV (Energie-Einspar-Verordnung 2002). So as to set stricter limits regarding energy consumption and thus accomplish a further CO_2 reduction in the residential building sector, two recasts of the EnEV were introduced, the first in 2007 and the second in 2009. Furthermore, according to the EnEV, in order to achieve the best possible result, focus is laid both on the building's envelope and on its HVAC systems.

1.1.2 Greek legislative framework

Greece signed the Kyoto Protocol in 2002 (Law 3017/2002) and adopted the 2. National Climate-Change Program (12). According to the targets set by the Kyoto Protocol for each country, Greece was allowed to increase its carbon dioxide emissions by 25% during the period 1990 - 2010. Unfortunately, this target has already been exceeded.

According to OECD and IEA data from 2006, Greece did not feature a comprehensive energy efficiency strategy, regarding energy supply, transport and non-industrial sectors (13). By way of example, the implementation of the European Buildings' Directive EPBD (Energy Performance of Buildings) of 2002 was accomplished in the summer 2010. In the line of the EPBD, the Greek Regulation on the Energy Efficiency of Buildings (KENAK) sets specific limitations and minimum requirements of energy efficiency concerning the design and construction of the various building types. However, emphasis is laid on improving the energy performance of the residential building stock. Households consume three to five times more energy than buildings of the public sector (14). This becomes evident if one considers that 71% of the existing Greek building stock is uninsulated and almost 80% of the stock involves residential use (15).The potential for energy conservation in existing dwellings is therefore high.

The first significant energy conservation measure in Greece, namely the Thermal Insulation Regulation of Buildings was introduced in 1979. It was followed by a 30-year hiatus, interrupted by sporadic, fragmented legislative acts, such as the Regulation on Rational Use of Energy and Energy Conservation (16) that was published in 1998, but never implemented in practice. Greece fulfilled its obligations regarding the implementation of the EPBD (Energy Performance of Buildings) Directive 2002/91/EC fairly lately; it was incorporated into the national legislation with Law 3661/2008 in 2008, however the necessary regulatory and administrative measures were completed as late as the summer 2010, with the publication of the new Energy Regulation (17) and the respective Technical Guidelines ((18), (19), (20), (21)).

Hence, there is a noteworthy potential for promoting energy conservation in existing buildings, as the majority of the building stock has been constructed before the introduction of the first Insulation Regulation of Buildings in 1979 (TIR) and even after its introduction, its implementation was for years rather hesitant (22). These buildings are, by and large, lacking adequate thermal insulation and state of the art HVAC equipment, and are primary candidates for a large scale energy renovation programme. However, in order to enhance the effectiveness of such programmes, both in terms of economics and energy efficiency, a deeper knowledge of the buildings stock's features is needed, to ensure the most suitable and efficient energy saving measures, with respect to the building's architectural, structural and operational characteristics.

2 Framework of the study

Designing measures for the reduction of energy consumption in urban areas is a complex venture indeed. In terms of urban sustainability, such measures affect energy efficiency as well as environmental, economic and social aspects. Numerous publications dealt with such methodological approaches in the past, whilst the subject of sustainable urban areas and cities is constantly gaining interest. Furthermore, energy performance is depending on building density, occupancy and consumer profile, climatic conditions, not least construction quality, factors linked, directly or not, to socioeconomic aspects. Greek cities are known for their density, their polymorphic structure and their complexity. Thus, planning energy conservation measures is a difficult task, demanding a precise methodological approach, which will embody most of these aspects to a great extent. This thesis proposes a methodology on how to manage Greek cities in terms of their energy efficiency, emphasizing on the residential stock.

Moreover, according to E.E.A., by 2020 approximately 80% of Europeans will be living in urban areas, whilst in some countries the quote will reach 90% or more (23). Besides the energy aspect, one should therefore consider the quality of living standards prevailing in the cities.

In this context, many studies have been carried out in order to estimate sustainability standards of cities both in developed and developing countries. Compact cities, megacities as well as city sectors and areas, have been a popular subject of thorough analysis ((24), (25)). Apart from high density in the urban environment, the urban sprawl phenomenon is also characterizing European cities: their compact nature and their random growth and expansion often lead to this urban sprawl (23), with apparent impact on increased energy consumption.

In addition, as Madlener et al. state in their work, cities are responsible for almost 75% of the global resource consumption, whilst this does not necessarily ensure proper living conditions. They also underline the great impact of urbanization on sustainability as well as on energy consumption and evince the main factors influencing energy behaviour of cities, among which private households (26).

The hereby presented methodology is based on the sequence of events and the interactive relationship between the need to control the global environmental and energy development as well as the sustainability and energy performance of urban areas and cities. These factors are both influencing and simultaneously being influenced by the anthropogenic activity, the local infrastructure, the buildings and of course the environment. In this framework, the proposed methodology is mainly based on the idea that any energy conservation policy should not only concern the buildings as units, but also the future impact of such measures on cities and urban areas as well as on economic, environmental and energy aspects, in this case of the Greek reality (Fig. 2.1). Hence, the focus is on buildings and their relation to the urban energy behaviour.

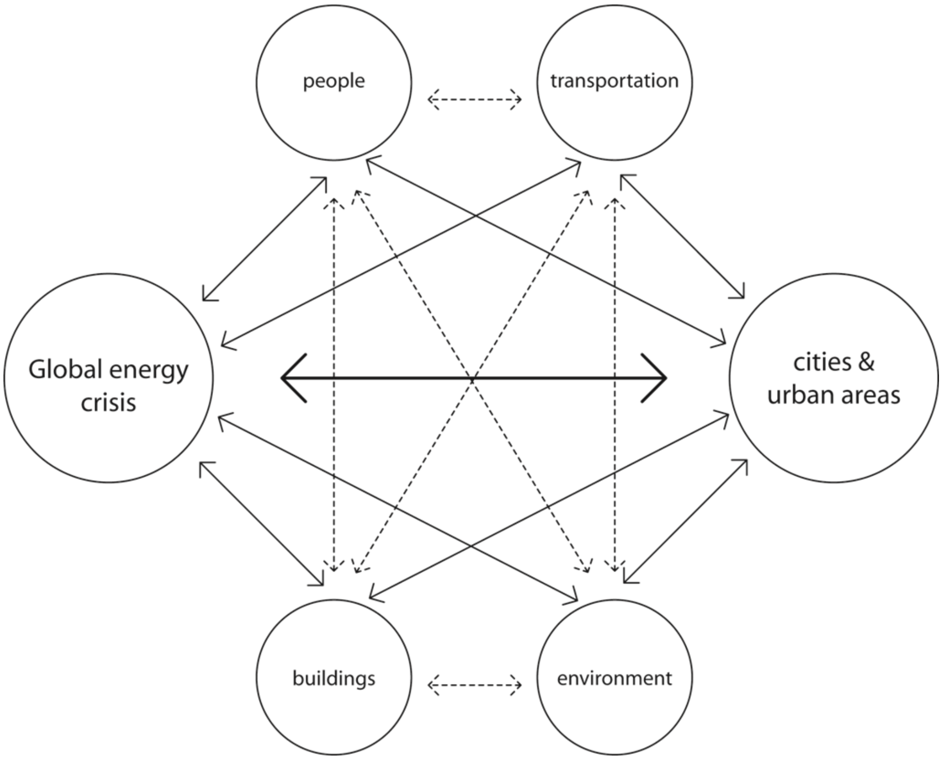


Fig. 2.1 Connection between the influencing variables

2.1 Cities

2.1.1 A brief overview

In order to assess the relationship between the building unit and the urban areas, the relevant terminology needs to be clarified. According to Neuman, cities are historic centres of government, industry, commerce, residence, and culture (27). Big cities (26), compact cities (28), urban blocks (29), historic cities ((30), (31)), city sectors (26) and urban regions (32) as well as Mediterranean cities ((33), (34)), not only are definitions found in the literature, but they also refer to specific typologies of the built environment. Each typology comprises numerous variables, often with no apparent relation to each other. However, there is a common characteristic that describes cities; they remind us of a complex organism. The hallmark concerns their aging process, thus, as some parts of a city grow older, others are still developing. This phenomenon is affecting a series of parameters, with an apparent chain reaction, among which their energy behaviour and the respective environmental impact. So how do we deal with an organism that doesn't age in a homogeneous way and needs retrofitting in terms of its energy behaviour? The scope of this thesis is to give the respective answer(s), especially as regards Greek cities and their energy performance.

2.1.2 Sustainable cities

The subject of sustainable cities and urban environment has become popular since the early '90s (25). Hence, respective terminology was developed in order to describe the relations between the built environment and sustainability, such as "sustainable city", "urban sustainability", "sustainable urban development" as well as "sustainable organisation". As regards the term "sustainable city", this is referring to self-sufficient cities, a goal that seems rather out of reach ((25), (35)); therefore, the term "sustainable urban development" seems to fit better to this methodological approach as it refers to the process towards the achievement of the goals set.

In this framework, several studies have been carried out. Egger aims at the specification of a sustainability model for cities. He considers, as this study also does, cities as open and therefore vulnerable systems. Hence, the determination of the term "sustainable city" requires a very careful analysis of multiple criteria affecting this system, concerning the city also as a part of a global net and, if possible, over time. The parameter of time, as regards sustainability of cities and household perspective, is also being discussed by Höjer et al. (36); namely setting clear long- and short term targets is of vital importance in order to indorse respective policies. The importance of such policies in order to revitalise cities is being underlined also by Haar (37).

The various criteria influencing urban sustainability have been the subject of numerous studies. More specifically, Tanguay et al. analyse 17 studies concerning the urban sustainable indicators in western countries and conclude that current practises cannot meet standard objectives. They also underline the fact that one of the most common practises refers to the comparison of municipalities in order to support local policy-tools (38). As regards the methodological approach, the municipality scale is also of great importance at the early stage of data collection, as municipalities are often the second most important source of official data input concerning energy consumption, infrastructure, maps, buildings' information, materials, occupancy, local policies and many more. These data are very important when analysing the residential building stock, the density factor and energy consumption information, three aspects that are strongly connected to urban sustainability. Similarly, Ravetz analyses the future prospects of the UK residential building stock on three different levels; the relation between existing and new buildings, the buildings' energy performance depending on the occupancy profile and of course the scale of the study (39). Thus, from individual building components, to blocks, cities and regional areas, the interventions may differ and must therefore be determined accordingly.

Furthermore, the typological classification of the housing stock plays an important role. For example, in order to estimate the relation between Dublin's housing stock and the mobility affect on the city's sustainability, Howley et al. refer to the dwelling typology and conclude that urban density is a system that should be supported in terms of sustainability (40). In general density is a subject of argument as regards sustainability of cities; smaller distances lead to less energy consumption for mobility and transfer (26), although Larivière et al. dispute the assumption that urban density is the main factor influencing energy use in cities (41). Undoubtedly though, row-system housing and built-up density are affecting energy behaviour of buildings, as they minimize thermal losses through the buildings' envelope, affect solar heat gains and shading as well as wind velocity and cooling loads, whilst they have strong influence on urban heat island effect. Therefore, dealing with energy performance of urban buildings, in this case the residential stock, imposes a comprehensive study of the built-up texture and the buildings' typology. Hence, the proposed methodological approach, concerns mainly the factors that affect energy behaviour of residential buildings, as they are the main feature of Greek cities, a fact thoroughly analysed in the following chapter.

2.1.3 Greek cities

Aristotelis once said "*a great city is not to be confounded with a populous one*" describing a fact that remains true until today. Greece is a highly urbanized country, with 73% of the total population living in urban areas, whereas in the two largest Prefectures of Athens and Thessaloniki, this percentage reaches 100% and 93% respectively (42). Furthermore, in the Municipality of Athens the population density rises up to 19,133.41 people/km^2, whilst in the Municipality of Thessaloniki the concentration is even higher, namely 20,429.20 people/km^2 (42). According to Eurostat Berlin had 3,796.3, inner London 8,902, Stockholm 280.9 and Zurich 733.5 inhabitants per km^2 in 2001 (43). These values rose up to 5.7% averagely by 2008 indicating a constantly rising density in urban areas of Europe.

Besides their high population concentration, Greek cities differ in some aspects substantially from other Western-European and North-American cities (44). The post-war Greek urban architecture becomes dominant through the absence of an "own identity" and is apparent through its chaotic forms (45). The main element that domains this unique architecture is its residential buildings, a multi-family building typology, the so called *Polykatoikia* (Greek: *polys*=many and *katoikia*= dwelling, pl. *Polykatoikies*). The remains of ancient Greece and the Byzantium, the influence of the Italic, German, Ottoman and French rule, are still evident, always accompanied by *Polykatoikies*. This typology managed to prevail in all urban areas, regardless of the climatic conditions and the historic background. Yet, how evident is cultural heritage when seeing a Greek city for the first time? Based on the various influences and according to the variety of historic background, the fact remains; the common characteristic of Greek urban areas is the *Polykatoikia*. *Polykatoikies* are met everywhere; in the city centres, in the suburbs, in old and new districts as well as, without any doubt, in future ones.

In both Athens and Thessaloniki approximately 80% of the buildings have an absolute residential use, whereas 90% of the mixed use is located in *Polykatoikies* dominated by apartments (Fig. 2.2). It becomes obvious that the typology of *Polykatoikia* is the central element in Greek cities. Furthermore, according to official data mixed use buildings with dominating office usage in the Municipality of Athens and Thessaloniki do not exceed 8% (Fig. 2.3). Therefore, *Polykatoikia* can be a pliable material in the hands of experienced architects and adjusted to various usage needs.

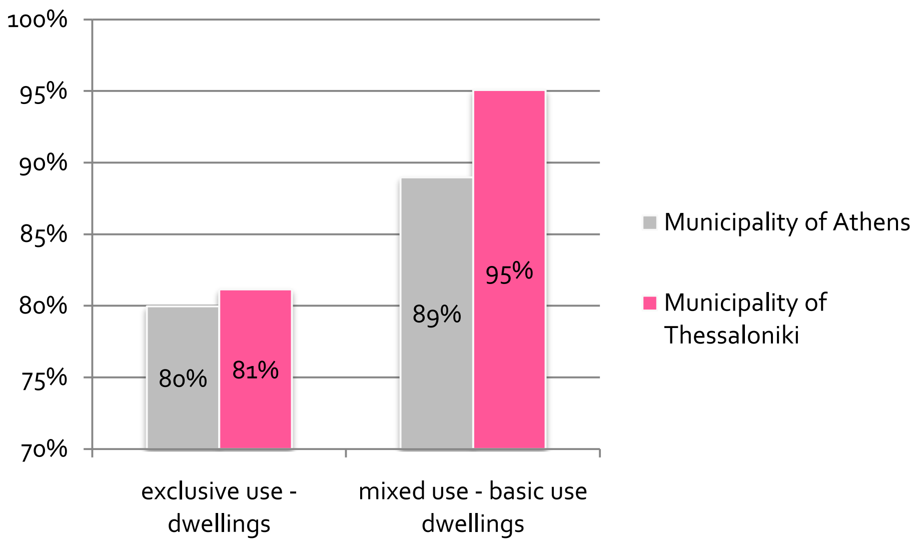


Fig. 2.2 Dwellings usage in the two largest Municipalities of Central and Northern Greece respectively (46)

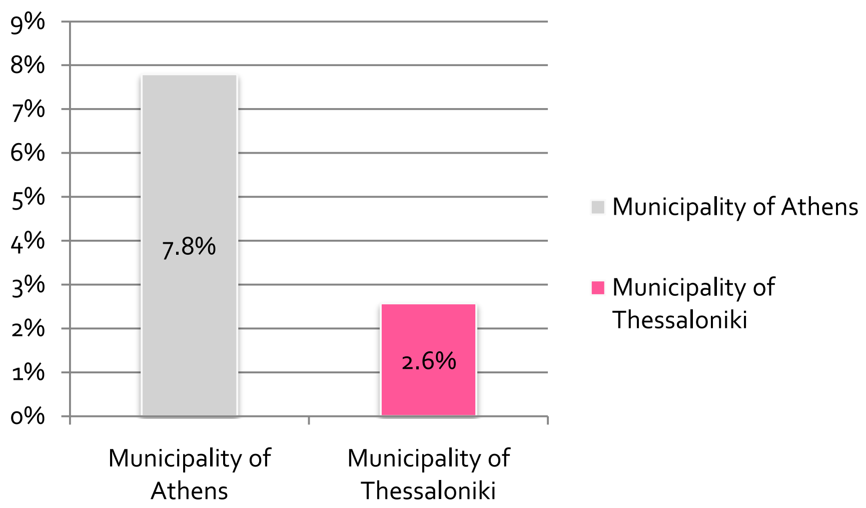


Fig. 2.3 Office usage in the two largest Municipalities of Central and Northern Greece respectively (46)

Hence, planning energy conservation measures for Greek urban buildings means more or less planning for the Greek residential stock. Thus, if any refurbishment measures are to be planned, one should consider the enormous impact of such actions on the urban environment and the great influence on our cities.

2.2 Refurbishment

What exactly is refurbishment? What does this term describe? Giebeler distinguishes various types of interventions; the main categories are reconstruction, restoration, deconstruction, demolition, renovation, repairs, refurbishment (partial or not), conservation and gutting with partial retention, although studies often refer to renovation and refurbishment as the same term. He furthermore underlines the fact that refurbishment does not lead to substantial changes regarding the load-bearing structure and the interiors, thus it is a combination of maintenance and conservation (47). Moreover, he refers to the case of multiple refurbishment scales as regards the urban fabric. This five-level scale starts with the dwelling unit, passes on to the storey level, refers afterwards to the building as a whole, then to the building-block, and finally to the town (47). The methodology discussed in this thesis also aims to create distinct parts of the respective approach concerning the design of energy upgrading measures.

2.2.1 Demolition versus refurbishment

The subject of density and dispersed urban areas often troubles researches when studying the future of our cities. Holden analyses the conflict between compact and dispersed city forms (28), whilst Kasanko et al. study 15 European cities in order to determine their expansion since 1950 (48). Hence, the conflict between those two terms raises some interesting questions; how compact is a compact city and how compact are the Greek cities? How much green space is sufficient? To what extent could there be a fusion of these two typologies? Either way, Greek cities are characterised by their density and the possibility of planning on a diverse basis would premise the demolition of an entire district and the shipping of specific infrastructures outside the city centre. The question though remains; would these measures lead to a dispersed city? If not, would they be sufficient for a friendlier city with a higher quality of living standards? In any case, such measures do not affect the main element of the Greek cities, namely the residential building stock. In this framework, demolition is being planned for urban areas that are not the main element of the built environment. On the contrary Greek urban multi-family (MF) buildings are those that lead to high built-up and population density.

Furthermore, the demolition of *Polykatoikies* would have negative influence on various aspects. Namely, beyond the problem of resettlement, based on each building's occupation, the problem of the infrastructure disturbance would be evident (49). Moreover, social parameters must be taken into serious consideration. In addition, housing capacity meets its lowest point during the demolition phase, leading to apparent practical problems, which cannot be easily dealt with if not thoroughly planed in advance. The design of a demolition process should actually include new infrastructure planning as well as site and energy efficiency planning, whilst the overall cost of such an action is much higher than the one of refurbishment. Given the fact that the Greek cities consist mainly of older buildings with residential usage, a demolition policy would imply unbearable costs if implemented by the state.

On the other hand as the construction sector is suffering a real depression, with a turnover drop of more than 62.4% compared to 2008 (50), the demolition and rebuilt progress could give great impetus, although this goal could also be met by mass refurbishment actions. However, one aspect that is not discussed neither by British or German studies, is the problem of the seismic activity and its influence on the building sector. As regards Greece, the first Greek Seismic Code was established in 1954, its first revision was endorsed in 1985, following the first Thermal Insulation Regulation of Buildings in 1979 (51). Hence, based on the fact that 71% of the existing buildings are constructed before these two Regulations, the question arises: are energy conservation measures feasible without the relevant provisions for the enhancement of the load bearing structure? How well prepared are our cities, thus our buildings, for a large scale seismic activity?

2.2.2 Combined refurbishment

In terms of the above arguments, this methodological approach considers refurbishment as the most suitable solution, with a reasonable cost-benefit proportion. Moreover, if energy upgrading measures are planned in order to achieve further goals, the expected benefits could rise significantly. Hence, under the term "combined refurbishment" the dual effect of this measure is to be understood. Namely, along with energy conservation, further goals can be achieved, such as:

- Economic growth, in terms of construction and real estate market boost (52); especially for Greece, this sector is going through the most sever crisis after the establishment of democracy in 1974, drifting construction materials market, engineers and all related sectors into the quagmire. Refurbishment programs supported by national energy policies will assuredly help the market to further develop.

- Environmental benefits due to lower energy consumption; according to the Kyoto Protocol in 2002, Greek emissions should not exceed 25% of the respective emissions recorded in 1990. This target should be achieved by 2012. Until now Greece has failed to comply with these commitments and is facing stiff penalties set by the European Emissions Trading Scheme (3).
- Development; this not only refers to state policies, as they would save on energy costs, but also to municipalities and prefectures, which would gain financial resources in order to further invest them in the urban development and infrastructures in general.
- Tourism enhancement; as already indicated Greek cities are influenced by their long history that is being projected on their architecture. Several monuments are located in urban areas, whereas a mosaic of architectural styles, due to the various influences, is dominant. Unfortunately, these are poorly highlighted, with the exception of Athens. In addition, the importance of tourism to the Greek economy in terms of its impact on foreign exchange earnings and the balance of payments is great (53). Therefore, marketing Greek tourism beyond the standard touristic targets, such as the islands and Athens' historic centre, is of vital importance. Greece is able to cover the needs of various touristic profiles (54) and Greek cities are a prosperous field. Hence, if *Polykatoikies* are to be part of a master-plan retrofit policy, they would largely contribute towards this direction.
- Redefinition of the urban architecture; as analysed in the previous chapter, Greek multi-family buildings are the governing element of the urban environment. Thus, the aesthetics of our cities depends on the way we will deal with the *Polykatoikia* typology. If energy policy refurbishment programs are to be endorsed, this parameter should be taken into serious consideration. Hence, the implementation of autonomous heating and cooling systems, such as split unit systems and gas boilers, should be carefully planned, in order to avoid images like the one depicted in Fig. 2.4. Along with the HVAC systems, shading devices should also be part of a carefully planning procedure (Fig. 2.4). The integration of these two factors as well as the wall finishing materials, colours, opening types involved in a refurbishment procedure, should be carefully standardised, in order to promote the *Polykatoikia*. Practical problems that may occur due to multiple ownerships should also be taken into consideration (55).
- Reinforcement of the bearing structure as regards seismic activity (56); security in terms of anti-seismic measures is a subject that must be reviewed as analysed in the previous chapters. The latest global examples of natural disasters should motivate us for *combined refurbishment* actions and respective policies.

- Higher living standards both for the open spaces as well as for the indoor environmental quality. This term, or otherwise the quality of life is difficult to quantify as it is being characterised by subjectivity. On the other hand, at least as regards Greek cities, some basic variables could and should be defined; green spaces, better public transportation, preserving and restoration of historic buildings and city regions, designate the natural element and many more.
- Social balance and security especially as regards city centres. These two aspects are determined by various parameters. Firstly, immigration; it is a fact that Greece is facing one of the largest immigration periods. Waters and Burnley thoroughly describe the effects of immigration on urban areas, which are apparent in Greek city centres as well ((57), (58)). Secondly, the occupancy profile in Greek cities is being characterised by mainly elderly people, students and families with low income (51). In the first case, the problem of mobility is obvious and on the other hand the determinate is the low rent pricing. Due to the fact that urban multi-family buildings are over 40 years old (59), the indoor air quality and the living standards are poor (60). Thirdly, the issue of security raises interest constantly and should be evaluated accordingly (61). Hence, the processes of mass buildings' refurbishment could be assigned on the basis of social development (62).
- New uses. The typology of *Polykatoikia* has already proven its multifunctional nature. Even though the majority of these multi-family buildings is mainly used to cover residential needs, mixed usage is also common especially in the city centres of the Greek urban areas; ground floors cover commercial uses, whereas in the upper floors offices and private practices are found. This characteristic of Greek multi-family buildings has drawn the attention of several non-Greek architects such as Rowe and Sarkis (63) as well as Woditsch (64), who believe that "a distinct quality of the *Polykatoikia* is its ability to adapt to a variety of uses within a small volume and within the same structure". This rare adaptable MF – building typology should earn respect also among Greek architects and be accordingly highlighted.

Similarly, various studies point out the benefits of *combined refurbishment*; Uihlein et al. underline the need to ensure the appropriate energy conservation measures, not only for large scale renovations but also for single buildings' refurbishment, in order to deal with the low stock turnover (65). Furthermore, Kaklauskas et al. created a multiple criteria analysis tool, in order to evaluate refurbishment measures, based on technical, esthetical, economic, technological, legislative, infrastructure and social aspects (66).

Hence, refurbishment aiming at energy conservation in the residential sector can have a multitude of beneficial effects, if properly designed. Therefore, energy conservation policies regarding the existing building sector should be based on the idea of *combined refurbishment* in order to promote Greek architecture, boost the construction sector and the economy as well as to ensure better quality of life and security for their inhabitants.

Fig. 2.4 Random installation of HVAC systems and shading in *Polykatoikies*

2.3 Methodological approach

2.3.1 Bottom-up methodology

The struggle towards sustainable development and the need for holistic energy policies have concerned researchers since the early 70s, leading to the establishment of various techno-economic energy assessment models often with focus on the residential sector ((67), (68), (69), (70), (71), (72), (73), (74), (75)), such as the top-down and bottom-up approaches; according to Sathaye et al. bottom-up modelling approach concerns the comparison of energy and environmental consequences between various energy conservation scenarios, leading to economic conclusions (76). While top-down approaches are based on macroeconomic features, bottom-up modelling is rather based on disaggregation, also taking into consideration various technical issues and parameters (77); in short top-down and bottom-up terms stand for aggregate and disaggregate models (78). Moreover, bottom-up methodologies usually deal with the implementation of specific energy technologies applied in various combinations (77).

Furthermore, researchers distinguish between bottom-up statistical techniques and bottom-up engineering techniques also for the residential building stock (79). In the first case, occupation plays a strong role on the energy consumption data, whereas in the case of engineering techniques the focus is on specific buildings' typologies and the effect of interventions on the energy behaviour as regards the buildings' envelope and HVAC systems. The proposed methodology is aiming at a combination of these two bottom-up approaches (Fig. 2.5). Thus, based on a survey and the statistical analysis of the collected data, important features of the residential stock will be highlighted, based on their typology, occupancy, energy behaviour as well as their built-up environment. Afterwards, the implementation of various interventions will be studied in terms of energy conservation and their economic feasibility.

A similar bottom-up, building physics based, feasibility study was presented in 2002 by Papadopoulos et al.. The research concerned 90 buildings in Northern Greece and showed that basic intervention measures, such as insulation of the buildings' envelope and replacement of old windows with new ones, can lead to a payback period of 8 years in 62% of the examined stock, whilst this percentage rises up to 81% if the pay-back time concerns 1/3 of the buildings' life cycle (80). These interventions were proposed based on the 2002 standards, thus an insulation of 3-5 cm for the vertical construction elements and 5-8 cm on the roofs, with double-glazed openings and U-Values less than 3.2 W/m^2K. Hence, according to the current legislative framework regarding the Energy Performance of Buildings, these values are rather low (18). Thus, the calculated payback periods are now expected to be more favourable, also given the fact that energy pricing is 18% higher as regards heating oil. Beyond the economic feasibility study based on sensitivity and parametric analysis of the methodological framework, a life cycle analysis (LCA) will be carried out as suggested by Anastaselos et al. (81).

An analogous approach was introduced by Pfeiffer et al. (82) based on the vision of the 2 kW society proposed by Kesselring and Winter (83); under the three main aspects of sustainability, namely economy, ecology and society, they approach the problem of residential energy reduction in Switzerland by analysing the existing housing stock as well as the future buildings according to the existing building standards and the expected technological development. A series of state of the art and future building technologies are then implemented in order to evaluate possible energy-savings in the residential building sector.

Overall, numerous bottom-up residential stock models have been introduced over the past years differing in various aspects of their methodological approach. However, the majority of these models use a typological classification for the buildings under study. In this framework the North Karelia Finland (84) model as well as other models compared by Kavgic et al., seem to have various similarities to the proposed methodology (85). Top-down models applied in Greece are very few compared to the rest of the scientific community. Lately, Hatzigeorgiou et al. presented a thorough analysis of the rather poor state of the art concerning the relation of CO_2 emissions and economic development, highlighting the apparent bi-directional causality between energy intensity and CO_2 emissions (86).

As regards household energy modelling, bottom-up models are mostly based on conventional end-use technologies, referring to the HVAC systems and the buildings' envelope, without taking into consideration the income of the inhabitants or the GDP, like the top-down models do. Consequently, these two methods are based on different economic feasibility approaches and may therefore lead to significantly diverse results. Therefore, hybrid models have been introduced by numerous researches ((87), (88), (89), (90), (91)), in order to ensure maximum accuracy and flexibility for the development energy efficiency intervention scenarios (77). According to Jacobsen, hybrid models use the energy efficiency rates calculated by the bottom-up methodology in order to quantify the exogenous energy efficiency in the top-down methodology; therefore, building's physics based results determine the energy demand exogenous factors of the macroeconomic model (77). Böhringer also studied various aspects of integrated models ((78), (92), (93), (94), (95)); he argues that the balance of such models is very vulnerable and distinguishes three different types, namely (a) the combined large scale existing bottom-up and top-down models, (b) the usage of mainly energy based data in the macroeconomic relation, thus a targeted and limited contribution of the bottom-up model in the integrated model and (c) a single mathematical format that combines technical and buildings' physics data with the macroeconomic features (78). Regardless the nature of the hybrid model, they all intend to combine the technological features of the bottom-up models and the economic diversity of top-down approaches. A simplified scheme of such integration regarding the residential stock for regional and national level was presented by Swan et al. (79), whereas Kavgic et al. offer a top-down bottom-up general modelling approach diagram (85). A simplified combination of these two schemes is considered to be characteristic for this methodological approach as depicted in Fig. 2.5.

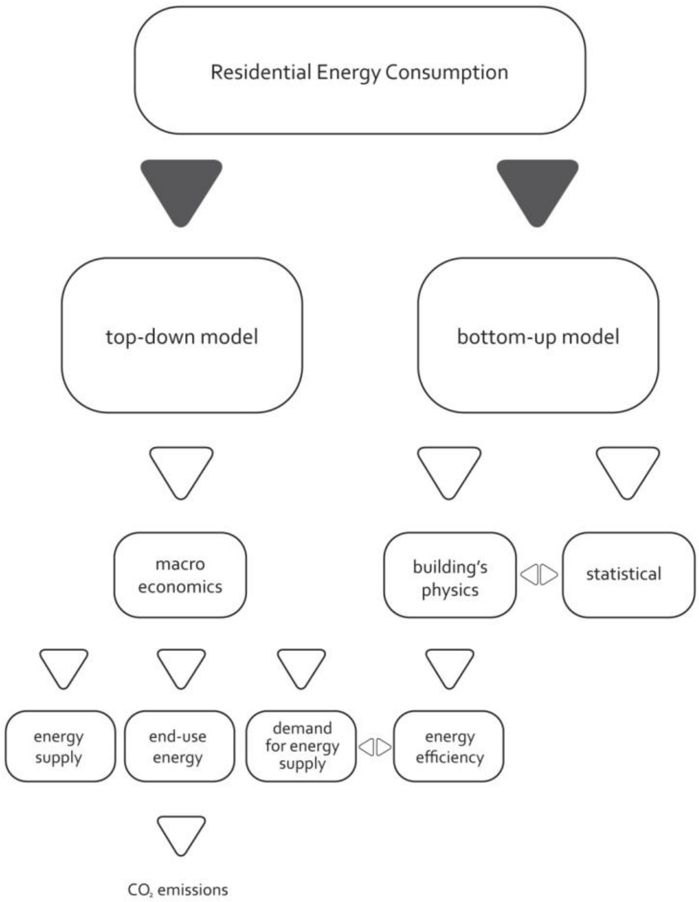


Fig. 2.5 Simplified representation of the general integration model in which the bottom-up methodological approach is being depicted

In this framework, the methodological approach is based on a combined engineering and statistical bottom-up model, providing data that can enhance a hybrid model, concerning Greek macroeconomic features and residential buildings' state of the art, thus a field for further research.

2.3.2 Facts and problems - Case study

Many studies dealt with the feasibility of refurbishment based on housing stock policies, especially in the UK ((96), (97), (98), (99)), also focusing on indoor air quality (100). More specifically, Atkinson et al. point out the need for rectification regarding the limitations set by the market, the low standard of information concerning the consumers as well as the unbalanced landlord/tenant relationship, which determines the responsible authority that will undertake the retrofitting works (99). These problems are also met in Greece and are difficult to manage. It is characteristic that the first National Grant Program regarding subsidies for energy-upgrading measures in multi-family buildings, issued in 2011, will be reorganised in order to better adjust to the Greek reality; in multi-family buildings the apartment owners are often more than ten, leading to a mosaic of opinions, rarely converging, according to individual beliefs and interests. Consequently, a common strategy on the energy upgrading measures for the whole building is rarely the case.

Moreover, funding issue becomes a major drawback due to the current economic crisis of Greece, leading to limited state subsidies, banks' low willingness to provide loans and poor loan capability of private investors. These are matters that strongly affect energy policies concerning the building sector.

A further parameter with strong influence on energy refurbishment policies is the low level of awareness as regards the environmental, economical and energy efficiency benefits. Energy conservation and sustainability are still not strongly endorsed by the Greek society. The social unawareness and scepticism against new efficient of still unknown technologies and the ignorance of energy conservation's benefits along with restricted financial inducements, are acting as a barrier for the broad implementation of such measures.

Last but not least, a very important aspect is the tenure status. As depicted in Fig. 2.6, Greece has a very large tenure quota, which mainly refers to apartments. In particular, ownership status in large MF – buildings, such as the Greek *Polykatoikia*, can influence the implementation of retrofit measures to great extents. As already described earlier issues concerning multiple ownerships and respective disagreements on matters of energy refurbishment measures are often the reason for their slow implementation as well as their rejection. More specifically, Athanassaki analyses this issue underlining the following aspects (55); unlike in the case of the Energy Building Certificate, the owners of a MF – building's apartment are not legally bind to implement any kind of retrofit measures. Furthermore, if such interventions are being implemented partially, i.e. the retrospective thermal insulation of flat roofs or the Pilotis floor, the concerned party/owner can act on its will. In any other case, where retrofitting measures refer to the whole building, the legal framework is not as clear as expected. Namely, according to the statute a reinforced or simple majority could be demanded. In addition, if one or more owners disagree to contribute to the respective costs, the legal procedure for the "res judicata" could last even up to 3 years. This is the reason why many owners avoid investing in energy upgrade related works. It is important to note that the respective legal framework goes back to 1929 with the Regulation on the "horizontal property" (N. 3741/1929), where the terms of jointly owned and shared parts of the building were introduced. Hence, the need to revise this legal framework is imperative, whilst it could be used for the link of the configuration of property pricing according to energy performance characteristics, within a specific legal framework.

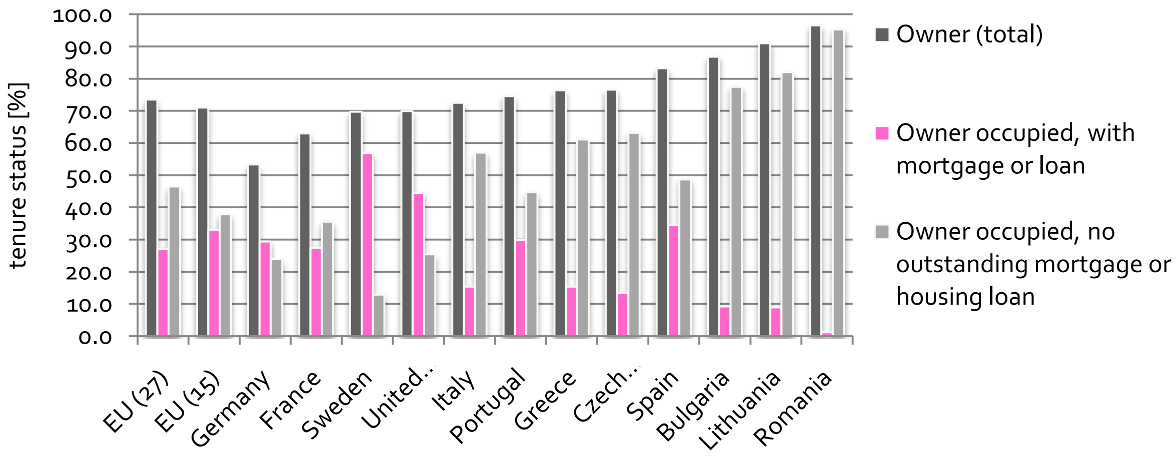


Fig. 2.6 Tenure status of households in EU for the year 2009 (101)
*The data regarding Germany refer to year 2005 (most recent available data)

2.4 Structure of the proposed methodology - overview

The main goal of the proposed methodology is to create a flexible tool that will allow the design of intervention scenarios for the Greek residential building sector. This tool takes into consideration several aspects of the Greek urban structure by means of its energy behaviour. Given the fact that little official data are available regarding the energy behaviour of the residential stock and the influence of the *Polykatoikia* on the urban built-up environment is undoubtedly large, the methodology introduces a system of data selection based on municipality/city scale level, which can be applied regardless the case study area.

More specifically, the Hellenic Statistic Authority provides data regarding the population and the age of the buildings, construction materials and usages per municipality, prefecture and for Greece in total. Hence, a basic statistical data elaboration can be carried out for the majority of the Greek cities. These data will allow a categorisation of the existing residential buildings according to their year of construction as proposed earlier, which can be enhanced by additional information from surveys, thus a statistical driven bottom-up model will be applied. Typical buildings for each category can then be selected and analysed in terms of their energy behaviour; a methodology applied by several building physics based bottom-up models (102). In order to do so, energy audits must be carried out along with in situ measurements that will provide information about the thermal comfort and the energy performance of the buildings under study. Subsequently, the real energy data will be compared to simulation results; in relation to these results and the buildings' energy behaviour, the thermal and cooling loads, the typology and the built-up environment as well as the orientation and the climatic conditions, specific intervention scenarios will be proposed in various combinations aiming at the elimination of cooling loads and minimization of heating loads as well as the maximum possible implementation of renewable energy sources (RES) for hot water and electricity production. At the next stage, each building will be simulated for all suggested combinations. The results will be evaluated in terms of their energy, economic as well as their environmental feasibility. Eventually, the most suitable measures can be extrapolated into a larger scale, namely a building block, a municipality or even a city. Shimoda et al. also approached the energy behaviour of residential buildings on a city scale by studying typical urban houses in Osaka city according to their occupancy and energy behaviour profile (103).

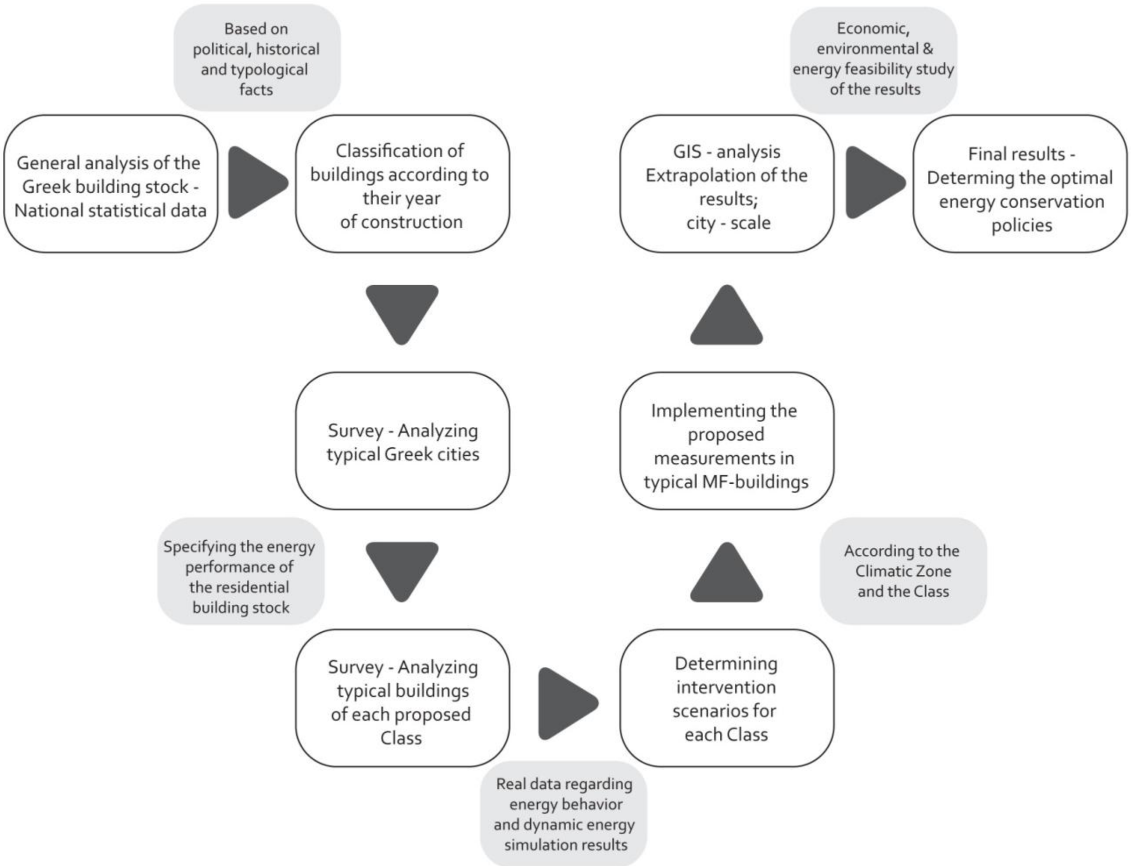


Fig. 2.7 Flow diagram of the proposed methodology

This extrapolation can be even more precise if GIS data are available; they are usually generated by Greek Municipalities and contain basic information concerning year of construction, usages of buildings, roof surfaces and number of floors. Hence, the results can be graphically depicted on maps automatically, providing illustrated information about conserved energy, CO_2 emissions and all related information as shown in Fig. 2.7. Similar work was introduced by Brownsword et al.; based on a bottom-up methodology the urban energy demand of the city of Leicester is being determined for various occupancy profiles and consumer behaviours. Afterwards intervention scenarios are being determined and the results of the CO_2 conservation are being displayed geographically by means of a GIS interface (104).

3 Typological evaluation of the Greek building stock

3.1 Typologies of the Greek urban residential stock

Based on the European Directive on the Energy Performance of Buildings a new regulation framework has recently been implemented in Greece, aiming at the CO_2 emissions reduction caused by the building sector. Given the fact that almost 71% of the Greek buildings were constructed before the implementation of the first Thermal Insulation Regulation (TIR), emphasis must be laid upon the existing building stock. Moreover, 83% of this stock consists of residential buildings, indicating the large potential in energy conservation. In order to plan and promote the respective energy renovation scenarios, a thorough analysis of the Greek building stock has to be carried out, especially regarding the urban built environment. In order to achieve this, a classification of the dominating multifamily building typology is presented and characteristic examples are studied.

3.1.1 Determining the energy behaviour of the building stock

A thorough investigation of the residential building stock was carried out, based on state of the art data collection procedures – used in various European countries and in Greece, so as to determine a basic classification of buildings, according to their typology and their year of construction. This classification resulted from the analysis of statistical data provided by the Hellenic Statistical Authority (EL. STAT.), concerning information about population, uses per building and age of buildings - as recorded in the last land wide census conducted in 2001.

In order to enable a focused research of the residential building stock and to elaborate specific intervention scenarios for the improvement of its energy behaviour, a categorisation according to the buildings' age is being proposed. The importance of the age criterion is significant, since it automatically reveals further information about the building's typology, the building materials, elements and equipment used as well as the construction practices applied, which are strongly connected to the building's energy behaviour. In Germany, for example, the Federal Statistic Authority classifies residential buildings according to their year of construction and thus divides the stock in 8 classes since the beginning of the 20th century (105). In Switzerland there is a categorisation for buildings regarding those built before 1920, during 1921-1980 and after 1981 (106).

Similar categorisation schemes are met in countries like England (107), Italy (108) and Denmark ((109), (110), (111)). Furthermore, Gustavsson et al. study energy intervention measures under the scope of life cycle primary energy analysis of residential buildings, also by using a classification based on the year of construction (112). Similarly, Jaber analyses the Jordan building stock according to the year of construction among other parameters (113). Balaras et al. distinguish between single and multi-family buildings and use a generalised categorization scheme according to their year of construction (114).

Apart from this classification procedure, as Zhang states in his work, estimating the energy consumption in the residential sector is a rather sophisticated procedure, mainly due to the lack of survey data (115). Up to now, several authors tried to investigate the residential energy consumption and demand in Greece (116), mainly focusing on heating and electricity demand ((117), (118),(119), (120)). In addition to this, Balaras et al. studied the energy behaviour and possible retrofit scenarios in various Greek residential buildings using the EPIQR methodology (121). Papadopoulos et al. thoroughly examined 90 buildings in Northern Greece during a 6-year period, in order to determine the most suitable energy saving measures under the aspect of their economic viability (80). Moreover, Santamouris et al. collected data from 1,110 households in Athens in the year 2004, in order to determine the relation between socioeconomic characteristics and energy behaviour of the residential sector (60).

Hence, this study focuses on the relation between the most important variables regarding the building stock, namely typological and energy behaviour characteristics, in terms of creating the basis for a bottom-up methodology, concerning the multi-storey and multifamily residential stock model in Greece. This methodology combines bottom-up models based on statistical and building physics data (85). The proposed methodology could be applied for both local decision authorities as well as for national strategic policies, like the North Karelia Finland model (79). The top-down approach is mainly based on economic comprehensiveness (92) linked to national energy consumption data. Various hybrid models have been presented over the past years combining top-down and bottom-up methodologies (93). The scope of this methodology is on the one hand to create an interactive relation between the parameters of energy efficiency and economic feasibility and on the other to evaluate energy intervention strategies taking into consideration their environmental impact. Thus, a basis for a building physics analysis of a typical bottom-up methodology is regarded as one of the primary contributions of this thesis.

3.1.2 Categorisation of the Greek building stock

Having in mind the introductory remarks on the history of Greek legislation on energy performance of buildings, it becomes clear that in order to achieve a reasonable clustering, it is necessary to identify classes based on parameters such as the year of construction, the technical, historical, political and social proceedings. Therefore classes need to be proposed and those are:

Class A (1919-1944)

This period was characterised by the regulations, which defined the legal framework for the building sector and urban planning. They were based on German and French architectural influences, leading to the so-called "Neoclassic" trend. During the decade 1920-1930 a new legislative frame was introduced in order to cover the demand for housing, under the severe pressure driven from the necessity to shelter 1.5 million refugees from Asia as well as after the 1920-1922 Greek-Turkish war, but also due to the urbanisation caused by industrialisation.

Fig. 3.1 The first *Polykatoikia*, Athens 1917

Furthermore, after 1922 the use of elevators was established, leading to an increase in the number of floors and the height of the buildings, while the entrances were restricted to one. Nevertheless, the facade structures remained the same, with small balconies, overhangs and openings, all in regular spaces, using the façade as a mansion house façade rather than a multi-storey MF - building façade.

Class B1 (1945-1960)

During this period the massive use of reinforced concrete resulted in a drastic recast of the construction practices. The prevalence of new building materials and methods and the drastic urbanisation after WW2 led to a steeply increasing need for accommodation in the urban areas and therefore to the construction of MF - buildings influenced by the Bauhaus style. This new form of apartment-buildings, as it emerged in the inter war years, sheltered most families. In addition to this, a large legislative work was introduced regarding the built space form, concerning the vertical and horizontal condominium. This regulation led to a massive MF - building construction based on quid pro quo, sheltering many people by spreading the costs to multiple co-owners. Furthermore the General Construction Regulation (G.C.R.) of 1955 defined the form of the cities with the continuous building system (row-system) for the densely populated centre, the detached type for the suburbs as well as the semi-detached buildings for rural communities.

Class B2 (1961-1980)

After 1960 there were consecutive corrections of the G.C.R. as well as a series of accompanying ministerial decrees, such as the imposition of a maximum allowed utilisation factor for the building plots. A new G.C.R. was issued in 1973 and, as expertise and experience accumulated, the typological features, the building services and the structural qualities of the buildings became different than those of earlier periods. Modernism became a dominant influence, apartments became bigger, oil-fired central heating systems became the standard and building elements like aluminium openings are met. Gradually the boost of population in the city centres led to their rapid expansion. This occurrence was observed firstly in Athens and Thessaloniki and afterwards in other Greek cities.

The introduction of the Thermal Insulation Regulation in 1979 and its actual implementation after 1981, allows us to classify Greek buildings accordingly. It is a turning point, as this Thermal Insulation Regulation was, until September 2010, the only legal contrivance for the improvement of the energy behaviour of Greek buildings.

Class C (1981-1990)

This class covers a rather blurred period, until the definite consolidation of the Thermal Insulation Regulation. The formal introduction of Pilotis in 1985, where the 1st floor was no longer attached to the ground was important for the buildings' typology. The Pilotis, i.e. the free space on the ground floor, which is usually 3 meters high, was mainly used as a parking area for MF - buildings. The vertical and horizontal structural elements were mostly uninsulated, leading to great thermal losses. This building form was used since the 70's and became vastly popular after 1985, along with the revised Greek Seismic Code of 1954 that came into force.

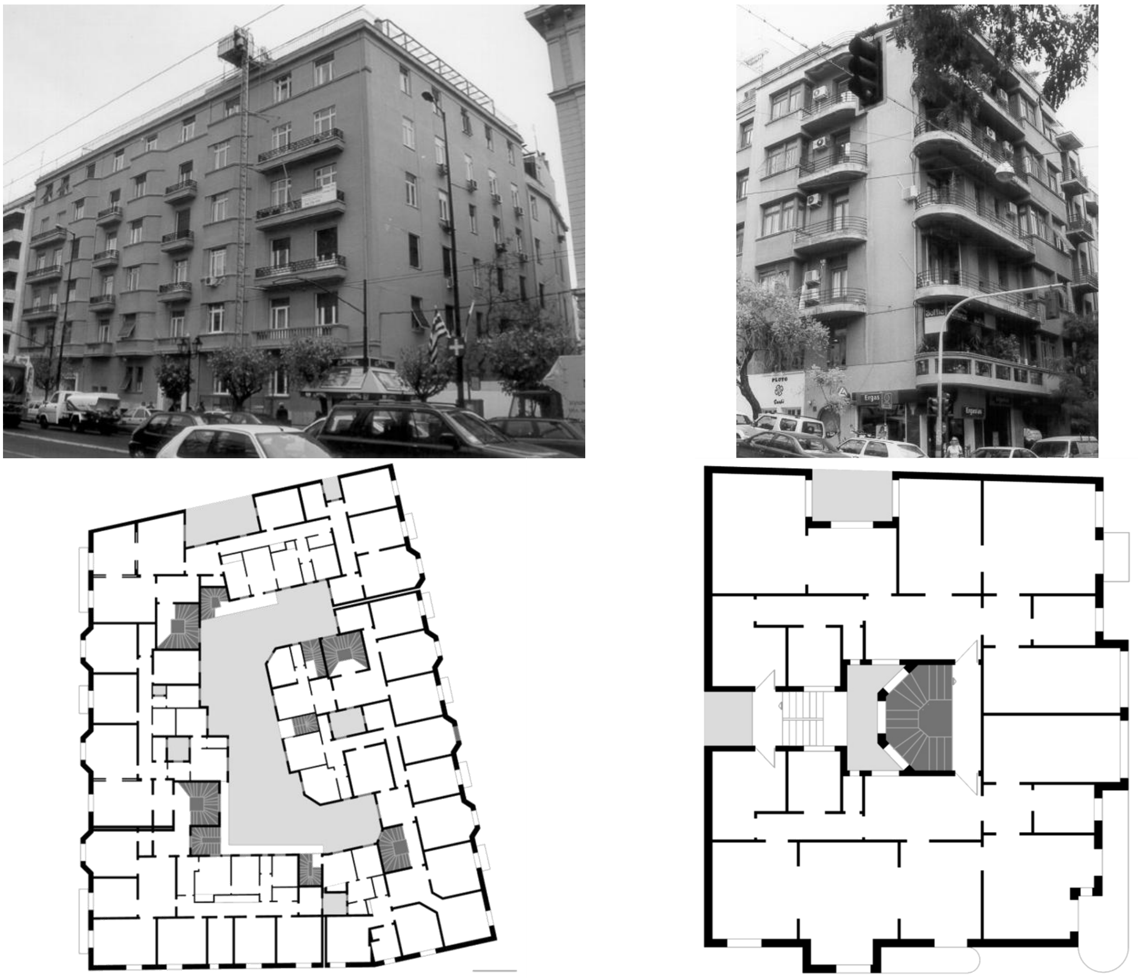
Class D (1991-2010)

The typological features remained similar to those of the previous period to a great extent. The Thermal Insulation Regulation was now applied to new constructions, though often not as foreseen. Furthermore, the New Greek Seismic Code of 2000, followed by several revisions, affected the construction materials, their width and the buildings' envelope in general.

Class E (October 2010-today)

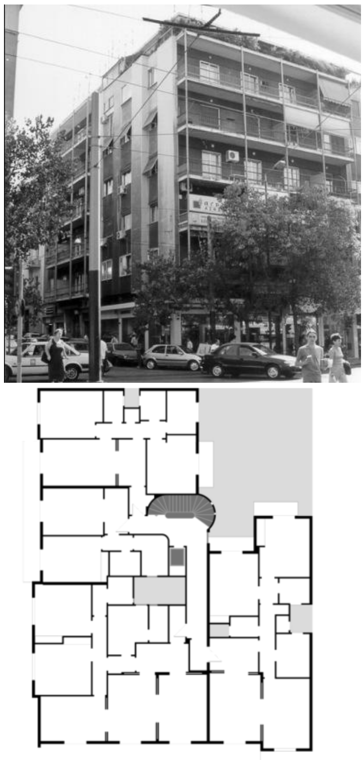
Since October 2010 the implementation of KENAK has set a new legal framework, which is expected to influence the new constructions significantly, as it imposes new, tighter energy standards. The actual impact of this procedure is however not yet apparent and can therefore not be considered within the frame of this study.

In the following figures (Fig. 3.2, Fig. 3.3, Fig. 3.4, Fig. 3.5, Fig. 3.6) typical *Polykatoikies* of each Class are presented.



Vasilisis Sofias Avenue, 1932 (122)　　　Patriarhou Ioakim Str., 1933 (122)

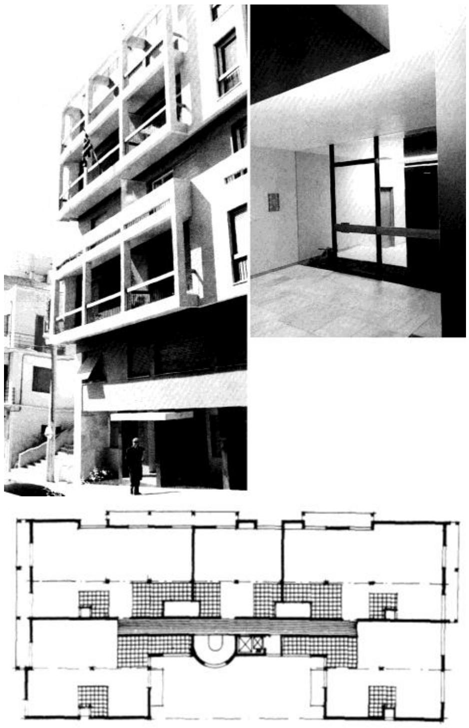
Fig. 3.2 Typical MF - buildings of the period 1919-1945



Semitelou Str., 1953 (122)

Patision & Pipinou Str., 1959 (122)

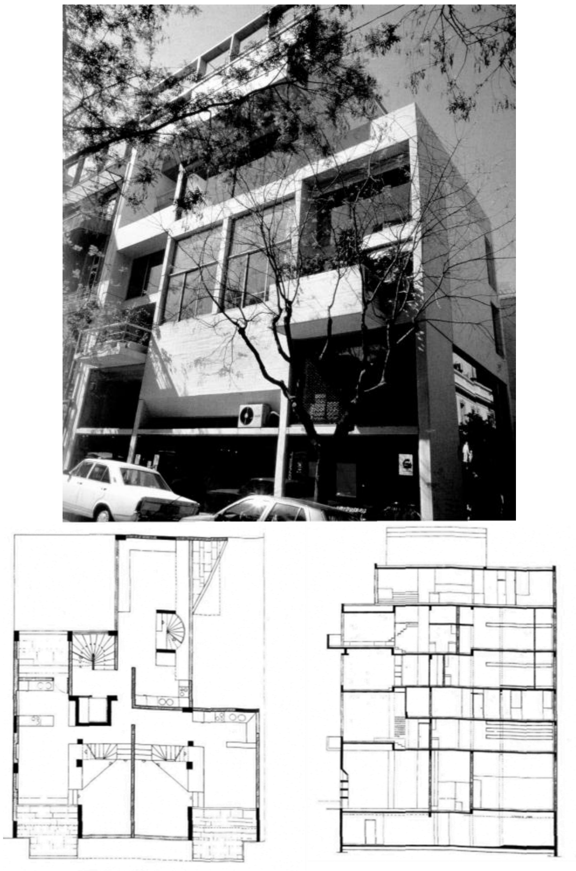
Fig. 3.3 Typical MF - buildings of the period 1946-1960

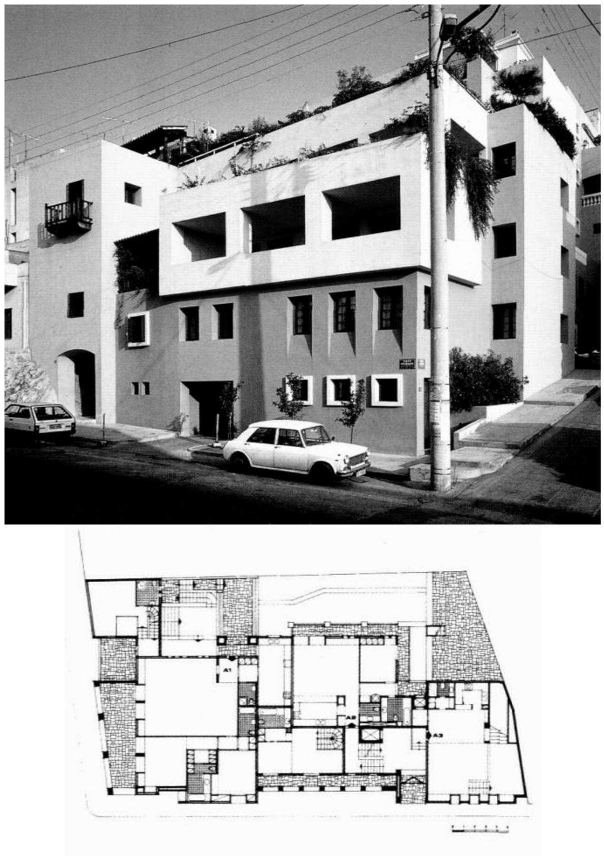


Patision & Kallifrona, 1962 (122)

Deinokratous Str., 1962 (123)

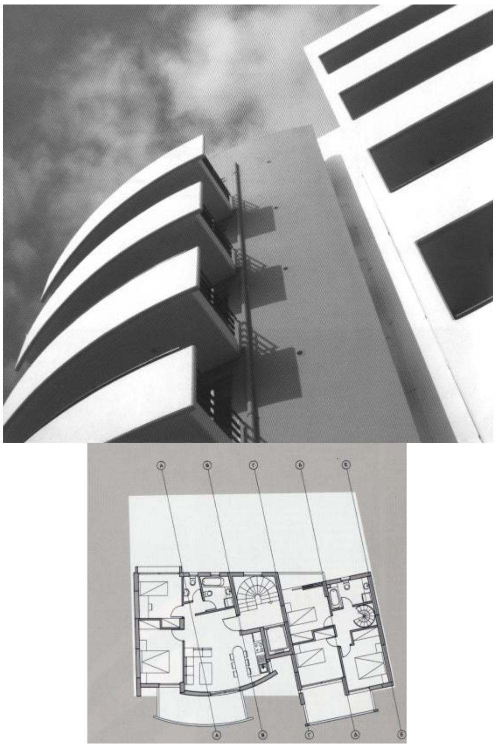
Fig. 3.4 Typical MF - buildings of the period 1961-1980

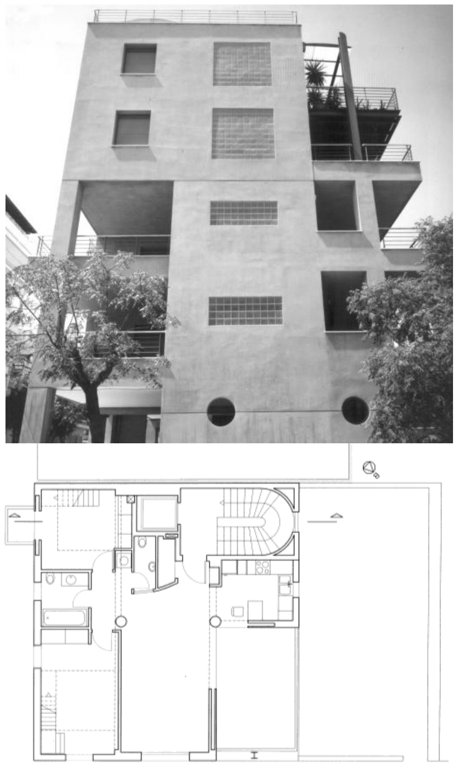




Didotou Str., 1987 (124) Mets, 1982 (124)

Fig. 3.5 Typical MF - buildings of the period 1981-1990





Sporting, 2005 (125) Perissos, 2006 (125)

Fig. 3.6 Typical MF - buildings of the period 1991-2010

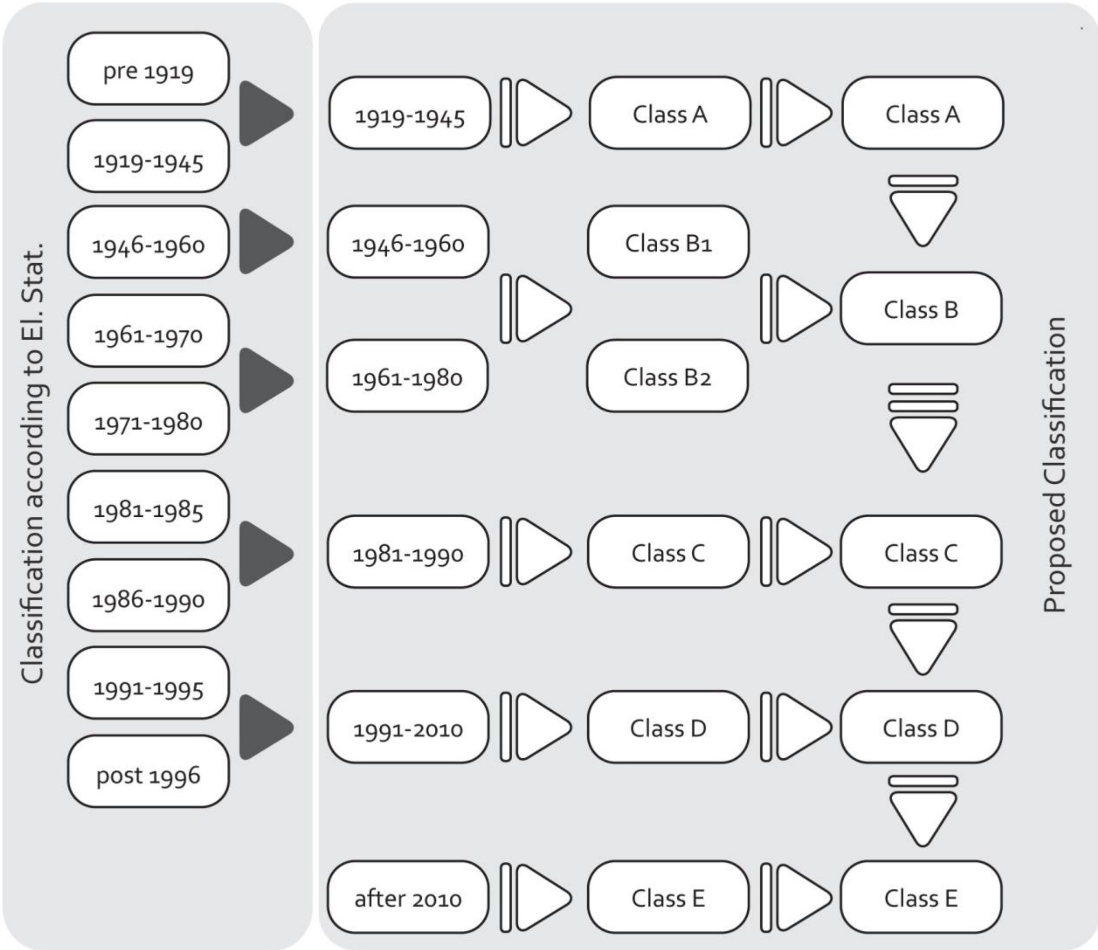
3.1.3 Available official data

Numerous sources provide data concerning the Greek building stock in general and the residential use in particular. Such sources include the Hellenic Statistical Authority (El.Stat.), the Organisation for Economic Co-operation and Development (OECD) and the International Energy Agency (IEA). Regarding Greek sources, the main and most important available data are given by El.Stat. and refer to the year of construction per area and for Greece in total, the construction materials, the existence of sloped or flat roofs, the number of floors, the type of building according to its use (residential, office, or mixed use building) and the existence of Pilotis. Consequently, based on the aforementioned classification, the existing building stock is presented bellow (Table 3.1).

Table 3.1 Existing buildings of each Class in Greece (46)

Greece overall	Class A	Class B		Class C	Class D
		Class B1	Class B2		
	pre 1945	1946-1960	1961-1980	1981-1990	Post 1991
Urban areas	180,871	290,615	802,627	387,039	240,254
Rural areas	425,272	374,700	696,130	314,612	193,100
Total	606,143	665,315	1,498,757	701,651	433,354
%	15.2%	16.7%	37.6%	17.6%	10.9%

The classification proposed relates to the El.Stat. official classification of buildings as depicted in Fig. 3.7.



**Note: Buildings constructed before 1919 in urban represent only 1% of the building stock and are therefore not included in the classification.*

Fig. 3.7 Relation between El.Stat. and the proposed classification

3.1.3.1 Data concerning the period till 2001

3.1.3.1.1 According to the year of construction

Taking a closer look at the aforementioned classification for other countries, the year 1980 turns out to be a nodal point; a remark valid for the case of Greece as well. In Fig. 3.8 the large boost in the building sector in the period 1945-1980 is depicted (46), indicating that the majority of the buildings, namely 71% of the total stock, are uninsulated (Table 3.2).

Table 3.2 Buildings constructed before and after 1980 (46)

	Buildings built before 1980	**Buildings built after 1980**
Rural areas	1,274,113	627,293
Urban areas	1,496,102	507,712
Total	2,770,215	1,135,005
%	**70.93**	**29.06**

It becomes clear that the majority of Greek buildings are built within the period 1946-1980, whilst the tendency regarding construction density, between urban and rural areas, is reversed from the beginning of Class B2 and onwards. Thus, the early stages of urbanisation, with the simultaneous drop of the construction activity in the rural areas can be detected.

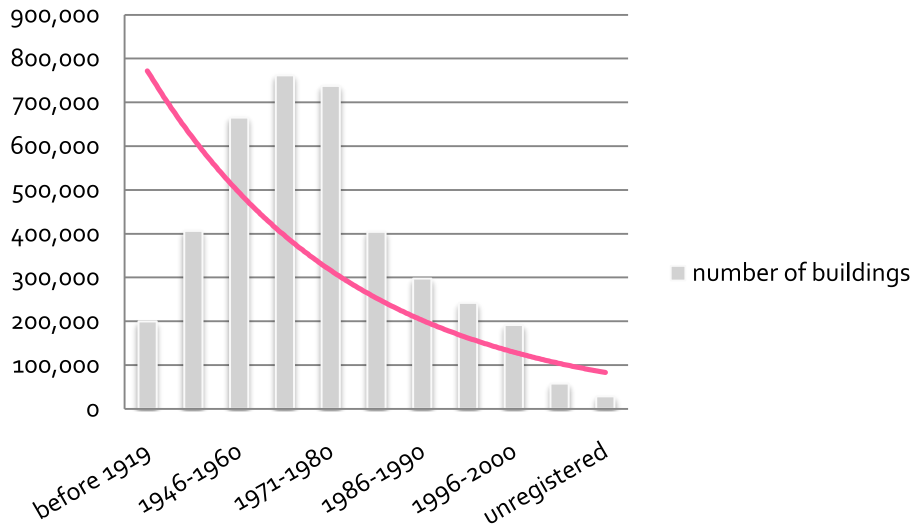


Fig. 3.8 Number of buildings per year of construction in Greece (46)

3.1.3.1.2 According to their use

The Hellenic Statistical Authority (El.Stat.), provides data by classifying buildings according to their usage, namely dwellings, churches / monasteries, hotels, factories / laboratories, educational buildings, shops / offices, parking blocks, hospitals, and others. The elaboration of these data shows that 89.6% of Greek buildings have an exclusive use and only 10.4% a mixed one. It is important to rank the existing buildings according to their exclusive use and the year of construction, as shown in Fig. 3.9.

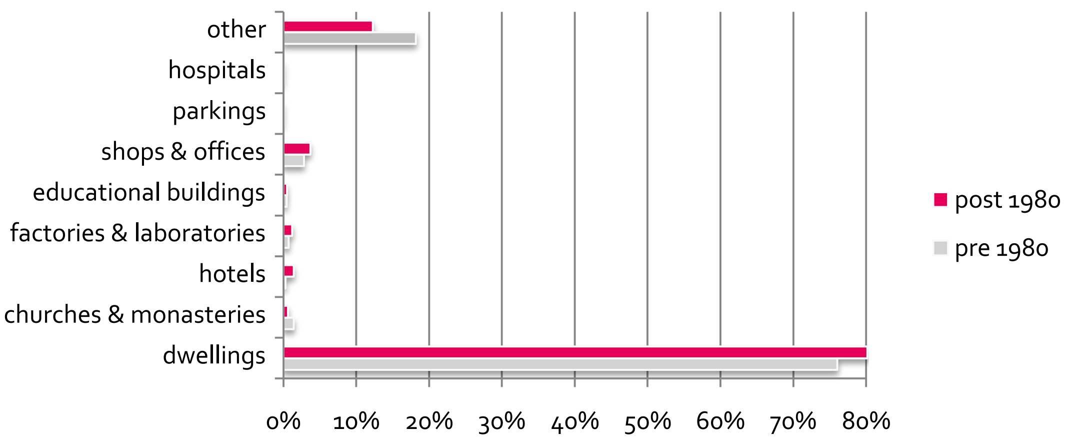


Fig. 3.9 Number of buildings per year of construction in Greece, exclusive use (126)

One can notice that the percentage of each typology tends to be similar for the post- as well for the pre-1980 period. In particular, the residential use is the most dominant, as dwellings account for 79% of the building stock, whereas all other buildings' uses sum up to 20.99%. Similar to the exclusive use, mixed use building stock analysis shows respective results, which are depicted in Fig. 3.10. It should be noted that mixed use is being presented according to the building's main use.

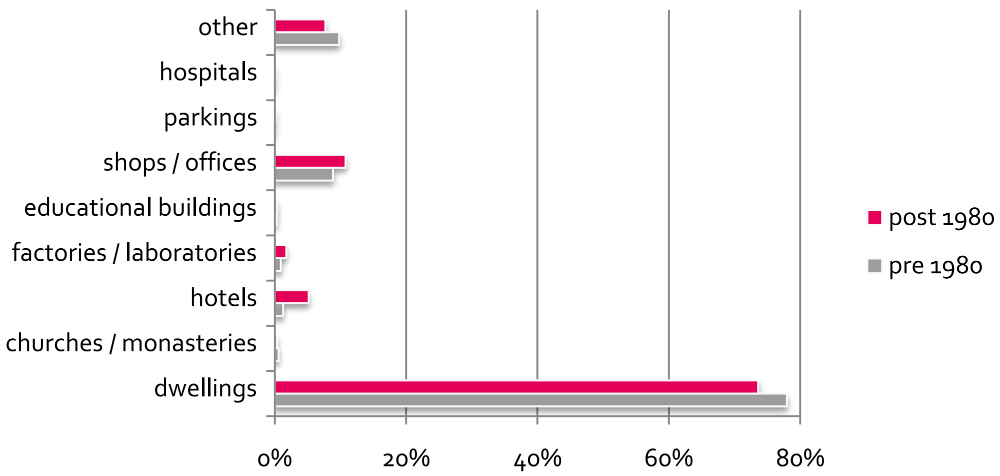


Fig. 3.10 Number of buildings per year of construction in Greece, mixed use (126)

Moreover, shops and offices account for a higher percentage of the buildings, while a small drop in dwellings can be observed. This is due to the fact that many multi-storey buildings combine uses like shops on the ground floor as well as offices, apartments and private practices in the upper floors, as depicted in Fig. 3.10.

It is therefore understandable that in urban areas the amount of mixed use building rises to 13.1% compared to 7.7% in the rural areas. Respectively, the exclusive use in urban areas is 86.9% and in rural 92.3%. The exclusive use concerns dwellings mainly, both in rural and urban areas. Eventually, 70.7% of the rural building stock comprises mixed and exclusive residential uses, whereas in urban areas this percentage rises up to 83.5%. This fact leads us to the conclusion that the urban as well as the rural built-up environment is being architecturally characterised by the MF – buildings (127). Hence, MF – buildings, the so called "*Polykatoikia*" are the main component of Greek city centres, determining their energy behaviour, their typology and aesthetic identity.

3.1.3.1.3 According to their number of floors

The height of buildings is a very important feature in order to determine the density, the approximate envelope surface, the typology and the available vertical and horizontal areas, green roofs and walls etc. Furthermore, it can be of great importance when studying the retrospective thermal insulation, the implementation of renewable energy systems, the solar radiation in urban areas, shading, and overall envelope surfaces. This more detailed approach is indeed a field requiring further analysis and will be discussed later on.

Fig. 3.11 illustrates the height of buildings in urban and rural areas, according to the number of floors. A unique category, the buildings with Pilotis, is depicted separately.

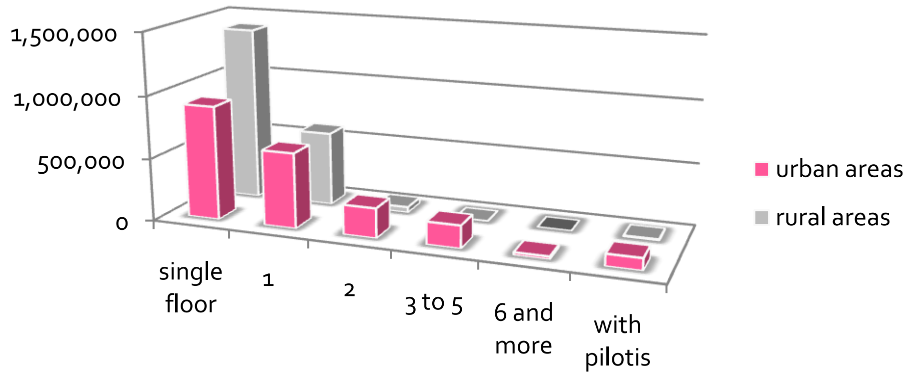


Fig. 3.11 Number of floors in urban and rural areas (126)

It becomes clear that overall the majority of buildings consists of single-floor buildings, regardless their use. This tendency is lower in urban areas.

3.1.3.1.4 According to the construction materials

One of the most important piece of data given by El.Stat., regards the materials of the buildings' envelope. In 66% of the urban buildings the main construction material is reinforced concrete, used for the load bearing structure according to the Greek anti-seismic regulations (Fig. 3.12). The walls are as a rule double brick walls. In rural areas, brick and stone walls are met more frequently, as the buildings are lower and the anti-seismic requirements are not as strict, whilst stone is in many cases a material in local abundance. Furthermore, some settlements feature landmark protected architecture, which presupposes the use of traditional building materials like stone.

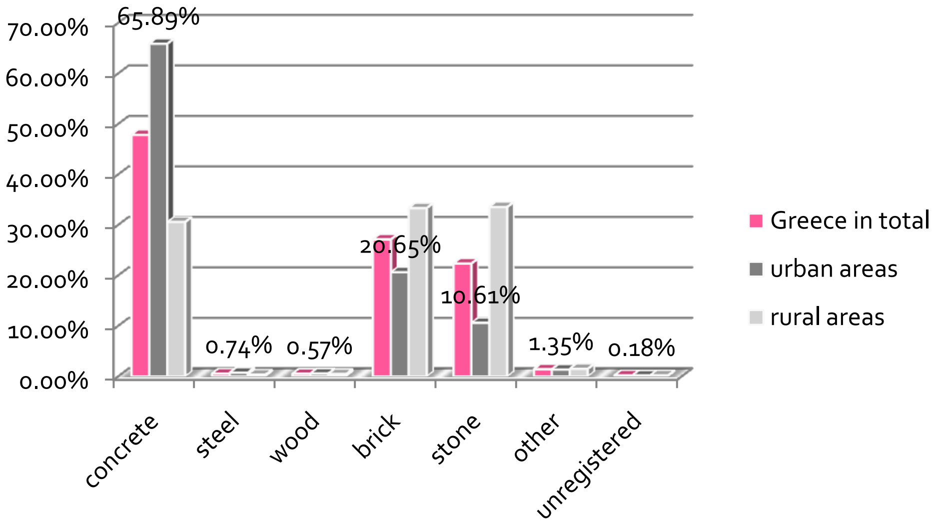


Fig. 3.12 Main construction material of the Greek building stock (126)

Thus, it becomes clear that Greek buildings especially in urban areas have a large heat storage capacity, a fact that should be taken into consideration when designing insulation interventions as well as passive cooling and heating systems.

It is also of great importance to distinguish between buildings with flat and sloped roofs, in order to correctly plan intervention scenarios for energy renovation. In the following figure (Fig. 3.13) the distinction between flat and sloped roofs is illustrated, for Greece in total, i.e. urban and rural areas.

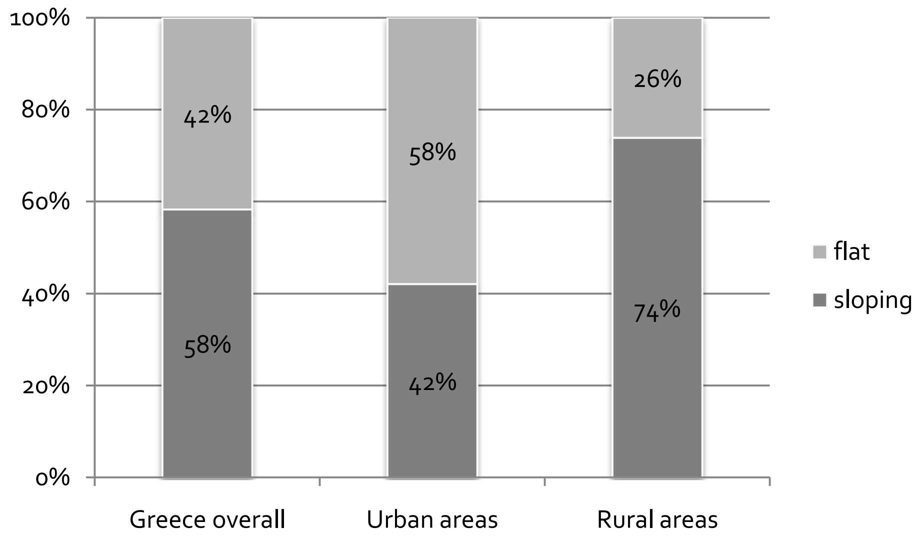


Fig. 3.13 Flat and sloped roofs (126)

Conclusively, sloped roofs are characteristic for single-family houses and for buildings in rural areas, whilst they can also be met in cities and villages in mountainous regions with harsh continental climate.

3.1.3.2 Data concerning the period after 2001

As already mentioned, the last census of the Greek building stock took place in 2001 and therefore there are no official data available for the last decade. However, as shown by the most recent data available, the growth of the building sector during this period is rather low, as depicted in Fig. 3.8.

According to these data, the phenomenon is even more intense in the area of Attica (Athens and surrounding areas) and in the northern part of the country, namely Central Macedonia (Thessaloniki and surrounding areas) (128). It is also clear that in the period 2007-2010 the largest drop in the building permits issued throughout the last decade occurred. The mean percentage for the annual building permits over this time spectrum is -2.35% with a constant downward tendency, with the only exception of increase recorded in the year 2002-2003 (128). These statistics cannot, however, substitute the missing data regarding the existing building stock during the decade 2000-2010, for two main reasons: (a) There is an unknown percentage of building permits which have not been carried into effect and (b) An unknown number of buildings have been constructed without building permits, or with older building permits. The data should therefore be used with caution.

3.1.3.3 Urban residential buildings' typology

The features discussed in the previous paragraphs refer to urban areas and their main characteristics. Nonetheless, the data given about urban areas by El.Stat. do not necessarily depict the exact characteristics of city centres. Thus, a further investigation will be presented, based on field surveys, in relation to large city centre typologies such as Athens and Thessaloniki as well as to a typical small-scale city, namely Kozani.

The main typology of buildings in cities and urban areas is the *Polykatoikia* and, either in Athens or in smaller cities, remains similar and dominant, with some variations mainly regarding the number of floors and the type of roofing. Due to the typology of *Polykatoikia* and given the fact that most of these buildings are uninsulated or poorly insulated, the significant renovation potential in existing MF - buildings becomes evident. According to a thorough thermographic control carried out during the winter of 2009 for 100 MF - buildings in the area of Thessaloniki, it was found that even the ones built between 1981 and 1990, are in most cases insufficiently insulated. Namely, in 92% of the cases the load bearing structure is completely uninsulated (80). Moreover, Chadiarakou et al. (129) showed that out of 65 buildings in the Municipality of Thessaloniki, constructed between 2002 and 2005, the thermal insulation foreseen by the TIR was implemented to the detail in only 4 (6,1%) of them, whereas in 36 (55,4%) of these buildings "acceptable" reductions were found and in 25 (38,5%) severe omissions were monitored. All the above indicate the need for retrofitting thermal insulation in existing buildings, in order to upgrade their energy performance.

3.1.3.4 Socio-economic aspects

The age of the buildings and the density of the urban layout, the lack of green spaces and the materials used, lead to rather poor living conditions in Greek city centres, considering both indoor air quality and thermal comfort ((130),(60)). With respect to the building, this discomfort is intimately linked to the lack of thermal insulation, the lack of effective shading and also the absence of passive cooling systems. This situation necessitates measures in order to upgrade the building stock in the city centres. Moreover, the lack of a common architectural language is dominant in Greek urban areas, creating the image of an aesthetic anarchy. These energy upgrading measures could and should contribute to the redefinition of the Greek urban architecture, determined mainly by the "*Polykatoikia*" typology.

Furthermore, related research shows that the lower the income, the worse the indoor conditions, especially during the cooling period ((131), (132)). Moreover, private investments in order to upgrade the energy behaviour of the buildings seem rather unlikely to be implemented under these circumstances. Based on this fact, the recently announced measures concerning energy conservation in residential buildings, particularly aiming to support low income owners, seem to be reasonable. They include subsidies, low interest loans and tax deductions for retrospective thermal insulation, installation of solar thermal collectors as well as replacement of windows and balcony doors, boilers and burners ((133), (134)).

3.2 Statistical evaluation of the urban residential stock

In order to evaluate the expected energy conservation following the implementation of KENAK in existing Greek residential buildings, a thorough investigation of the energy behaviour of the building stock has to be carried out. In this line of thought, Theodoridou et al. (51) deliver detailed statistical data, focusing on residential buildings, namely MF- buildings, as part of a bottom – up research. The current study aims at enhancing these data with further information regarding energy consumption, by performing a more detailed evaluation, in order to draw conclusions about the expected benefits of the KENAK regulation. The aim of this study is to enrich official data concerning the energy behaviour of the existing building stock with additional information driven by questionnaires and statistical analysis.

A similar strategy has been introduced by Swan and Ugursal (79), whilst Ballarini et al. analysed the potential on energy conservation measures in existing buildings by a chronological and typological categorisation and using the European Standard methodology for their calculations (108). In the Netherlands a survey of 15,000 houses was statistically processed, taking into account the occupant behaviour and its influence on the energy consumption mainly for heating (135). Ingradanti et al. investigated variables affecting thermal comfort in Indian residential buildings also using survey-data sets (136). Furthermore, Lai et al. used a specific questionnaire in order to collect important data to obtain indoor environmental quality of high-rise residential buildings (137). Such procedures are common since early 1970s, mainly in the USA, most of which are thoroughly compared by Eichen et al. (138). Moreover, Caldera et al. created a statistical model in order to estimate the heating energy demand for residential buildings based on a 50 multi-family buildings' sample in the district of Torino (139). Al-Ghandoor et al. suggest a statistical regression model analysis, which can be used to estimate potential energy conservation in the residential building stock of Jordan (140). In Greece, similar efforts have been made by Doukas et al., who proposed a methodology in order to collect and validate renewable energy sources, expenditure and end-use efficiency data throughout Europe ((141), (142), (143)). In their work emphasis is laid on the systematic collaboration of researchers with different "professional" backgrounds and different specialties, such as statisticians, energy technology experts and energy socio-economists.

In order to determine the future energy conservation strategies of EU, these data collection strategies are of vital importance. Moreover, Sardianou also used survey data statistical analysis in order to evaluate space heating determinants in Greek households as well as energy conservation policies ((144), (145)). Assimakopoulos applied a multivariate statistical technique aiming at the forecasting of residential energy demand for the Cyclades residential building stock (146). A similar approach was introduced by Santamouris et al. focusing on school buildings by using intelligent clustering techniques for the classification of schools according to their energy performance (147). In addition, clear definitions for building energy standards should be made, referring to a specific classification system of residential buildings, providing the respective economic support. Such promising undertakings are met in many European countries, including Germany and the UK (148).

In this line of approach, the study discussed in this chapter concerns two typical Greek cities, a large one and a smaller one, namely Thessaloniki and Kozani respectively, both located in Northern Greece. Thessaloniki falls within climatic zone C and Kozani in climatic zone D, in other words the two coldest climatic zones in Greece, where heating loads are predictably significant, with heating degree day values ranged between 1,780 and 2,300 HDD, and with climatic similarities to cities like Toulon in France and Stuttgart in Germany (80). The results of the elaborated survey data are presented below and refer to the energy behaviour of the MF – buildings' typology.

3.2.1 Survey – City of Thessaloniki

A questionnaire was created, in order to collect data concerning the energy performance of dwellings, both of single-family (SF) and multi-family (MF) buildings. This questionnaire was used in the greater area of Thessaloniki, the second largest urban area of Greece, with a population of some 1,100,000 inhabitants. The questionnaire was electronically distributed, leading to a sample of 772 dwellings, 88% of which refer to apartments (680) and 18% (112) to single family houses. Following, the questionnaire was filled in by means of a door-to-door interviews, mainly in the Municipality of Thessaloniki and Kalamaria, the biggest municipalities of the area. Overall 200 interviews were carried out and in order to ensure a representative sample, only one apartment per building was visited. The characteristics of each apartment were thoroughly examined so as to exclude duplicated input of data and to ensure the best possible dispersion and a truly representative sample. This was proven by the statistical validation carried out, leading to 83% of the total sample being appropriate for further investigation.

The questionnaire's structure is based on five sections concerning the typological and structural characteristics of the building, the determination of the heating, cooling and domestic hot water system as well as their operational mode in addition to their operational profile and their maintenance costs. Finally, information about interventions and renovation measures implemented in the past were collected. Given the fact that data on the buildings' features have been considered by previous studies ((146), (121), (119), (116), (60)), the main goal of this survey was to deliver data regarding the actual energy behaviour of typical Greek MF - buildings. Thus, the main conclusions refer to the following questions:

- To what extent does the occupancy affect the energy behaviour of the apartments?
- Is there a relation between the age as well as the income of the inhabitants and the structure and quality of the building?
- Do rented apartments behave differently in terms of energy efficiency than those that are self occupied, i.e. occupied by their owners?

The respective answers will be given in the following sections.

3.2.1.1 Sampling and sample computation

The Municipalities of Thessaloniki and Kalamaria are the largest Municipalities of Northern Greece and two of the largest in Greece overall. Therefore, they can be considered as typical for sampling with respect to the buildings' typologies. Since the 1980's the two municipalities are merged into one urban area. The Municipality of Thessaloniki forms the city centre, a typical example of Greek urban development, which reached its saturation in the late 90s. On the other hand, the Municipality of Kalamaria is a typical example of a rather newly developed area, with the majority of buildings constructed after the 1970's, particularly in the 1980's and 1990's. Most of the buildings in Kalamaria are detached and the built up density is not as high as in the Municipality of Thessaloniki.

The statistical analysis was carried out by using the SPSS Data Mining and Statistical Analysis Software. The data elaboration includes frequency, crosstabs and clustering analysis. In order to ensure qualitative results a sample computation was of vital importance. The main goal of this procedure was to adjust the sample according to objective data. The results presented in this chapter refer to MF - buildings, due to their typology and the fact that the sample variance was rather large.

3.2.1.2 Statistical analysis results

3.2.1.2.1 General results

According to the statistical analysis the mean year of construction is 1980, thus the majority of buildings are constructed before the implementation of the Thermal Insulation Regulation (in 1979) and are therefore uninsulated. In Fig. 3.14 two periods are representative for the growth in the construction sector; for the Municipality of Thessaloniki, with its city centre developed after it was totally burned in 1917 and re-built after 1945, these values lie mostly between 1960 and 1970, whereas for the Municipality of Kalamaria, which was developed after 1970, the most intense building period lies, between 1980 and 1990. The evolution of the construction rate and the cumulative distribution for the area considered are depicted in Fig. 3.14.

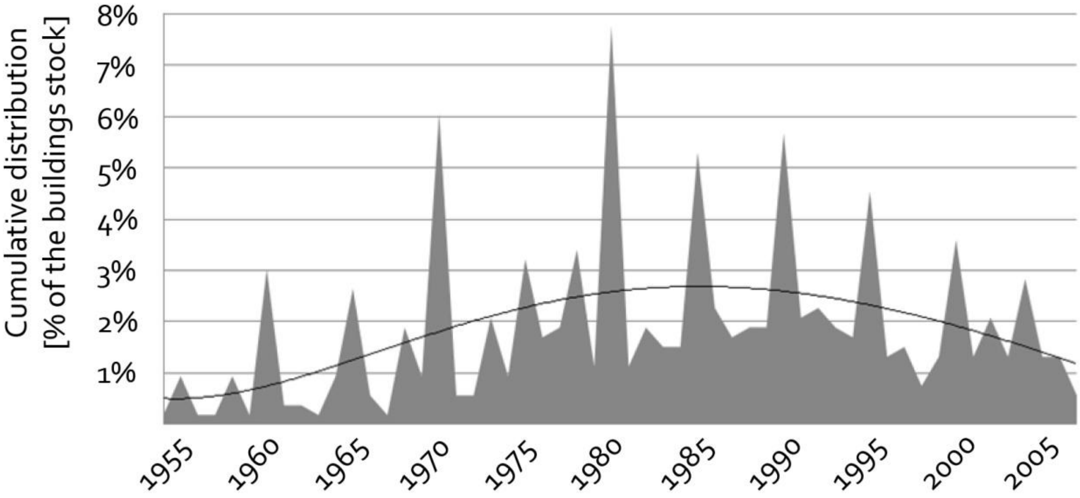


Fig. 3.14 The evolution of construction rate for the areas under study

The majority of buildings featured are four and five-storey buildings, with a respective percentage of 26.5% and 20.11%. Furthermore, 17.1% of the MF – buildings have only one apartment per floor, 28.5% have two, 25.7% have three, whilst 14.1% have four apartments per floor. Floors with five and six apartments constitute less than 10% of the sample. Thus, the occupancy profile varies from floor to floor.

3.2.1.2.2 Results regarding the buildings' envelope

A very important issue, regarding the retrofitting options, is whether the buildings have an attic or not. An overwhelming majority of the buildings, namely 93.4%, doesn't have an attic, complying with the typology of a typical *Polykatoikia* (127). Furthermore, 63.6% of the sample didn't have a Pilotis, whereas 36.4% did. The Pilotis floor is mostly uninsulated, and therefore increases the uninsulated total external surface of the building, and thus the thermal losses.

Another very important aspect, strongly influencing the energy behaviour of a building, is whether it is attached or not to other buildings. The majority of buildings, namely 47.1%, are attached to two buildings, 31.2% are attached to one building and only the 2.1% are attached to three buildings. This is a common characteristic of buildings in Greek urban centres, which are extremely densely built. It is of interest to notice that the detached buildings are mostly located in the Municipality of Kalamaria, accounting for 19.60% of the building's sample.

3.2.1.2.3 Results regarding occupancy

It is a fact that economic growth and changes in lifestyle on the one hand as well as progress in energy efficiency technologies and expertise on the other hand are both driving forces, albeit in the opposite direction, for the development of energy consumption in the building sector (149). Numerous studies showed the indissoluble connenction between building occupancy and the energy behaviour of dwellings ((150), (135)). Papakostas et al. introduced occupancy profiles for the Greek residences (151), which featured also typical occupancy outlines for MF - Buildings. Similar research has been carried out by Linden at al. (152), also indicating the great role of occupancy and the role of energy-efficiency awareness of inhabitants, beyond common economic based measures, such as pricing and taxing of fuels.

A very important fact is the number of inhabitants per dwelling. According to this survey 32.4% of the households refer to families with four members, followed by families with two members (27.3%). Households with over four inhabitants concern only 5 % of the examined sample. One - member and three - member households refer to 13.9% and 20.9% of the sample respectively. The mean number of inhabitants per dwelling is 2.8. It should be underlined that this value diverges significantly from those foreseen by KENAK. More specifically KENAK indicates a mean number of inabitants of 5 per 100 m^2 for dwellings, whereas according to the survey, 3.04 people per 100 m^2 live in each apartment.

In addition to that, KENAK considers 18 hours as the mean occupancy duration, compared to the 12.8 hous per day monitored in this study. Furthermore, according to the results of this study, the highest percentages of occupancy are met in the 10 - 12 and 14 -16 hours per day intervals. A difference of 8 hours is beyond doubt significant. Finally, there is a small percentage of inhabitants, namely 2.3% that declare staying at home constantly, which mainly refers to elderly people or people with kinetic problems.

In particularly, in the area of the city centre (Municipality of Thessaloniki), where the MF - buildings are mostly uninsulated and over 30 years old, the main inhabitants' groups are students and elderly people, mostly retired. It is very important though to underline the fact that their occupancy schedule, their needs regarding the heating and the cooling systems as well as their sense of thermal comfort differ significantly. Any energy upgrading intervention scenarios in such buildings should take this fact into account and allow autonomous control of the HVAC systems and the natural ventilation.

On the other hand in the recently developed areas of Thessaloniki, such as the Municipality of Kalamaria, most inhabitant profiles are families, young couples and pensioners. Except from young couples, with extended working hours, these profiles mainly share the same needs regarding heating and cooling demands as well as thermal comfort. The detailed users' profile is depicted in Table 3.3.

Table 3.3 Users' profiles

	Municipality of Kalamaria	Municipality of Thessaloniki
Families with children	34.7%	11.2%
Couples	31%	6.5%
Students	3.5%	38.4%
Offices	5.5%	3.5%
Pensioners	25.3%	40.4%

Overall, this occupancy profile can strongly influence the results of an energy audit or study, as it affects the time of the HVAC systems' operation, the natural ventilation loads, and the internal gains of the thermal zones.

Office usage represents a small percentage in both cases, mainly found in MF - buildings with mixed use complying with data published by El. Stat. (46).

Indeed, in the Municipality of Thessaloniki 95% of the buildings represent mixed use, combining dwellings and offices (mainly in upper floors) or/and shops (in the ground floor), whereas in the Municipality of Kalamaria 96% represent mixed use, with almost exclusively commercial uses in the ground floor.

3.2.1.2.4 Results regarding HVAC systems

Considering HVAC systems, 68.5% of the MF - buildings uses oil-fired central heating systems, whilst almost 19% of them changed to gas-fired systems after 2001, when natural gas was introduced in Thessaloniki, which was the first city to use this fuel in Greece. Moreover, 1.7% of the dwellings use a fireplace as their main heating system and another 2.3 % use air-conditioning systems. In addition, 5.5% of the MF - buildings changed from central heating systems to autonomous heating systems (wall mounted, integrated gas boilers) and 3.1% use electrical storage heaters. Hence, central heating systems are indeed the most common heating system in MF – buildings. In the buildings constructed after the mid 1980's the central system feature thermostatic controls for each apartment and are therefore operationally autonomous. The same applies for the older apartments retrofitted with wall mounted gas boilers.

3.2.1.3 Correlation

3.2.1.3.1 Correlation between the heating energy consumption and the sample of buildings

In Table 3.4, the Pearson correlation coefficients between the heating energy consumption and total floor area, inhabitants, year of construction and the attachment to other buildings are presented with the respective levels of significance. It becomes clear that energy consumption increases as the year of construction decreases. Furthermore, the heating energy consumption is positively associated with both the number of inhabitants and the total floor area, indicating similar linear trends.

Table 3.4 Heating energy consumption correlations for the whole sample

Dwellings in total	**Floor area**	**Inhabitants**	**Year of construction**	**Attached to other buildings**
Heating energy consumption	0.430*	0.301	-0.026	0.028
	Strong positive association	Weak positive association	No association	No association
Heating energy consumption / m^2 / person			-0.021	-0.054
			No association	Little negative or no association

**Note. Correlation is significant at the 0.05 level (2-tailed).*

As regards buildings predating 1980 (Table 3.5), this linear correlation tends to be slightly stronger regarding the actual year of construction. On the other hand, it seems that the attachment to other buildings has a larger influence, which, in this case, is reasonable as the older buildings feature no thermal insulation whatsoever. However, if the heating energy consumption per m^2 per person is considered, the attachment to other building does not seem to have any effect.

Table 3.5 Heating energy consumption correlations of buildings constructed before 1980

pre 1981	**Floor area**	**Inhabitants**	**Year of construction**	**Attached to other buildings**
Heating energy consumption	0.366	0.242	-0.089	0.062
	Weak positive association	Weak positive association	Little negative or no association	Little positive or no association
Heating energy consumption / m^2 / person			-0.131	-0.01
			Little negative association	No association

On the other hand (Table 3.6), buildings constructed after 1980 are characterised by a strong positive relationship with the total floor area and the inhabitants. Considering the heating energy consumption per m^2 per person, a positive, more intense linear correlation is exhibited with the exact year of construction. Thus, the newer the construction the higher the heating energy consumption per square meter and person is estimated. This can only be explained by the fact that the TIR (Thermal Insulation Regulation) of 1980 was never implemented correctly. Furthermore, newer constructions are connected to inhabitants with a higher income as a rule, presenting increased requirements for thermal comfort and therefore increased heating energy consumption. Therefore, the attachment to other buildings parameter does not influence as much as it does in older buildings.

Table 3.6 Heating energy consumption correlations of buildings constructed after 1980

post 1981	**Floor area**	**Inhabitants**	**Year of construction**	**Attached to other buildings**
Heating energy consumption	0.466*	0.327	-0.062	0.006
	Strong positive association	Weak positive association	Little negative or no association	No association
Heating energy consumption / m^2 / person			0.21	-0.084
			Little positive association	Little negative or no association

**Note. Correlation is significant at the 0.05 level (2-tailed).*

3.2.1.4 Mean values of energy consumption per m^2

3.2.1.4.1 Energy consumption per m^2 according to the year of construction

In Fig. 3.15 the heating energy consumption per person and total floor area are depicted. It is of interest to once again notice that buildings of the last building class, which include buildings with thermal insulation, have a higher energy consumption than buildings of the second category, which are definitely not insulated.

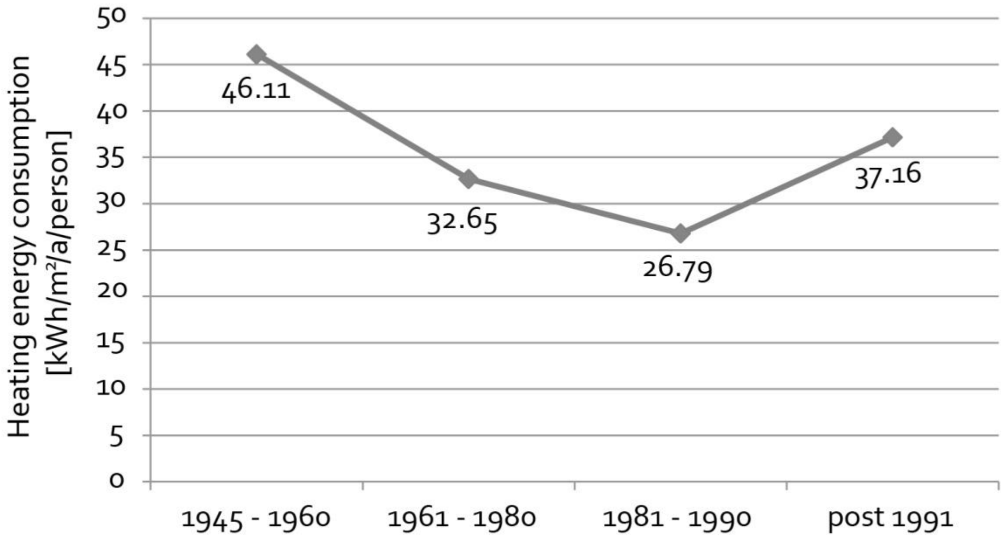


Fig. 3.15 Annual heating energy consumption in kWh per person and total floor area according to the year of construction

Fig. 3.15 underlines the fact, that it is unsafe to directly relate newer constructions to better energy behaviour, as KENAK proposes. The complexity of the Greek construction practices and other socioeconomic parameters, affect the energy behaviour and may lead to false conclusions.

3.2.1.4.2 Energy consumption according to the buildings' typology

The following figure indicates the importance of the building's typology as regards its energy behaviour's evaluation (Fig. 3.16). According to this study the annual heating energy consumption can vary by up to 15 kWh/m^2/person, regardless of the building's year of construction and the quality of its envelope. Hence, a MF - building of 1974, attached to two other buildings, could have the same heating energy consumption, as a 1990 building, detached and newly constructed. One should underline the fact that this is a common phenomenon in city centres across Greece, due to the construction practices in the period 1960-1980, with the so called "row-system", namely buildings adjacent to neighbouring buildings. This fact should be taken into consideration during the energy efficiency evaluation process, as concerns the urban residential building stock.

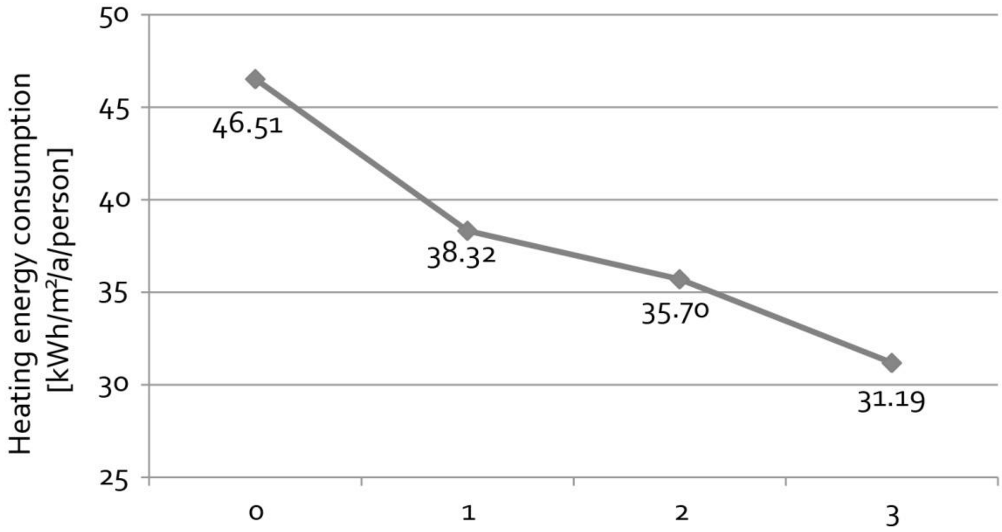


Fig. 3.16 Annual heating energy consumption in kWh per person and total floor area according to the attachment condition

3.2.1.4.3 Energy consumption according to the glazing type

As regards heating energy consumption according to the type of glazing used, a clear difference is noted, however not to the expected degree (Fig. 3.17). This is mainly due to the fact that, the implementation of TIR defined maximum allowed U-Factors of 3.26 – 5.23 W/m²K, thus no drastic improvement was achieved as regards the thermal resistance properties of openings before and after 1980. Respectively, the improvement of the energy behaviour was rather meagre. Furthermore, the substitution of old wooden framed, single glazed windows and balcony doors with new, aluminium framed, double glazed ones, was a renovation measure carried out in many older buildings since the late 1980's. Currently, KENAK sets new limits for the thermal insulation properties of openings for the four climatic zones of Greece. These heat transfer coefficient requirements, with U_w- values varying between 2.60 and 3.20 W/m²K, though still lagging behind state of the art windows technology, are a certain progress compared to the requirements of the previous regulation.

Fig. 3.17 Annual heating energy consumption in kWh per person and total floor area according to the glazing type

3.2.1.4.4 Energy consumption according to the income

Many studies tried to relate energy consumption of households and income, by using various methodologies, both in developed and in developing countries, often leading to contradicting results ((152), (153)). However, many European countries have implemented financial and taxing measures in order to reduce energy consumption in households (154). Based on the findings of this research, it is confirmed that the higher the income, the higher the energy consumption, as depicted in Fig. 3.18. It is also important to underline the fact that the higher incomes of the sample are met in relatively new constructions. Hence, given the fact that the construction quality did not improve drastically, even after the introduction of the Thermal Insulation Regulation in 1980 , it can be easily understood that even newer constructions after 1990 tend to perform worse than older ones as regards their energy consumption. The improvement in the energy performance of the building's envelope and heating systems is offset by the higher living standards of the inhabitants, which leads to demanded comfort levels and therefore to higher energy consumption.

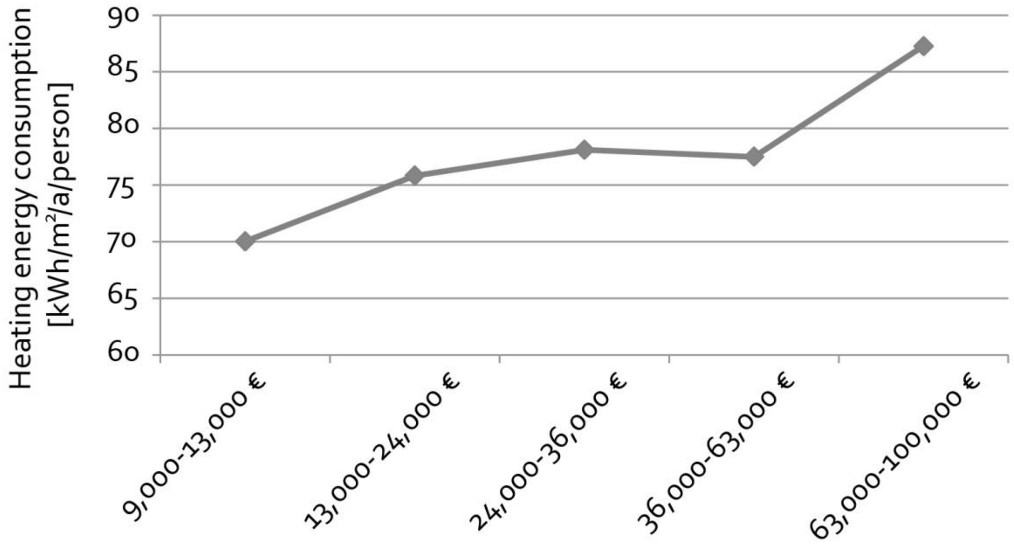


Fig. 3.18 Annual eating energy consumption per total floor area according to the inhabitants' income

4 Case study / building unit analysis

4.1 The main characteristics of Polykatoikia

As already indicated the urban area of Thessaloniki is considered typical concerning its residential buildings' typology. Similar to the majority of the Greek city centres, *Polykatoikia* is the domain architectural structure with the following main characteristic elements:

- The balconies are intensively used for 3- 5 months per year according to the climatic zone. They function as a buffering zone, as shading elements, and as a free recreational space zone.
- The awnings made of textile or metal, which are also used as an extra shading device. They are suspended at the lower surface of the balcony usually with an angle of 45° mainly.
- The Pilotis floor, a 3-4 meters high open ground floor, mostly used as a parking space and circulation area. The Pilotis floor is often uninsulated leading to high energy losses.

Angelidakis characteristically describes the influence of the *Polykatoikia* by means of its balconies and awnings on the Greek urban environment "The Greek city is made up of balconies and awnings. When there are no balconies the façade is simply blank. [...] But perhaps nobody noticed that the Greek City was born out of the coupling of horizontal planes of concrete and vertical surfaces of fabric" (155) (Fig. 4.1).

Fig. 4.1 A typical Greek *Polykatoikia* with awnings and balconies (155)

As regards the structure of the *Polykatoikia*, the floors communicate via a central circulation zone, with a stairwell and elevator. The free height between successive floors must be at least 2.70 meters according to the Building's Regulation and rarely exceeds a height of 3 meters. A "*Polykatoikia*" usually has one to four apartments per floor, according to the size of the building. The main entrance are located on the ground floor, along with the building's utilities. In case of a Pilotis this entrance area is combined with the parking use. In any other case, the ground floor has a commercial use with shops and/or offices. The basement is used for storage needs and HVAC installations (boiler room).

Furthermore, heating needs are being covered by central heating systems, usually with oil-fuel boilers combined with convective baseboard heaters. Cooling demands are covered individually with randomly installed packaged terminal heat pumps, namely A/C split units. This tendency increased particularly since the mid 80s after the major heat wave in 1987 (156).

The load bearing structure of the buildings is constructed with reinforced concrete, as Greece is one of the most seismogenic areas if not in the world certainly so in Europe, and features very strict regulations regarding anti-seismogenic measures. In that sense, reinforced concrete plays a dominant role in buildings, which leads to heavy construction types with respectively amplified heat capacity (Fig. 4.2).

Fig. 4.2 Typical image of load bearing structure

All non-bearing external vertical elements are constructed as double brick cavity walls, consisting of 2 layers of bricks of at least 6 and 9 cm thickness each. In the case of buildings constructed after the implementation of the first Thermal Insulation Regulation in 1979, piers and beams are externally insulated mainly with extruded polystyrene, whilst the brick walls are insulated by a layer of expanded or extruded polystyrene inside the cavity. Consequently, this construction type leads to several linear thermal bridges, at each conjunction of brick walls with concrete vertical and horizontal construction elements.

As regards the finishing of external walls, a thin layer of plaster, usually 2–2.5 cm and light coloured, is applied on both sides. In rare cases, the facades are decorated with bricks, ceramic tiles, natural stone or, in cases of luxurious buildings, marble stone. In most city centres the *Polykatoikia* have conventional flat roofs, whilst after the implementation of TIR the "inverted"-flat roof type began to emerge.

Concerning the openings of the *Polykatoikia*, windows are rather rarely found, except in bathrooms and kitchens. The main opening type is the balcony-door, offering direct access to balconies. In both cases, the frames and dividers of such openings are aluminium or plastic, combined with single glazing in older buildings and double glazing in newer ones. Similarly to the frames of the opening, even in the case of double glazing, the materials are usually not certified without special membranes or relevant gas fillings. Besides the aforementioned canopies used for the external shading, synthetic roll-up blinds were and are still being used for safety reasons as well. Furthermore, in almost all cases drapes of various colours and transmittance are used both for shading and decorative reasons.

With respect to the internal vertical and horizontal partitions, walls are usually constructed as single brick walls of approximately 10 cm width. Moreover, internal floors are covered with ceramic tiles or marble that is widely quarried and manufactured in Greece, whilst in bedrooms wooden floor boarding are widely used, even until today.

Mechanical ventilation in Greek residential buildings is almost a taboo, regardless their typology. More specifically, all multi– and single –family buildings are almost exclusively naturally ventilated. A slight exception can be found in kitchens and bathrooms with no openings, where small exhaust fans are used.

In the following figures newer and older variations of the *Polykatoikia* typology are depicted.

VICE
ΦΡΕΝΑ






Moreover, many architects underlined the structure of the Greek *Polykatoikia* and its similarity to the Corbusian "Domino" system (Fig. 4.3), enabling maximum flexibility of program ((123), (64)). Thus, although the *Polykatoikia* is considered to be a rather typical building typology with repetitive characteristics, often of monotonous nature, it can adapt and transform itself to great extents. Even under the same conditions, referring to climatic data, urban texture, year of construction, economic and social level of the inhabitants, it is possible for *Polykatoikies* to differ significantly, at least with respect to their architectural design. In this framework, finding "a common denominator" is a difficult venture, though of vital importance, especially in the case of their energy behaviour analysis.

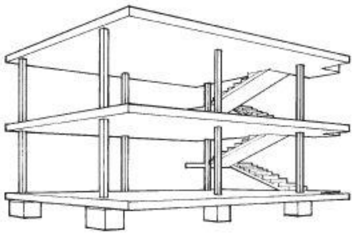


Fig. 4.3 The famous "Domino" system of Le Corbusier

Hence, the actual difference between *Polykatoikies* consists of the variation of the organised spaces within the construction of the Domino building system (64). This was also proven by the statistical data analysis in chapter 3, where the mixed use becomes evident as regards the urban built environment, thus the *Polykatoikia*. In particular, apart from partial mixed use in terms of apartments occupied as praxis and offices, *Polykatoikies* can be retrofitted into a new use. An example is given by Krokos, who created a museum in a *Polykatoikia*, originally planned by an anonymous architect, going back to the 70s (Fig. 4.4).

Fig. 4.4 New usage in a typical *Polykatoikia* ((157), (124))

Moreover, construction elements can differ in their dimensions, such as balconies, openings, whilst the number of apartments per floor also varies. The existence of Pilotis – floor is also a non constant parameter, along with the position of the circulation area, the elevators and the staircase. On the contrary, the height of floors remains constant, whilst the majority of *Polykatoikia* are constructed in orthogonal shapes. Conclusively, a general typological rule regarding the design of *Polykatoikies*, throughout the decades, is always evident, despite the differences that may occur, due to the planners' efforts to adjust to the General Construction Regulations (158). Hence, citing Woditsch "*Polykatoikies* are shaped, located and oriented by human agency, but in the light of laws which control their effects" (64).

4.2 Buildings' classification

As already underlined, planning for the urban environment, presupposes a fundamental classification for all building typologies. In this line of thought, "encoding" *Polykatoikia* is of immense importance, in order to assess the energy behaviour of Greek urban environments. The specifications of this procedure are being analysed in the following chapter.

Swan and Ugursal argue that it is profound to control the energy consumption of the residential sector mainly due to its polymorphic typology, the variety of the occupancy behavioural profiles as well as technical, cost and privacy parameters that complicate the procedure of data collection, in-situ measurements and elaboration of energy indicators (159). Due to these reasons and in order to plan retrofit scenarios for the urban built environment, the classification of buildings becomes of vital importance. Several studies used an age-based classification ((105), (106), (107), (109), (110), (111), (113), (114)), which determines construction practices and materials to a great extent. Similarly, Barelli et al. (121) propose a further classification mainly dependent on dimensionless energy performance values.

Gadsden et al. (160) propose a multi-criteria analysis of a solar energy planning (SEP) system for the urban domestic sector. It is of great interest to notice, that their work recognises the problem of (a) energy consumption estimation, (b) buildings' classification and (c) energy modelling in general and so they suggest a holistic evaluation methodology, which takes into consideration all the above factors. Initially, as far as energy consumption information is concerned, they propose a monthly energy consumption tool rather than an annual one, in order to gain information on a seasonal basis. Moreover, they use a buildings' classification that is based on the year of construction, the building's form and the attached or detached to other buildings parameter, whilst they develop a customised GIS tool that allows the recognition of the outlines of buildings as closed polygons. They further believe that this classification procedure enables the use of available statistical data from respective surveys (e.g. English House Condition Survey (EHCS)) concerning the energy performance of buildings. In this line of thought, this thesis proposes a typical classification regarding Greek urban residential buildings, which are being thoroughly analysed in the following chapter.

4.3 Typical buildings under study

Based on the statistical analysis presented in chapter 3, a thorough field research has been carried out in the city of Thessaloniki, the biggest urban centre in climatic zone C, in order to collect data about buildings that are representative for the most important Classes, namely B2, C and D as presented in Table 3.1. The research included the extensive energy audits of more than 20 buildings, with measurements of the indoor air quality and thermal comfort conditions, thermographic controls as well as the collection and processing of energy consumption data for the last 4 to 6 years. Four buildings were chosen to represent the residential building stock of this case study area; they are depicted in Fig. 4.5, based on the statistical analysis of the Greek building stock and the GIS analysis for the greater urban area of Thessaloniki, which is presented in the following chapter. These buildings are real constructions located in the city of Thessaloniki, in the 3rd climatic zone of Greece (Fig. 4.6) and were carefully chosen in order to represent each Building Class.

Fig. 4.5 The 4 typical MF – buildings (MF1, MF2, MF3 and MF4)

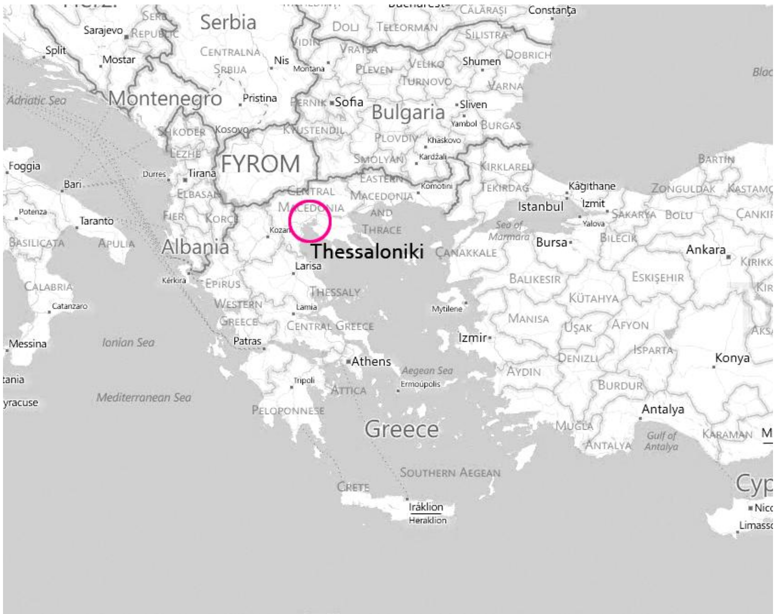


Fig. 4.6 Geographical position of the city of Thessaloniki (20)

Fig. 4.7 Case study area- Municipality of Thessaloniki and Kalamaria

More specifically, two typical six-storey MF - buildings have been chosen for Class B2, one located in the city centre (Municipality of Thessaloniki) and one in the suburbs (Municipality of Kalamaria) constructed in 1969 and 1976 respectively. Hence, the first MF - building (MF1) represents a typical row system - construction with south orientation in the city centre, whilst the second one (MF2) is a typical free standing MF - building of this Class with Pilotis.

For Class C a typical building of 1985 in row system (MF3) was chosen, whereas for Class D a free standing MF - building (MF4) constructed in 1998 was studied, both located in the Municipality of Kalamaria. Some basic features of these MF – buildings are presented in Table 4.1 and Table 4.2.

Table 4.1 Typical buildings of the case-study area

	Class B2 (1960-1980)		Class C (1981-1990)	Class D (1990-2010)
Code	MF1	MF2	MF3	MF4
Year of construction	1969	1976	1985	1998
Location	Municipality of Thessaloniki	Municipality of Kalamaria	Municipality of Kalamaria	Municipality of Kalamaria
Short description	row-system	detached, with Pilotis	row-system, with Pilotis	detached, with Pilotis

Table 4.2 Main characteristics of the buildings

	Pilotis	Storey nr.	Use	System	Built-up density
MF1	no	6	Mixed with commercial	row system	very high
MF2	yes	6	residential only	detached	medium
MF3	yes (by 50%)	4	residential only	row system	high
MF4	yes	7	Mixed with commercial	detached	low

The four categories of Table 4.1 are characteristic for the majority of the sample, a fact that is also proven by the outcomes of the GIS-based analysis, which are presented in the following chapter. In addition, smaller subcategories are being introduced in order to describe slight deviations. These mainly concern the state of attachment and therefore, by and large, refer to Class C and Class D. Hence, in the following chapter, MF3 building was also studied as fully detached as well as attached to one building, whilst MF4 building's energy behaviour was determined in the case of a row system construction, thus attached both to one and two sides respectively. For Class B2, MF1 building was considered also as attached only to one side. It is important to note that buildings constructed before 1960 were not studied, due to the lack of typological pattern and the fact that they are often characterised by landmark use. In the following figures the typical floor plans in 1:200 for each building and their location in the building block are depicted.

4.3.1 Building MF1

Fig. 4.8 *Polykatoikia* MF1

Fig. 4.9 Position of the *Polykatoikia* MF1 in the building block

Fig. 4.10 Surrounding buildings of the *Polykatoikia* MF1

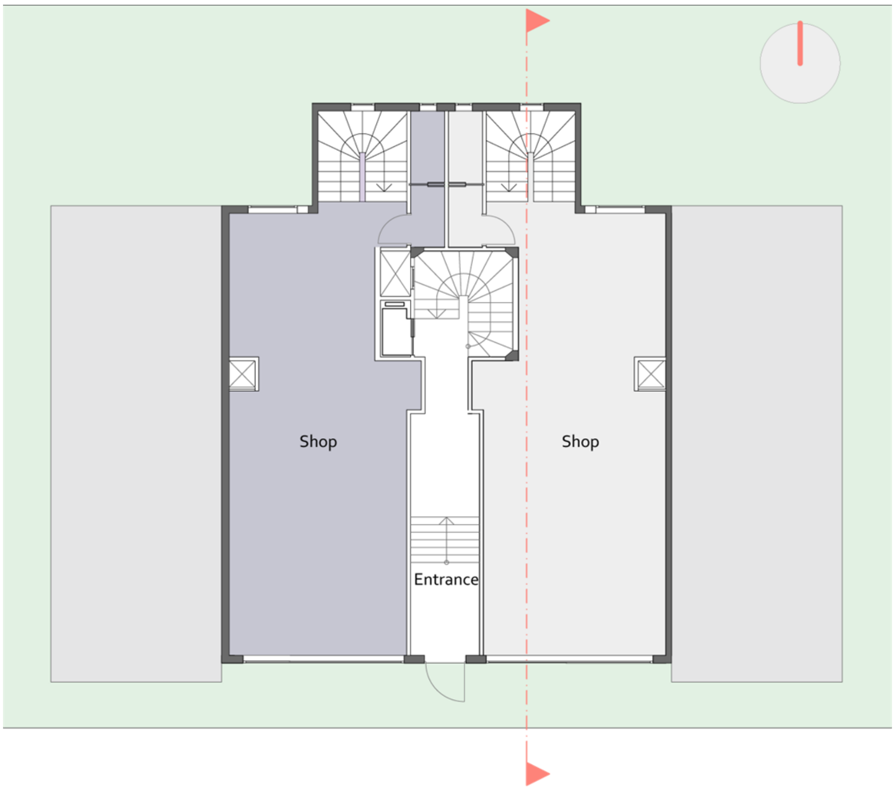


Fig. 4.11 Ground Floor plan of building MF1

Fig. 4.12 Typical Floor plan of building MF1

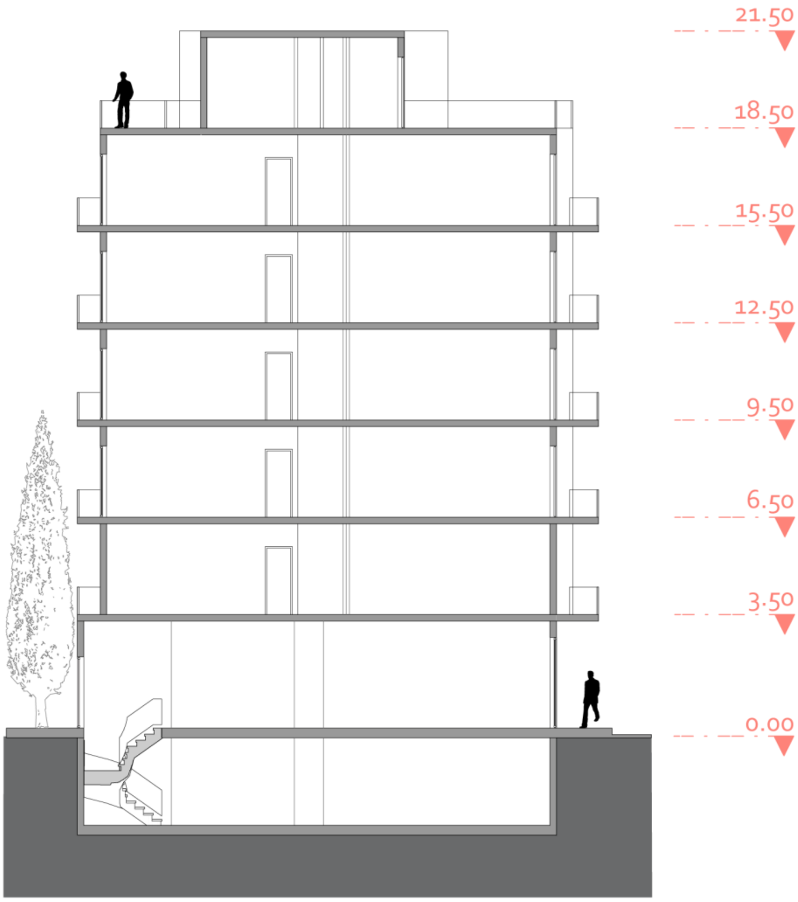


Fig. 4.13 Section plan of building MF1

4.3.2 Building MF2

Fig. 4.14 Floor plan of building MF2

Fig. 4.15 Position of the *Polykatoikia* MF2 in the building block

Fig. 4.16 Surrounding buildings of the *Polykatoikia* MF2

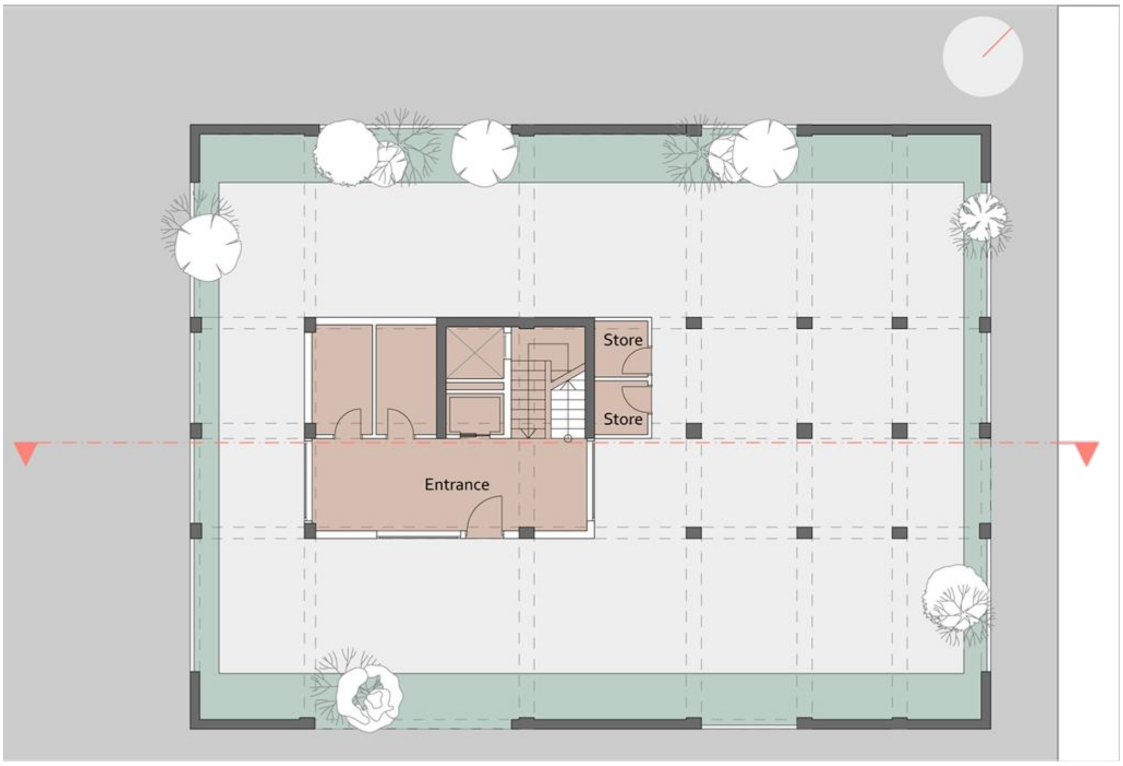


Fig. 4.17 Ground Floor plan of building MF2

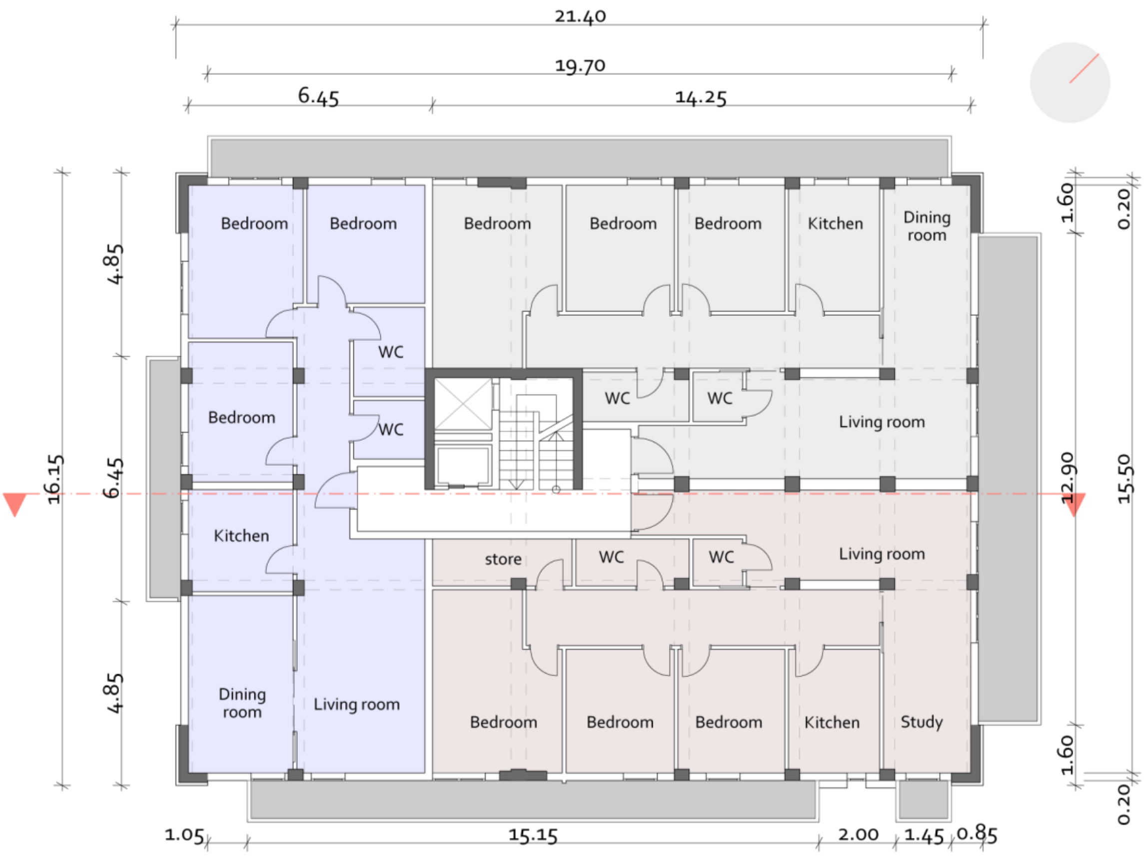


Fig. 4.18 Typical Floor plan (1st, 4th and 5th floor) of building MF2

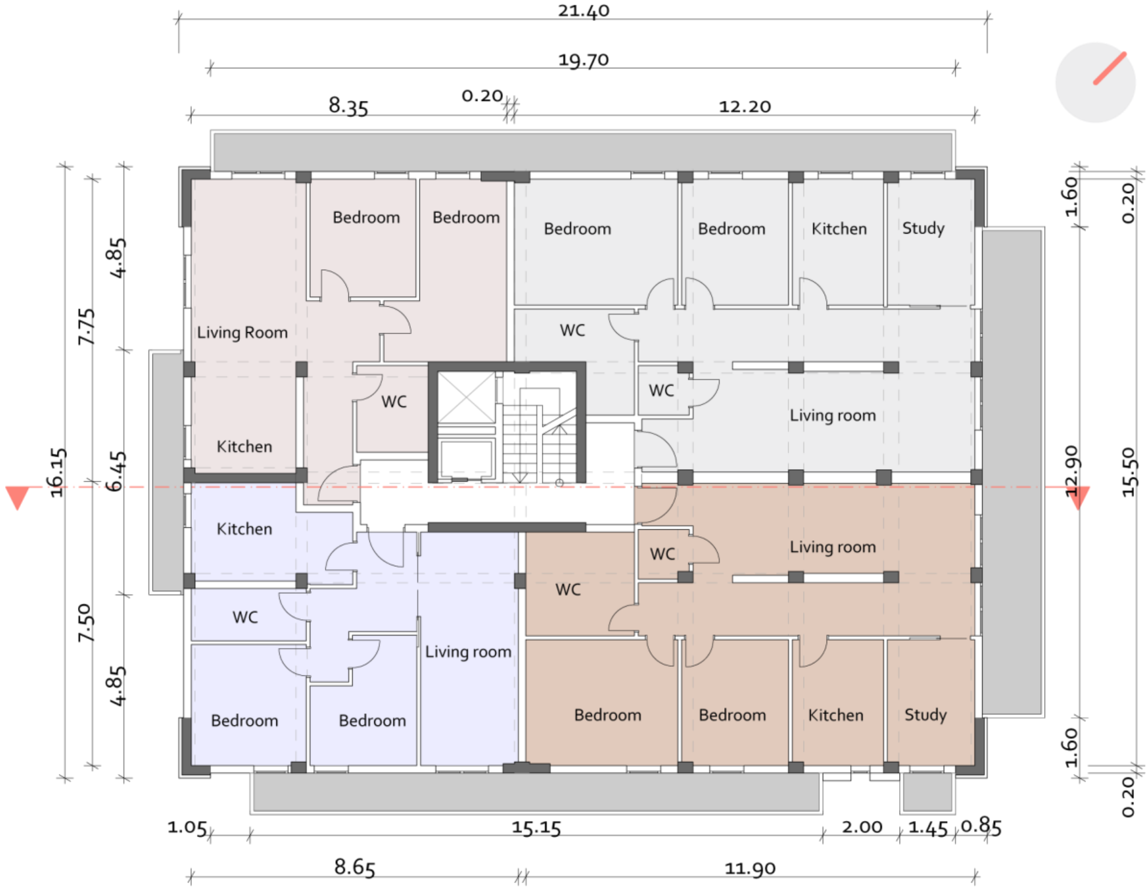


Fig. 4.19 Typical Floor plan (2nd and 3rd floor) of building MF2

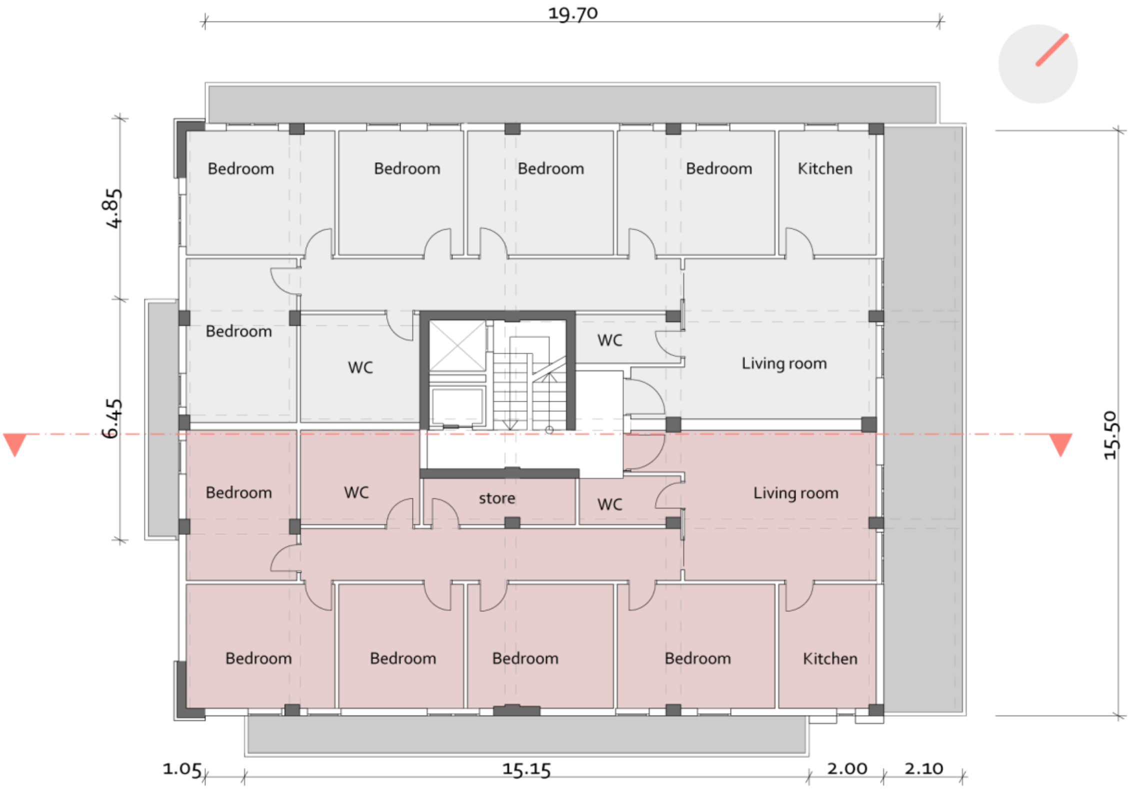


Fig. 4.20 Floor plan (6th floor) of building MF2

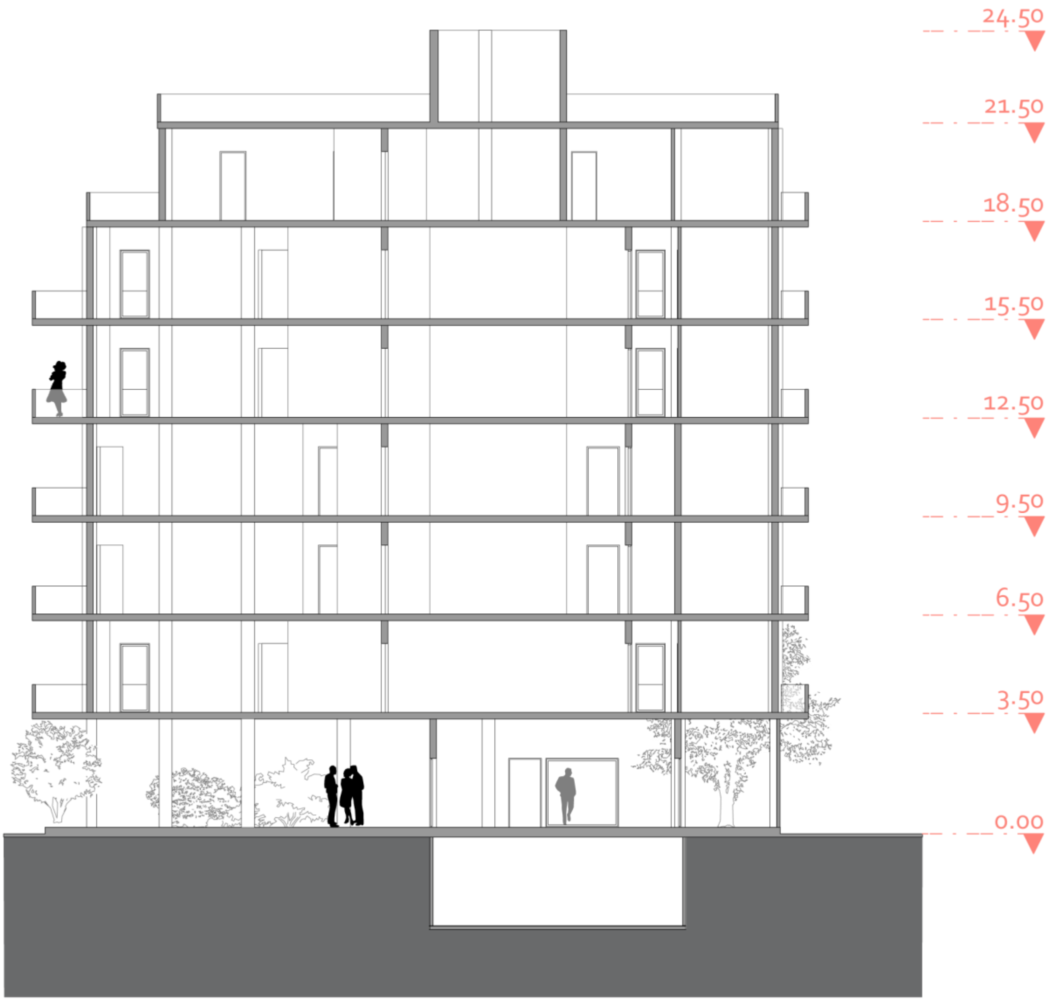


Fig. 4.21 Section plan of building MF2

4.3.3 Building MF3

Fig. 4.22 *Polykatoikia* MF3

Fig. 4.23 Position of the *Polykatoikia* MF3 in the building block

Fig. 4.24 Surrounding buildings of the *Polykatoikia* MF3

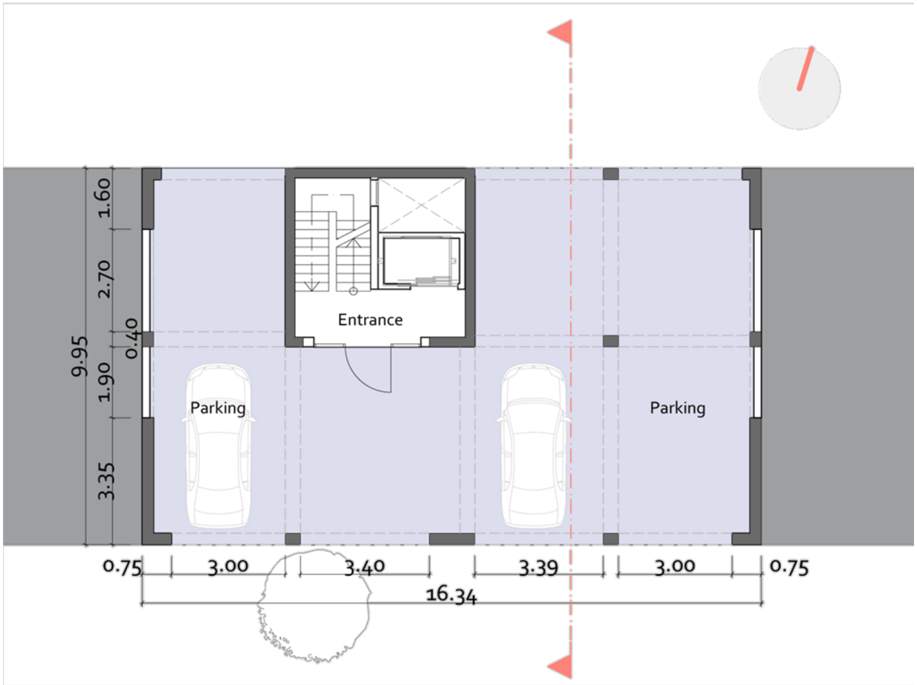


Fig. 4.25 Ground Floor plan of building MF3

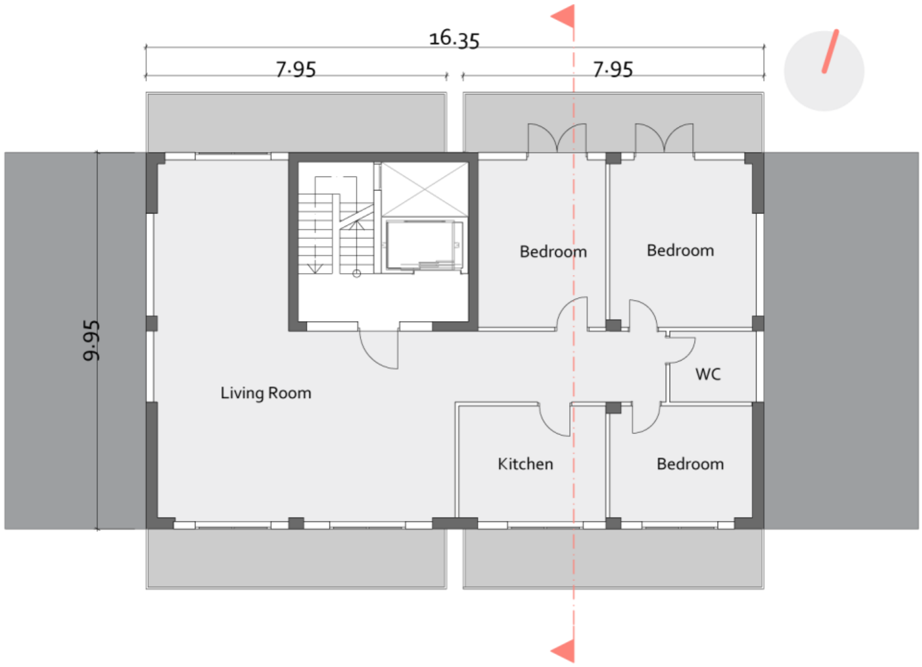


Fig. 4.26 Typical Floor plan of building MF3

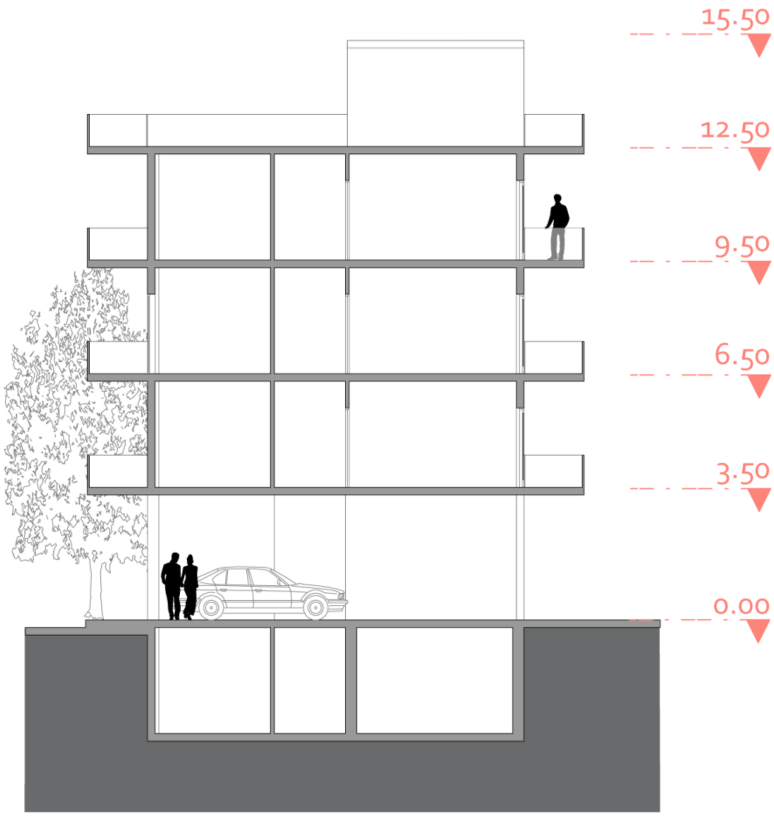


Fig. 4.27 Section plan of building MF3

4.3.4 Building MF4

Fig. 4.28 Building MF4

Fig. 4.29 Position of the *Polykatoikia* MF4 in the building block

Fig. 4.30 Surrounding buildings of the *Polykatoikia* MF4

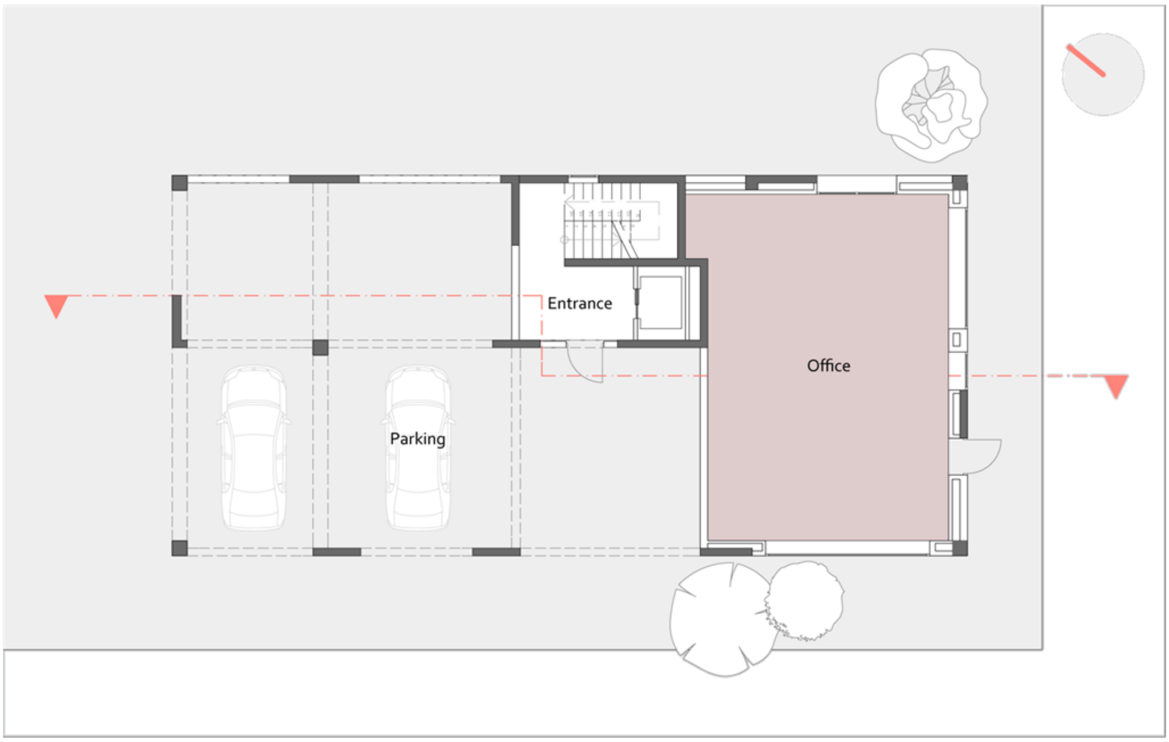


Fig. 4.31 Ground Floor plan of building MF4

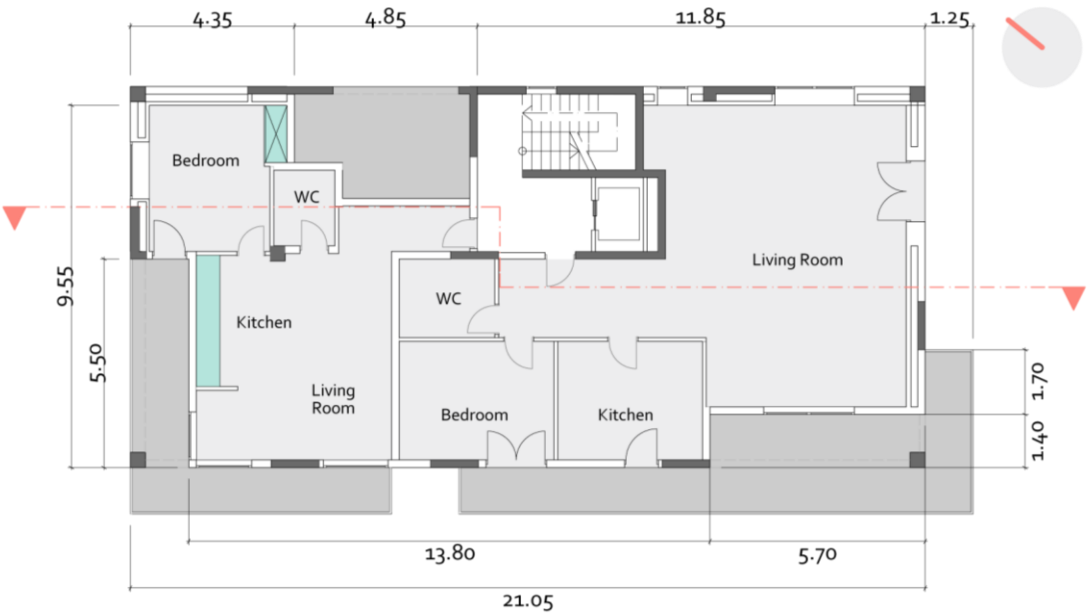


Fig. 4.32 Typical Floor plan (1st and 2nd floor) of building MF4

Fig. 4.33 Typical Floor plan (3rd and 4th floor) of building MF4

Fig. 4.34 Typical Floor plan (5th and 6th floor) of building MF4

Fig. 4.35 Floor plan (7th floor) of building MF4

Fig. 4.36 Section plan of building MF4

4.3.5 Constructional characteristics

The constructional characteristics of the buildings mainly differ in the existence of thermal insulation. In other words, buildings MF1 and MF2 share similar constructional details, along with building MF3 due to their year of construction, whilst building MF4 is insulated. Below, details about the constructions and materials used in the buildings under study are presented, indicating the need for thermal insulation. The following figures describe the common construction practices that were described earlier in 1:10.

In the case of flat roofs, insulation was mainly used in newer buildings constructed after 1990. In addition Pilotis floors have started being thermally insulated only recently. In general buildings MF1 and Mf2 are not insulated (Fig. 4.38, Fig. 4.40, Fig. 4.43, Fig. 4.45, Fig. 4.47), whilst building MF3 reflects the common practice in terms of vertical elements' thermal insulation (Fig. 4.41). Building MF4 is constructed according to TIR of 1979, and represents construction practices of buildings of its period (Fig. 4.39, Fig. 4.42, Fig. 4.44, Fig. 4.46, Fig. 4.48); it should be underlined though that the constant swing of the thermal insulation's position causes thermal bridging effects.

Stonewool was often used as a thermal insulation material of cavity walls, whereas extruded polystyrene was used for the vertical elements of the load bearing structure. Variations in flooring and roofing finishing materials can be met; however the most common materials are wood, marble and ceramic tiles (Fig. 4.37).

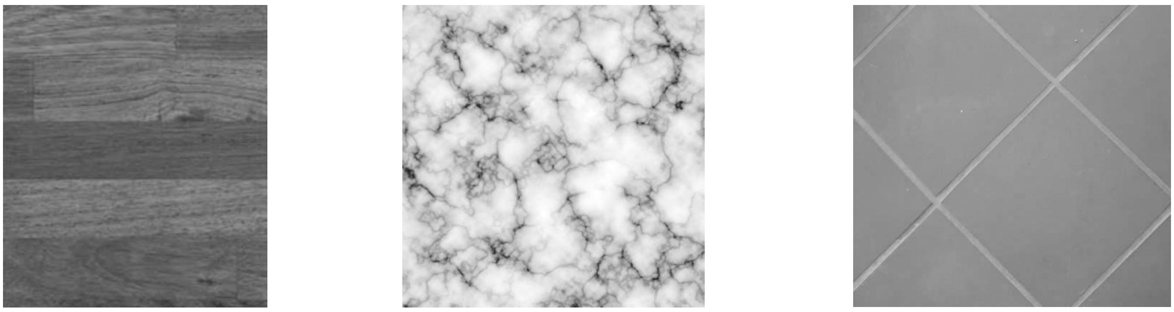
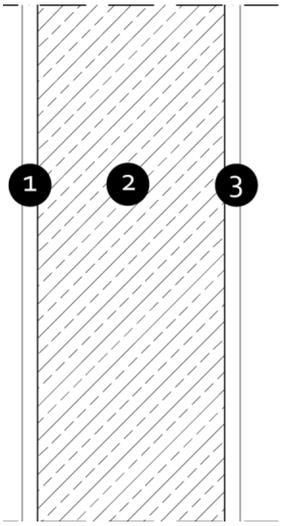
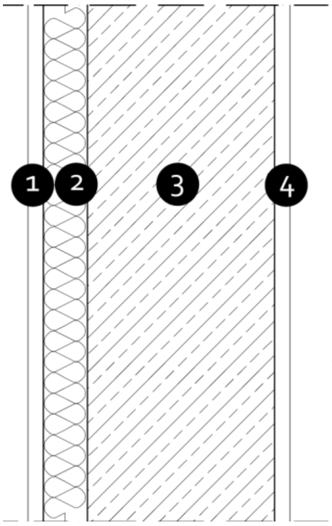


Fig. 4.37 Main flooring materials



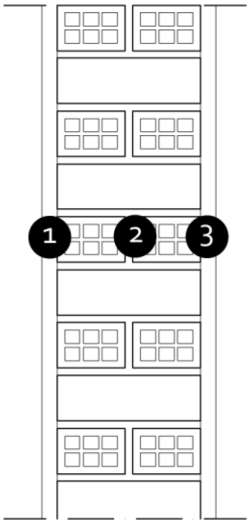
1. exterior plaster
2. reinforced concrete
3. interior plaster

Fig. 4.38 Common practice load bearing structure – Buildings like MF1, MF2, MF3 (161)



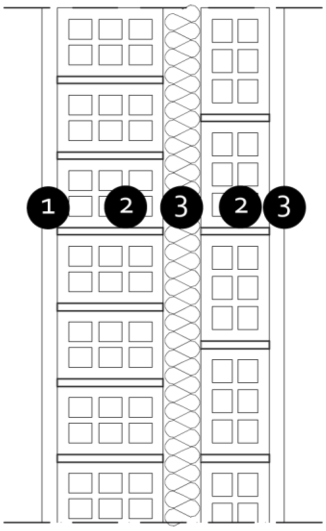
1. exterior plaster
2. thermal insulation
3. reinforced concrete
4. interior plaster

Fig. 4.39 Common practice load bearing structure – Buildings like MF4 (161)



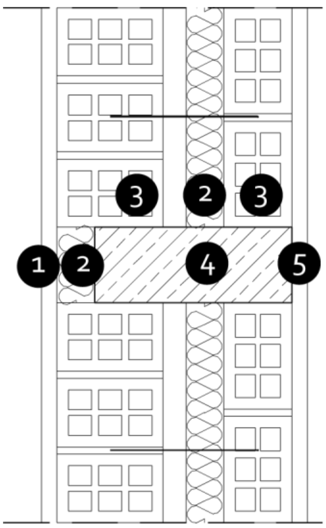
1. exterior plaster
2. brick wall
3. interior plaster

Fig. 4.40 Common practice brick walls - Buildings like MF1, MF2 (161)



1. exterior plaster
2. brick cavity wall
3. thermal insulation
4. interior plaster

Fig. 4.41 Common practice brick walls - Buildings like MF3 (161)



1. exterior plaster
2. thermal insulation
3. brick cavity wall
4. ring beam (wall tie)
5. interior plaster

Fig. 4.42 Common practice brick walls - Buildings like MF4 (161)

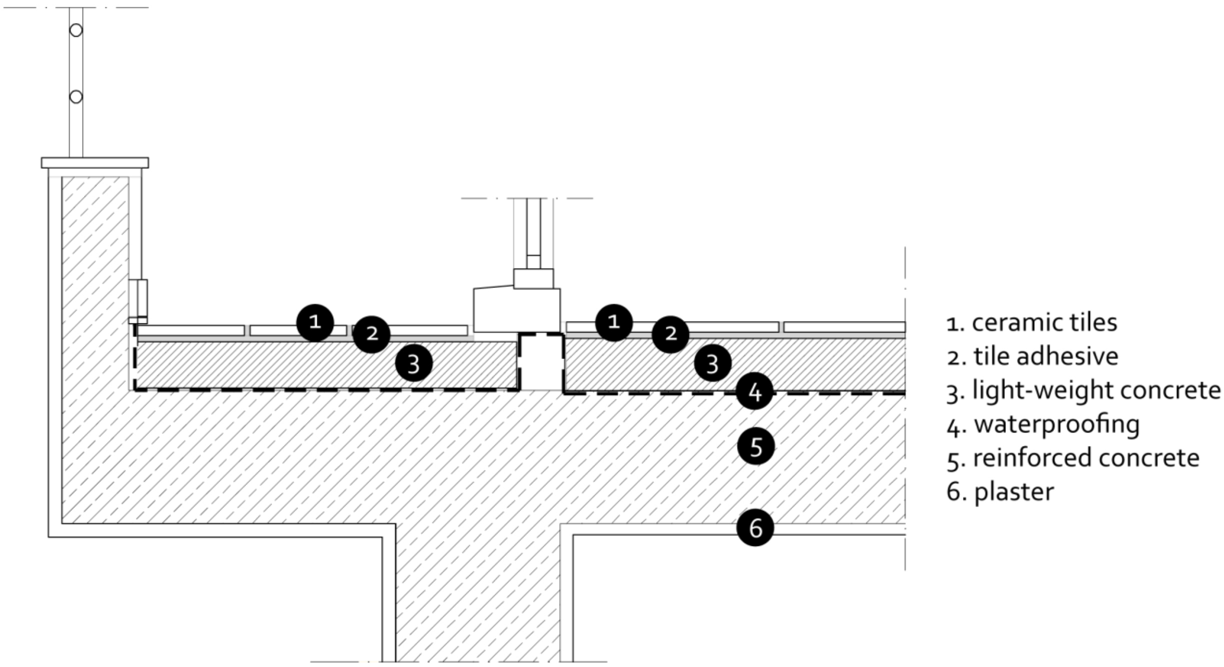


Fig. 4.43 Common practice balconies - Buildings like MF1, MF2, MF3 (161)

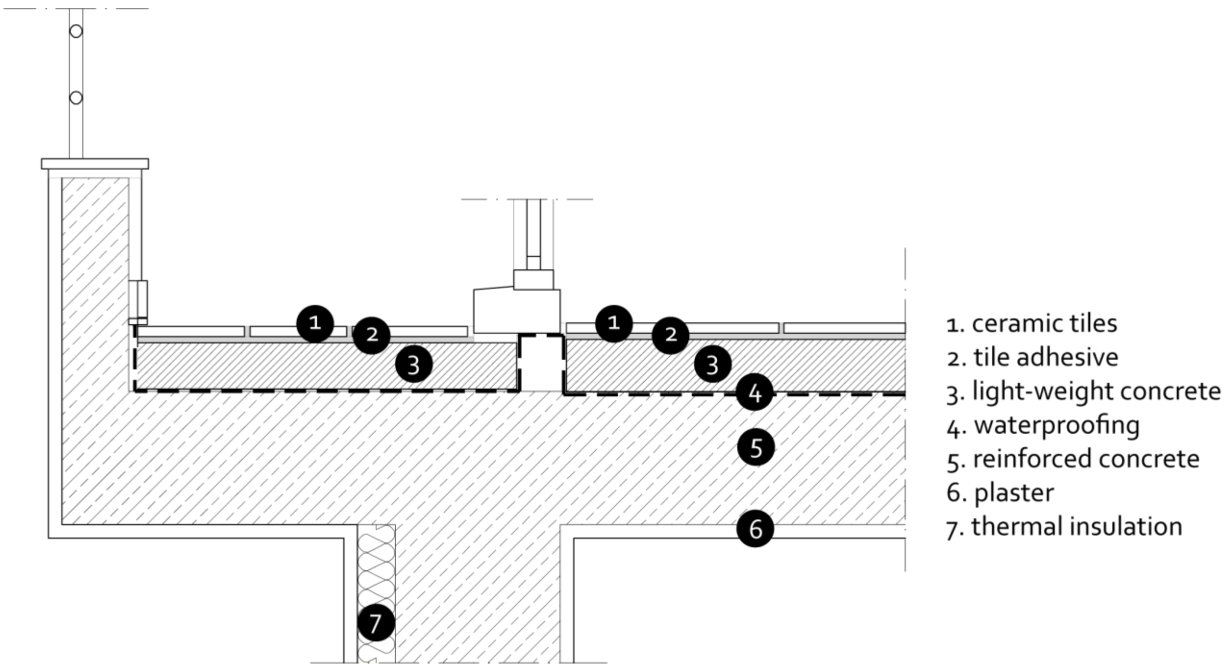


Fig. 4.44 Common practice balconies - Buildings like MF4 (161)

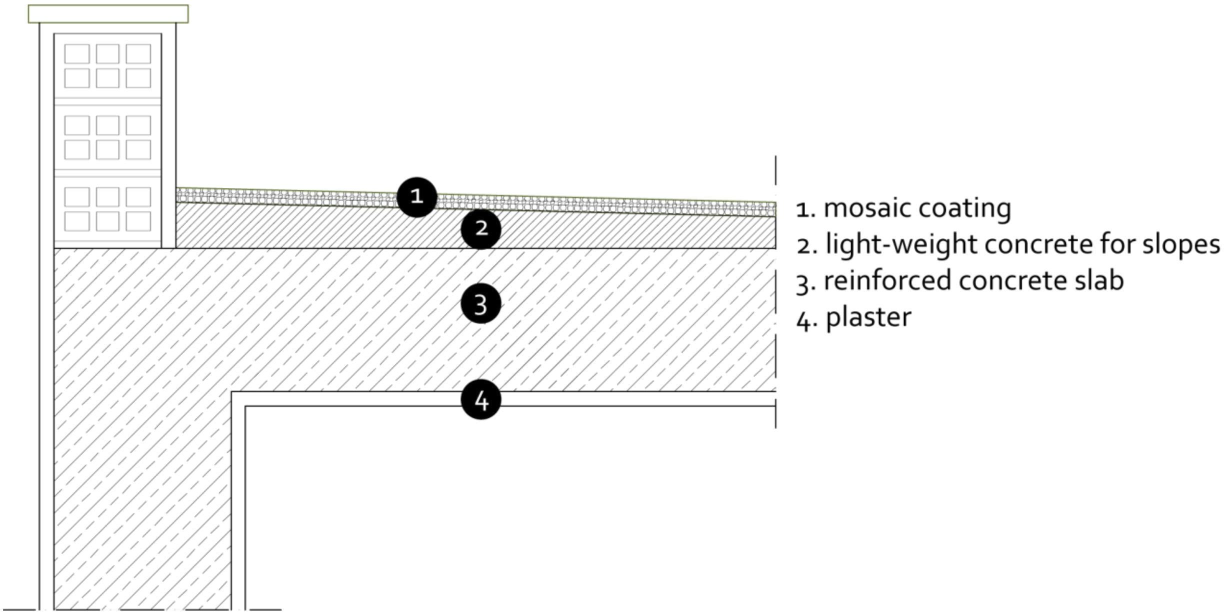


Fig. 4.45 Common practice flat roofs - Buildings like MF1, MF2, MF3 (161)

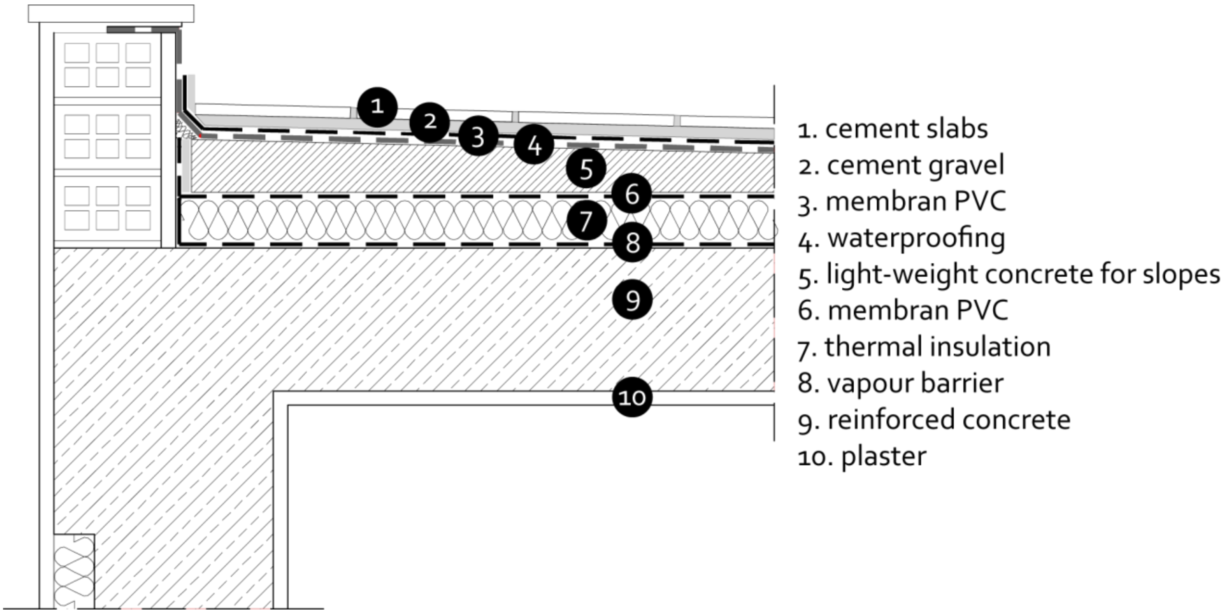
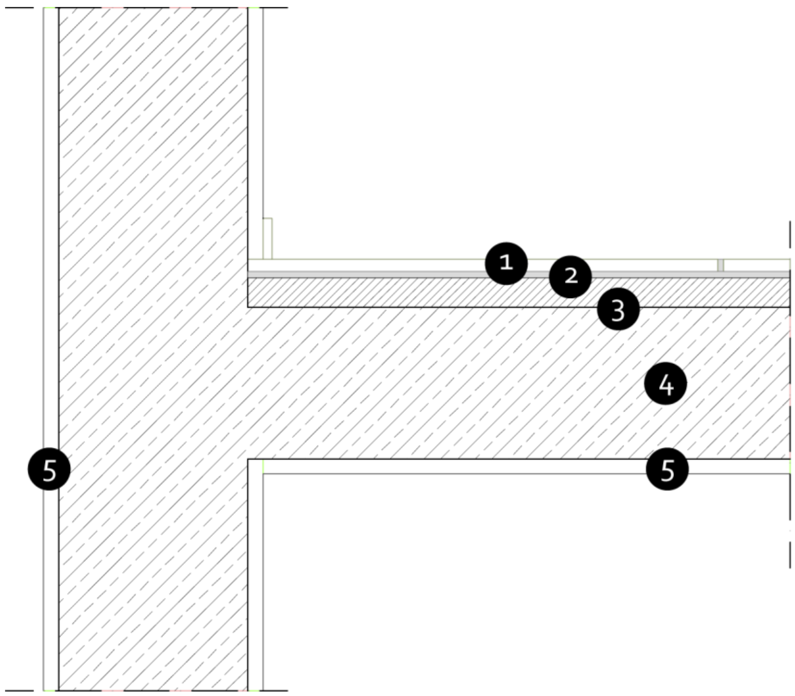
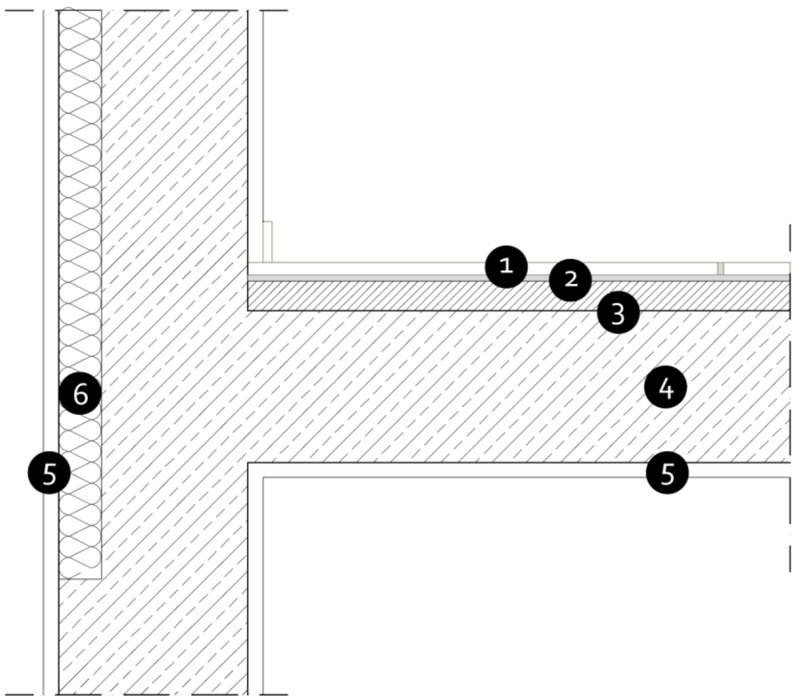


Fig. 4.46 Common practice flat roofs - Buildings like MF4 (161)



1. ceramic tiles
2. tile adhesive
3. light-weight concrete
4. reinforced concrete
5. exterior plaster

Fig. 4.47 Common practice Pilotis - Buildings like MF2, MF3 (161)



1. ceramic tiles
2. tile adhesive
3. light-weight concrete
4. reinforced concrete
5. exterior plaster
6. thermal insulation

Fig. 4.48 Common practice Pilotis - Buildings like MF4 (161)

4.4 Energy behaviour of the typical buildings

4.4.1 Simulation parameters

Apart from the real heating energy consumption data, the energy behaviour of the buildings under study has been evaluated using the dynamic simulation tool Energy Plus Version 6.0 (162), based on the National Technical Directives (T.O.T.E.E.) of KENAK ((18), (19), (20), (21)) and the specifications regarding residential buildings. The buildings' operational schedules, the thermostatic control, the internal heat gains, the hot water demand, the ventilation loads and the U-values according to the year of construction are in all cases equal for all buildings, according to KENAK.

4.4.1.1 Climatic conditions

Thessaloniki is located in Northern Greece and is characterised by a Mediterranean climate (Köppen climate classification "Csa"). More specifically, its climate is being strongly affected by the nearness to the sea leading to high humidity levels. According to KENAK the 3rd climatic zone is the second coldest in Greece (Fig. 4.49).

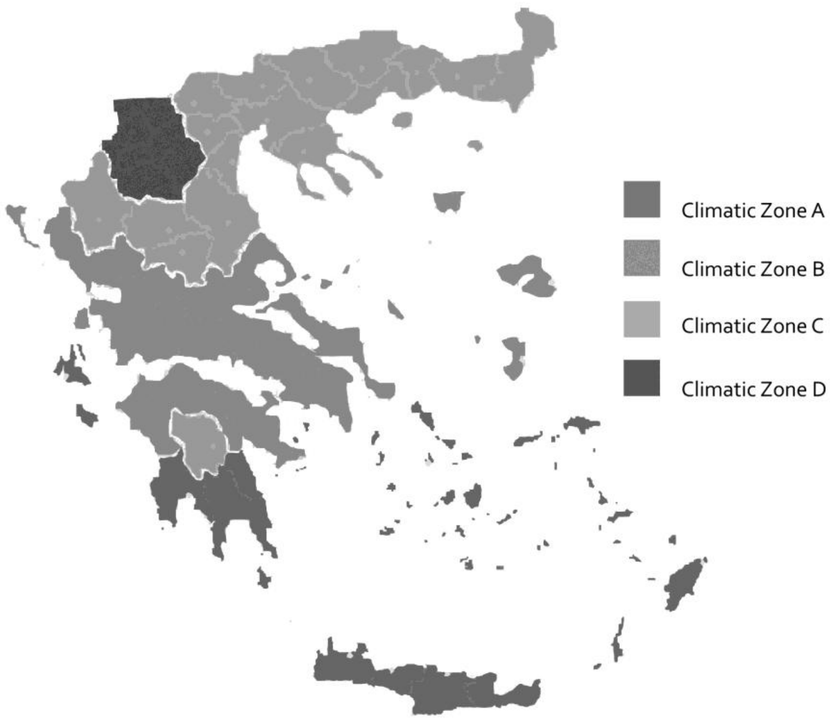


Fig. 4.49 The four climatic zones of Greece according to KENAK (20)

In the following figures and tables the main climatic features for the 3rd climatic zone and for Thessaloniki are presented (Fig. 4.50, Fig. 4.51, Fig. 4.52, Table 4.3, Table 4.4).

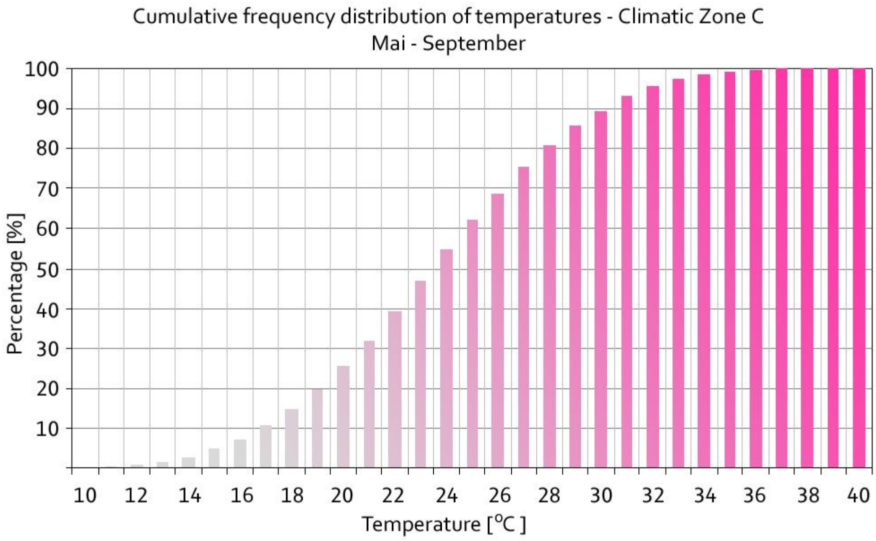


Fig. 4.50 Cumulative frequency distribution of temperatures for the 3rd climatic zone (Mai-September) (20)

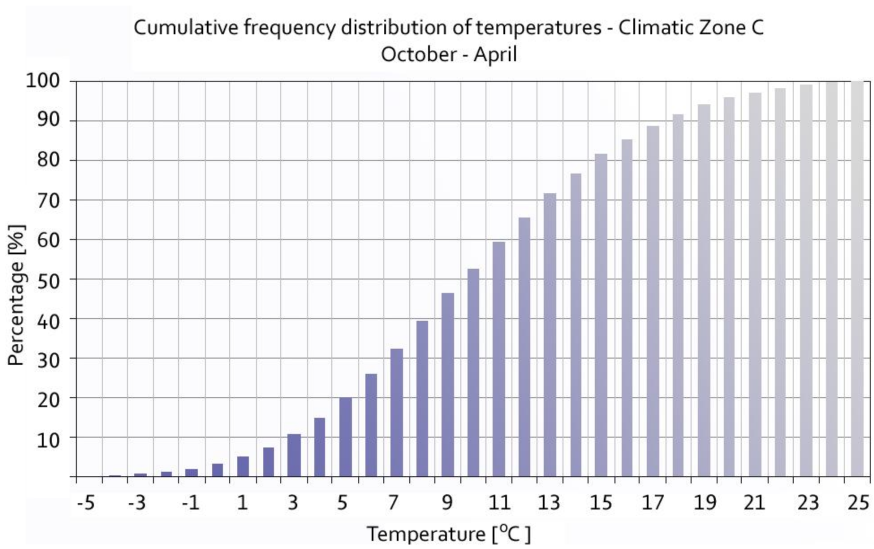


Fig. 4.51 Cumulative frequency distribution of temperatures for the 3rd climatic zone (October-April) (20) (20)

The above figures depict the cumulative distribution of temperatures for the cooling and heating period respectively. It becomes clear that for the cooling period the rising trend of the cumulative distribution is lower for the temperature range between 30-36 °C, implying larger concentrations for temperatures 18-28 °C. Similarly, for the heating period the cumulative distribution is more intense for the temperature range between 5-19 °C.

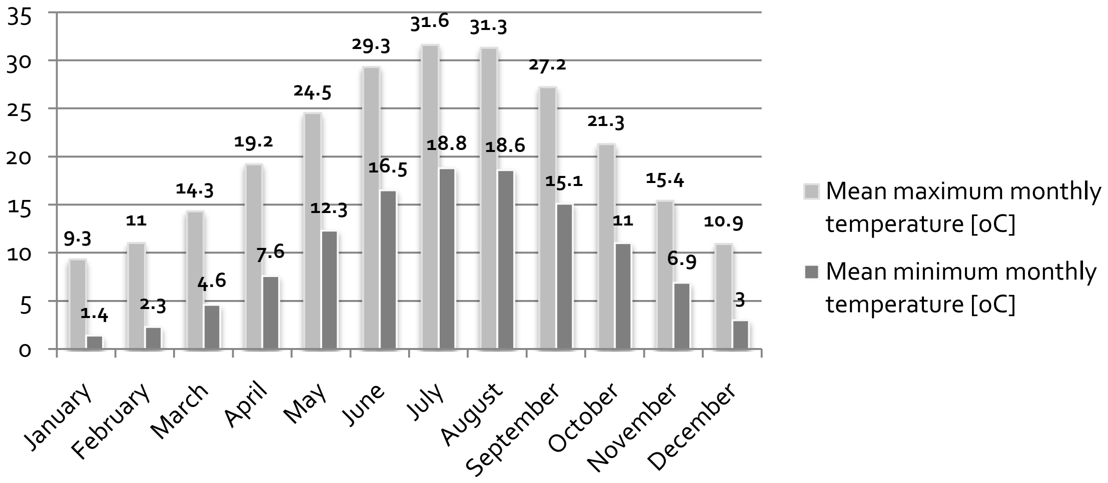


Fig. 4.52 Mean maximum and minimum monthly temperature °C (20)

Meanwhile, according to Fig. 4.52 the mean maximum monthly temperature does not exceed 31.6 °C in July, whilst the lowest temperature for the heating period is recorded in January with 1.4 °C. In addition, the following tables describe this trend of mild climatic conditions during winter and warmer days during summer for the city of Thessaloniki. Concerning the cooling degree hours, for June, July and August, a total sum of 2795 cooling degree hours are accounted for, with a reference temperature of 26°C (Table 4.3).

Table 4.3 Cooling degree hours for Thessaloniki (reference temperature 26°) (20)

	January	February	March	April	May	June	July	August	September	October	November	December
CDH	-	-	-	-	-	526	1211	1058	-	-	-	-

Unlike the cooling degree hours, the heating degree days for Thessaloniki are more equally distributed among the heating period leading to an overall sum of 1677 heating degree days with a reference temperature of 18 °C (Table 4.4).

Table 4.4 Heating degree days for Thessaloniki (reference temperature 18°) (20)

	January	February	March	April	May	June	July	August	September	October	November	December
HDD	394	314	254	111	-	-	-	-	-	53	207	344

By means of the dynamic energy simulation, the weather data used for the energy simulation software Energy Plus are the official American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) climatic data for the city of Thessaloniki (163), (164).

4.4.1.2 Building envelope

As regards the building envelope and the U-values of its construction materials, they are depicted in the following table (Table 4.5). More specifically, all building elements were analysed according to the specifications of KENAK concerning thermal conductivity for each construction material.

Table 4.5 U-Values of the envelope's materials of the buildings under study [W/m²K] (18)

	Brick walls	Concrete elements	Flat roofs	Pilotis
MF1	1.58	3.13	3.06	-
MF2	1.58	3.13	3.06	2.76
MF3	0.80	3.13	3.06	2.76
MF4	0.66	0.71	0.50	2.87

For the opening's properties the regulated terms of KENAK were assumed (18). Hence, Table 4.6 depicts the U-values used for the glazing and the frame materials of each opening.

Table 4.6 U-Values of the openings' glazing and frame materials [W/m²K] (18)

	glazing	frame
MF1	single glazing 5.70	aluminium frame (no thermal break) 7.00
MF2	single glazing 5.70	aluminium frame (no thermal break) 7.00
MF3	double glazing (6mm) 3.30	aluminium frame (no thermal break) 7.00
MF4	double glazing (12mm) 2.80	PVC frame 2.80

Based on the Technical Directive of KENAK the infiltration was separately calculated for each frame material (Table 4.7). For that purpose, certain input data were required related to the type of the material of the window frame, the ratio of the exterior to the interior openings of the thermal zones and the wind exposure of the examined building within the urban area. These variables were particularly used in the following equation in order to calculate the overall infiltration V_{inf} (m^3/h) for each thermal zone based on the openings' quality features:

$V_{inf} = \Sigma(l.\alpha) \cdot R \cdot H$

where,

l represents opening's perimeter,

α is defined based on the window frame's material and accounts for the infiltration coefficient of the windows (18),

R sets the opening's penetrability coefficient considering the ratio of the exterior to the interior openings in a thermal zone and

H refers to the wind exposure of the examined building (as if it is located in suburbs, city centre etc.).

Table 4.7 Infiltration coefficient of window openings based on the frame material (18)

Frame material	Infiltration coefficient α	α [$m^3/(h*m)$]
Wooden	Frame with single glazing system	3
	Frame with double sliding glazing system or without certified technical properties	2.5
	Frame with double airtight glazing system with certified technical properties	2
Aluminium or PVC	Frame with single glazing system	1.5
	Frame with double sliding glazing system or without certified technical properties	1.4
	Frame with double airtight glazing system with certified technical properties	1.2

4.4.1.3 Operational characteristics

The operational characteristics of the buildings, which are based on the standards set by the relevant Technical Directives (19), are described in the following table (Table 4.8). For all residential the building's operating schedule, the thermostatic control, the internal heat gains, the hot water demand as well as the ventilation loads are the same.

Table 4.8 Main characteristics regarding the operation of residential buildings according to KENAK (18)

Thermostatic control	**heating period [°C]**	**cooling period [°C]**
	20	26
Ventilation	**people per floor area**	**natural ventilation [m^3/h/person]**
	0.05	15
Internal heat gains	**people [W/person]**	**mean occupancy coefficient**
	80	0.75
Internal heat gains	**equipment [W/m^2]**	**mean operation coefficient**
	4	0.75
Domestic hot water demand*	**DHW demand [l/person/day]**	**person/bedroom**
	50	1.5
Lighting	**illuminance [lux]**	**nominal power [W/m^2]**
	200	3.6

** Data according to the revised TOTEE*

The respective ventilation and lighting demand were estimated and used as an input for the dynamic simulation process for each building under study. In the same line of thought, the values regarding the internal heat gains were included in the Energy Plus simulation program.

4.4.1.4 HVAC systems

Regarding the simulation of the heating systems, they have been examined based on the actual efficiency given by the annual maintenance report. The overall system's efficiency includes also distribution, over-dimensioning and water tank's losses, which are set in correspondence with specific coefficients of the Technical Directive T.O.T.E.E. 20701-1/2010 (18).

Concerning particularly the over-dimensioning evaluation, a loss factor in actual efficiency of heater is estimated applying an over-dimensioning empirical rule, defined in the Technical Directive for the theoretical estimation of the appropriate heating system's capacity, as depicted in Table 4.9.

In detail, this algorithm is based on parameters such as the building's envelope and its mean U-value according to the year of construction and the climatic zone as well as a correction coefficient of 1.8 standing for the distribution losses, the intermittent operation of the heating system and the infiltration and ventilation loads. An additional test was carried out in order to evaluate the losses occurred, due to the over or under capacity of the existing heating systems. This was succeeded based on the results of the dynamic simulation analysis of the heating loads for the same parameters; the results showed that the boilers should have been rated with 200 to 300% less capacity compared to the one theoretically dimensioned by the aforementioned empirical rule (Table 4.9).

The energy simulation tool calculates the nominal capacity of the boilers according to the heating loads of the building. It does not consider any over-sizing for intermittent use of the system and distribution losses, but it does consider infiltration losses. According to the Technical Directive T.O.T.E.E. 20701-1/2010 (18), these three parameters account for an over-sizing factor of 1.8, as remarked above (i.e. 180%). A respective figure can also derive from the DIN 4701/1983, which was the main standard used in Greece for heating systems' sizing over the last 40 years. It is difficult to try to isolate the difference of infiltration losses alone, but even so a difference of 300% is a significant one and has to be considered as part of a future research study.

Similar assumptions, though with different distribution losses set according to Directives, were made for water heater's efficiency in cases where hot water is supplied by the central heating system, i.e. the building MF1.

Table 4.9 Nominal capacity of the heating systems in kWatt

	Real	According to Technical Directive	According to the energy simulation program
MF1	116.00	136.50	43.77
MF2	290.00	252.34	131.73
MF3	47.00	55.88	27.20
MF4	144.00	67.13	35.69

Furthermore, according to KENAK, residential buildings cooling systems are considered to cover at least 50% of the total net conditioned area, an assumption which determines the calculated cooling loads. However, this is a theoretical value not applying to the buildings under study, which are only partially air-conditioned and in most cases feature a one room air-conditioner (a split unit system). Furthermore, some apartments do not have any air-conditioning system at all. Hence, the assumption proposed by the Technical Directive may lead to over estimated cooling loads and therefore higher electricity consumption.

In Table 4.10 and Table 4.11 the overall efficiencies of the existing and the newly proposed heating and DHW systems of the examined MF-buildings are presented.

Table 4.10 Current heating systems of the examined MF-buildings

	Heating boiler Fuel	Capacity [kW]	Actual efficiency [%]	Overall efficiency [%]	Over-dimension coefficient	Well insulated boiler shell	Well insulated heating distribution network
MF1	Diesel oil	116	93.0	57.0	2.65	No	No
MF2	Natural gas	290	93.0	66.0	2.20	Yes	No
MF3	Diesel oil	47	92.0	70.0	1.20	No	No
MF4	Natural gas	144	91.5	65.0	4.00	Yes	Yes

Table 4.11 Current DHW systems of the examined MF-buildings

	DHW heater Fuel	Capacity [kW]	Actual efficiency [%]	Overall efficiency [%]	Well insulated heater tank	Well insulated DWH distribution network
MF1	Electricity	-	100.0	81.0	Yes	No
MF2	Natural gas (during winter)	290	93.0	56.0	Yes	No
	Electricity (during summer)	-	100.0	81.0	Yes	No
MF3	Electricity	-	100.0	81.0	Yes	No
MF4	Natural gas	144	91.5	60.0	Yes	Yes
	Electricity (during summer)	-	100.0	93.0	Yes	Yes

4.4.2 Simulation results

Table 4.12 presents the difference between the actual and the calculated heating energy consumption. In the case of building MF1 the calculated heating energy consumption is 39.4 % lower than the real energy consumption. This is mainly due to the lack of thermostatic control, the over-dimensioned boiler and the operating schedule. More specifically, in reality all apartments are heated for the same hours, without any thermostatic control, leading to high energy consumption, apart from the low thermal comfort levels. Moreover, the buildings under study have different orientation profiles, depending on the actual urban structure of Thessaloniki and their built environment.

Table 4.12 Mean annual heating energy consumption according to actual measurements and the simulation results

	Real heating energy consumption [kWh/m^2]	Simulation results [kWh/m^2]	
MF1	102.36	62.02	
MF2	101.03	112.78	
MF3	109.95	According to TIR	According to actual situation
		49.28	90.23
MF4	111.47	84.70	

Furthermore, according to the Technical Guideline - T.O.T.E.E. 20701-1/2010 (18) buildings constructed after the implementation of the Thermal Insulation Regulation of 1979 such as MF3 and MF4 must be considered as insulated. This leads to better envelope U-values for the simulation data input than in reality, resulting in a significantly better, theoretical, energy performance. For instance, a thorough thermographic control of the building MF3 showed the lack of thermal insulation in the load bearing structure, a common characteristic for many constructions of Class C. In the case of MF4 the building is insulated, however it is highly possible that smaller insulation widths were applied and the insulation materials were not certified. Therefore, the corrected input data regarding the thermal insulation of the envelope, lead to results that differ less from the actual heating energy consumption. In addition, the results concerning building MF2 seem fairly rational due to the high A/V ratio and the uninsulated building's envelope. In addition, the over-sized heating boilers and the non-equal operational schedule of the heating systems leads to higher heating energy consumptions as regards the real energy consumptions, similarly to MF1.

Table 4.13 Total final annual energy consumption according to the energy simulation results

	Total final energy consumption [kWh/m²]
MF1	102.07
MF2	166.33
MF3	123.56
MF4	143.14

In addition, penthouse apartments have an average heating energy consumption exceeding the mean value of the building by 15-18%. Respectively, apartments over the Pilotis consume 17-19% more energy in order to cover the heating demand than the building's mean value, due to no solar heat gains on the one hand and increased thermal losses due to higher convective losses through their floors. As a result, and despite the comparatively mild Greek climate, the annual final heating energy consumption of urban residential buildings in climatic zone C is high, indicating the significant energy conservation potential.

Concluding, the assumptions made for the thermal properties of the building's envelopes, as foreseen by the National Technical Directives, used for the calculation of the energy performance of residential buildings, differ quite significantly from the real features, especially for buildings constructed in the 1980's, as the implementation of the thermal insulation regulation was partially optimum. Eventually, this leads to significant differences of the calculated energy consumption values compared to the actual ones.

5 Case study / a large scale analysis

Urban sustainability is a research field that constantly gains interest and significance. With respect to various aspects that determine the energy efficiency of the urban built environment, numerous studies have proposed methodological approaches and evaluation tools in order to plan intervention scenarios in a more efficient way ((165), (111), (166), (167), (80)), many of which focus on the reduction of CO_2 emissions and as a result the minimisation of electricity loads as well as the utilisation of renewable energy resources (RES) ((168), (169), (170)). Besides energy efficiency Owens stresses that the effectiveness of such measures must involve and satisfy democratic criteria. Otherwise, in case of inequality between these two aspects, the energy efficiency legal and support systems might be unsuccessful (171). Meanwhile, Yiftachel and Hedgcock argue the importance of the social aspects concerning urban and regional development and underline the relation between urban social sustainability and urban planning (172). Hence, urban sustainable development reflects the polymorphic synthesis of numerous parameters, which are connected to urban life.

As concerns energy conservation, retrofitting of urban buildings is often equivalent to retrofitting of cities as a whole. As cities differ in their structure, their typology and like so, in their energy profile, developing a flexible evaluation tool of their energy performance is a rather complex procedure. The scope of this chapter is to suggest a holistic evaluation approach as a part of a bottom-up methodology in order to evaluate the present state of the art concerning energy efficiency in urban areas as well as respective retrofitting measures and their impact on the urban built environment. Based on detailed buildings' classification, parameter analysis and spatial analysis, the proposed methodology can be equally implemented by individual planners, municipalities, prefectures, other public authorities as well as by ministry bodies on a national level.

However, in order to ensure the efficiency of this tool data, various data sources are necessary, which are hard to retrieve. Crawford and French underline the need for exquisite and continuous collaboration between planners, regulators, development agencies and, last but not least, developers in order to achieve effective zero-carbon urban development at both micro- and macro-scale (170).

Unfortunately, in Greece little progress has been made towards this direction. The existing research on the residential building stock focuses on topics such as:

(a) Energy consumption estimation

(b) Building classification and

(c) Retrofit scenario assessment

Similarly, as regards residential energy consumption, most researchers examine heating and electricity demands ((117), (118), (119), (120), (173), (174)). Rapanos and Polemis (116), for instance, present the determinants of residential energy demand in Greece for the period 1965–1999. In a similar way, Papadopoulos et al. (80) perform a bottom-up building physics based feasibility study for Northern Greece. Additionally, Santamouris et al. (60) gather information about 1,110 households in Athens, by using a questionnaire that led to remarkable conclusions concerning the relation between socioeconomic characteristics and the energy behaviour of households. In correspondence with data collection strategies, Doukas et al. propose a methodology for the collection and elaboration of renewable energy sources, expenditure and end-use efficiency data ((175), (176), (177)) whilst Assimakopoulos describes a multivariate statistical technique (146) and Sardianou analyse survey statistical data so as to evaluate space heating factors that affect the Greek residential stock and propose efficient retrofit policies ((144), (145)). As regards building classification, Santamouris et al. study the energy performance of school buildings according to their typology, based on intelligent clustering techniques (147). Additionally, Balaras et al. study group single and multi-family (MF) buildings according to their year of construction (114) and analyse their energy performance as well as respective energy conservation measures using the (EPIQR) methodology (121). It is important to notice that no holistic assessment methodology has been presented yet, which eventually deals with the multi-complex issue of Greek cities. Thus in Greece, little progress has been made in terms of integrated energy related assessment tools, especially as regards urban areas.

Concluding, only few examples of extensive assessment tools have been published, although several researches on urban sustainability are based on GIS analysis. Hence, most of GIS based analysis concerning energy performance of cities, study only one evaluation parameter, such as RES implementation (178), or infrastructure and CO_2 emissions (179) or air pollution (180). The scope of this thesis is to redress these literature inadequacies by making a first step in exploring the concept of GIS-based multi-variable energy behaviour assessment of the urban residential buildings and the degree in which this concept impacts sustainable urban planning.

In current work, a case study is presented regarding the city of Thessaloniki, a typical urban Mediterranean region characterised mostly by residential multi-storey buildings, whilst emphasis is laid on the integration of GIS into the proposed assessment tool. The demonstrated evaluation GIS methodology builds on a bottom-up building physics and statistical based assessment tool as proposed earlier. The main scope of this methodology is to assess the energy behavioural pattern of the case study area and explore the potential for retrofit actions, concerning the buildings' envelope and the implementation of RES. The respective outcomes can form the foundation for a future targeted retrofit policy planning, which will address matters of energy conservation, environmental impact and overall feasibility assessment of such measures. The procedure is depicted in Fig. 5.1.

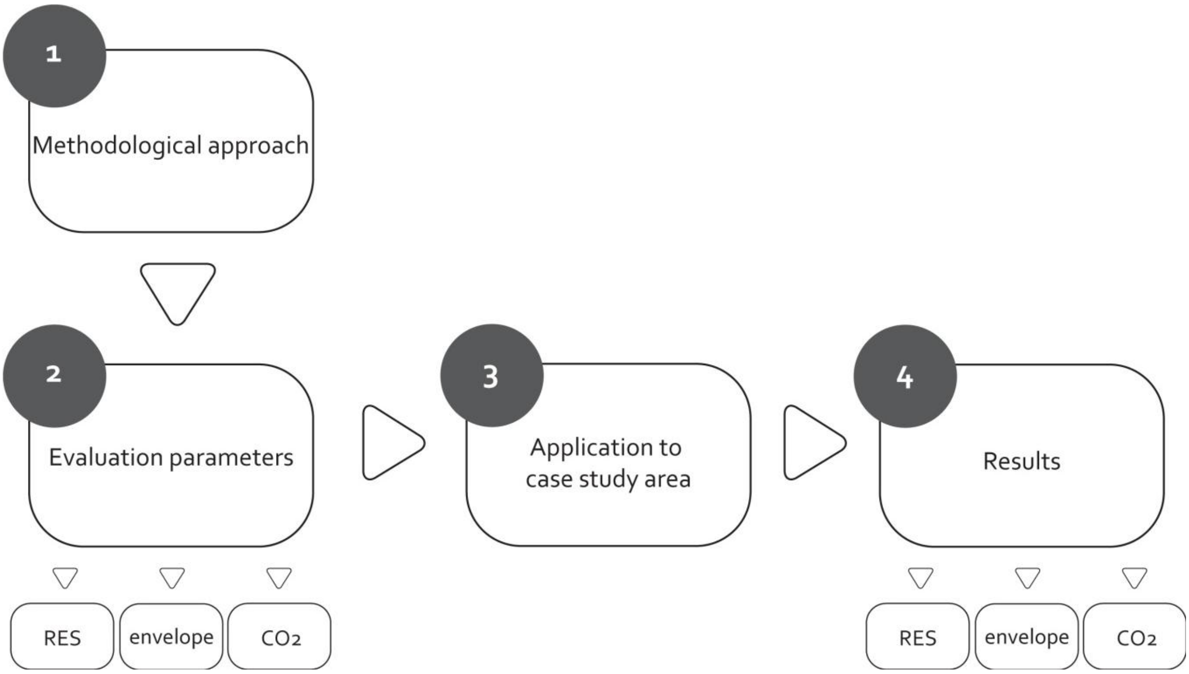


Fig. 5.1 Application of the methodological approach

5.1 Methodological approach

5.1.1 Theoretical background

The main goal of the proposed methodology is the development of a valid integrated assessment tool, applicable to the urban built environment, which will particularly focus on the residential stock and its energy performance. This tool is applied to a typical Greek city, namely Thessaloniki, the second largest city in the country. After a thorough elaboration of the available statistical data as well as a survey and literature research, a GIS based analysis is carried out concerning the structural typology of a typical urban environment, completing an impact assessment of various retrofitting scenarios on a city level (Fig. 5.2).

As depicted in Fig. 5.2 the proposed GIS based methodology is divided to two phases; during the first phase the urban built environment and the nature of the urban structure are analysed, whilst during the second one the effect of various energy conservation measures on the city's energy performance are examined.

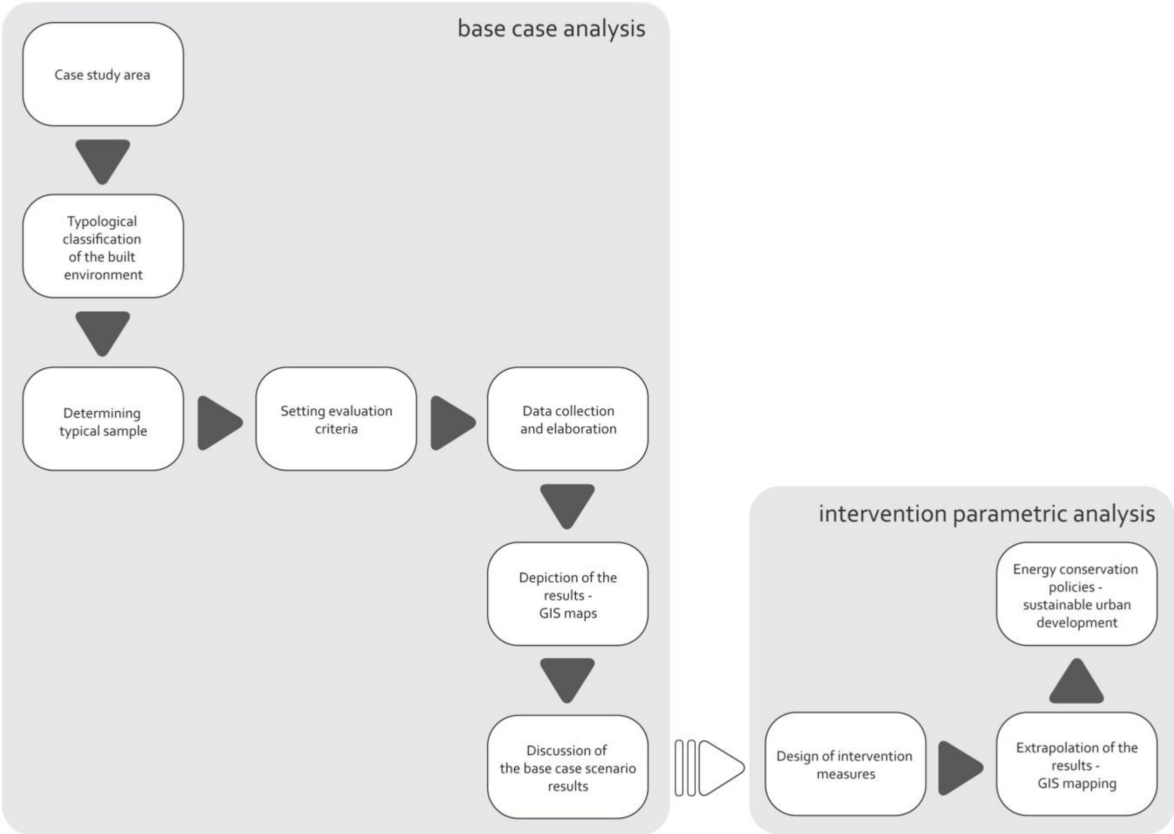


Fig. 5.2 Methodological approach of the GIS based assessment tool

In order to ensure safe conclusions, a thorough investigation of the building stock under study is of vital importance. Exclusively, this analysis will lead to a typological classification of the built urban environment that facilitates straightforward planning of retrofitting measures. Such methodological procedures presuppose access to a variety of data, exported from a combinative elaboration of miscellaneous information. Hence, likely to the most evaluation models, the efficiency of a bottom-up approach is strongly affected by the precision and diversity of the updated and relevant available data. The more direct access to these data is provided, the more pertinent conclusions can be drawn and, therefore, the more optimized interventions can be planned. However, in Greece there is rather limited access to such official GIS data, a drawback also underlined by Nghi and Kammeier (181). In this case, digital mapping information was mainly acquired by the corresponding municipalities. More specifically, they developed GIS maps, within the scheme of past European funded projects, importing information both on a building unit level and a building block level, which mainly concerns infrastructure construction parameters, buildings' and land uses as well as public and green spaces. Inevitably, the elaboration of this information can lead to further conclusions that thereafter can easily be linked to public services and urban management. Moreover, enriching these data with national based information and scientific research outcomes will definitely set out the broader spectrum for the application of the proposed methodology.

5.1.2 GIS analysis

Urban spatial databases contain both geometry data (coordinates and topological information) and attribute data, i.e., information describing the properties of geometrical spatial objects such as points, lines and areas, making Geographical Information Systems (GIS) an indispensable tool for handling these datasets (182). GIS are defined inter alia as a set of computer tools for the storage, retrieval, analysis and display of spatial data. They can also be used to supply data to numerical models of spatially explicit urban environmental problems and processes as well as to display the results of these models as cartographically acceptable screen and hard copy images (183).

Hence, in studies conducted in order to determine the availability of renewable resources, GIS are necessary since they can be used both in data processing and in the demonstration of their local impacts ((184), (185)). Apart from the spatiotemporal analyses and visualisation of resources and demand, GIS can also function as a Decision Support System when implementing location-specific renewable energy technologies (186). Furthermore, due to the spatially explicit information stored and processed within the GIS, urban planners and managers have the potential to address problems at multiple scales of the urban fridge landscape. At a city level for example, they can conceive and plan interventions at a block, street, neighbourhood scale as well as at a building level to propose and design specific conservation and enhancement interventions that pay particular attention to the ecological and energy dimensions (187).

5.1.2.1 State of the art

Examples concerning decentralised energy planning at district level, energy and environmental planning models and resource energy planning models from Germany (188), China (189), India (190), UK (178), are presented. These examples underline the important role of GIS based analysis in energy modelling in a broad spectrum of research fields, such as sustainable planning of rural areas, implementation of RES, wind energy and solar energy planning in urban areas, hence a broad spectrum of research field (191). Furthermore, GIS can be used for urban planning issues (192), occupancy behaviour in residential buildings (193), green roof studies and their impact on urban watershed (194), ecotourism (195) as well as the potential for RES implementation, such as photovoltaic and various solar systems ((178), (189), (160), (196)). GIS can be an important assessment tool in the fields of sustainable accessibility (197), of stream power (198), in climatic assessment methodologies (199), CO_2 emissions produced by vehicles (179), in the evaluation of thermal comfort conditions in urban public spaces (200) and air-pollution in the urban environment (180) as well as the assessment of landscape and ecological connectivity at regional scale (201).

In the same line of thought, Xia et al. used GIS for the assessment of spatial restructuring of land use patterns in fast growing regions (202), whilst Ross et al. used it in order to estimate spatially explicit analysis of habitat value (203). Furthermore, Oh presents a methodological approach based on GIS and computer graphics simulation techniques in order to manage urban landscape information and visualise the outcomes of development assignments, called LandScape Information System (LSIS) (204). Similarly, Stevens et al. developed a GIS based tool in order to predict urban growth, called iCity - Irregular City (205) .

Concluding, apart from the research regarding energy behaviour of certain buildings' typologies and top-down macro-economic assessment methodologies the majority of the studies are based on plain energy simulation software and generalised census results. With respect to the aforementioned urban planning trends proposed by the global research community, this is a rather outdated approach, which cannot carry on supporting future sustainable urban development policies. Hence, new flexible and effective tools must be developed, which will efficiently promote the introduction of large scale energy efficiency measures. In this line of thought, the methodology proposed, includes the elaboration of GIS data outcomes, which will provide us with important information as regards the implementation of various retrofit scenarios, specially designed for cities and urban built environment. The proposed methodology is rather flexible and can therefore be applied for different city structure typologies.

In this framework, the proposed GIS methodology aims at the determination of the energy profile for a larger built environment, thus not only for a building unit. In order to achieve this, the GIS data are elaborated in 3D format and can deliver results for typological characteristics that are described in following chapters.

5.2 Evaluation parameters

In order to examine the energy performance of the urban buildings and plan the suitable retrofit measures, the definition of the necessary evaluation parameters is prerequisite. Within this context, GIS is applied allowing us to analyse the potential for renewable energy systems implementation, interventions concerning the buildings' envelope as well as CO_2 emissions based on energy performance of the buildings under study. The requested variables are depicted in Fig. 5.3.

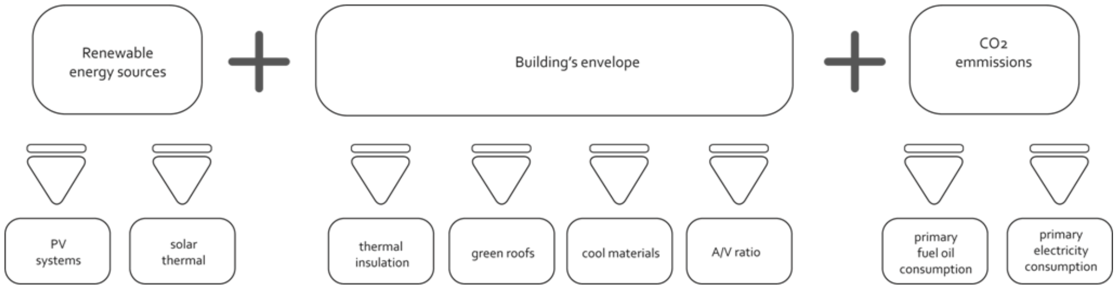


Fig. 5.3 Evaluation criteria according to the GIS methodology

In current work, analysis is carried out regarding energy demands and consumptions of a typical existing urban region, namely the city of Thessaloniki in Northern Greece, by applying the described GIS formula. The most important results, which are presented in the following sections, will eventually contribute to the development of an efficient decision making policy concerning energy interventions scenarios in the overall building sector.

5.2.1 RES implementation

As far as photovoltaic (PV) and solar water heating (SWH) systems are concerned, this chapter demonstrates a methodological approach for solar resource availability in urban areas, which combines the capabilities of GIS, aerial object-specific image recognition and existing urban morphology characteristics determination (e.g. density of building blocks, building site layouts, buildings' orientation, height, geometrical shape and envelope configuration etc). The approach firstly aims at defining solar architecturally suitable rooftops for solar technologies in a typical Greek urban region, such as the city of Thessaloniki. Secondly, it indents to compensate to a degree for the lack of methodologies that have already been developed for those purposes and presented in past literature.

Within this framework, it should be remarked that the complexity of the urban environment and building heterogeneity requires in general assumptions and input data for the solar energy use computation to be set and applied, which will conclude to safe proposals and information and will not mislead researchers and energy policy makers. Furthermore, the key to increase the significance of that kind of research is, as also supported by Gadsden (160), to develop an attractive alternative method, which will extract acceptably accurate values for solar energy from digital urban maps, without the need for time-consuming and expensive site surveys.

Therefore, the primary objective of this research is the recognition of the most significant construction limiting parameters that interfere with solar energy utilisation in residential MF - building typologies, concerning the majority of urban building stock in Greece. The second objective regards the formulation of an accepted and validated process and a comprehensive set of rules of thumb for the approximation of suitable areas for PV and SWH use under architectural and solar aspects, which initially, involve the determination of roof (and façade, in future analysis) architecturally unavailable areas and thereafter the approximation of unsuitable shaded areas, by using digital maps. Finally, the methodology attempts to account for potential power and energy output by PV and SWH systems compared to baseline energy demands of MF - building typologies for electricity and domestic hot water (DHW).

5.2.1.1 Solar potential on roof-top areas

Most of the past researches do not involve thorough quantifications of suitable areas for solar systems on buildings, and especially for roof surfaces, for which no direct data and information exist. Thus, they can only be defined in an accurate way through individual in situ surveys, which are undoubtedly expensive and time-consuming. However, several authors estimate suitable solar roof-top areas for municipality territories or even for entire country regions, by using aerial roof element image recognition, GIS maps and CORINE land use data, initiating from the examination of a representative sample of existing buildings ((206), (207), (178)). Within the same context, the methodological approach for the approximation of solar roof-top areas in urban regions is developed as follows:

At first combined aerial images with GIS maps are used (Fig. 5.4), which allow the recognition of roof objects (e.g. elevator shaft, chimneys, HVAC, parapet etc) as well as penthouses. In this way, the available (A_a) roof-top areas for PV and SWH technologies are computed, by subtracting the area of these objects from the gross built-up areas. This task is carried out by taking advantage of useful measurement tools provided by available GIS maps (Fig. 5.5). Of course, the recognition of roof elements cannot be avoided, as it is an unpredictable parameter that varies among buildings. Therefore aerial image definition is needed at least for an adequate sample, which should be representative of the under study building typologies, in this case MF-buildings. Afterwards, the results can be scaled for the whole urban region. On the contrary, the gross built-up areas are directly obtained from GIS maps, as they contain roof print shape files with the outline of all buildings.

Secondly, when it comes to the estimation of the shaded areas, the common criterion implemented is that the solar systems will optimally operate for at least a four hour interval during winter solstice. This will result in the estimation of the overall solar architecturally suitable areas (S_a) and solar utilisation factor (SU_f) per built area or capita. It should be noted that this criterion is stricter for PV systems than for SWH systems, due to the inevitable higher operational sensitivity of the former when shadows are presented in the installation field. More specifically, the shading factors are estimated, by simply setting the following roof configuration parameters: (a) the placement of the staircase, elevator shaft and chimneys; (b) the orientation, the perimeter and the shape (rectangular, angular or polymorphic) of the roof and (c) the ratio of roof's near south facing side to east/west facing side as well as the fraction of roof perimeter to gross area. Last but not least, the absolute location of each building is also taken into consideration, providing information whether it is detached or attached to higher neighbouring buildings on its near south, well orientated facing side. In this case, available GIS information is used concerning the number of floors and the total height of each building. All the above parameters can be directly exported with the aid of GIS maps, given that roof object-image recognition is completed.

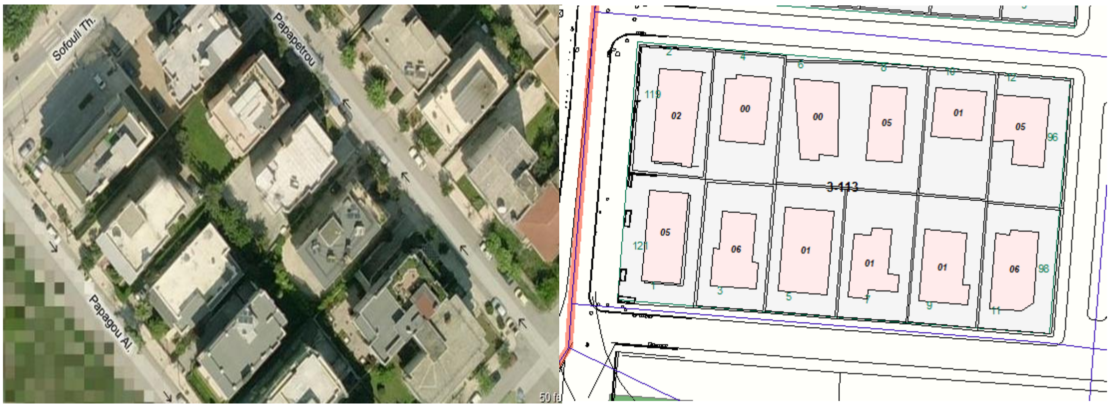


Fig. 5.4 Aerial image (left) of a typical building block, where roof elements, such as stairwell and elevator shaft are easily recognized and defined and the respective GIS image (right)

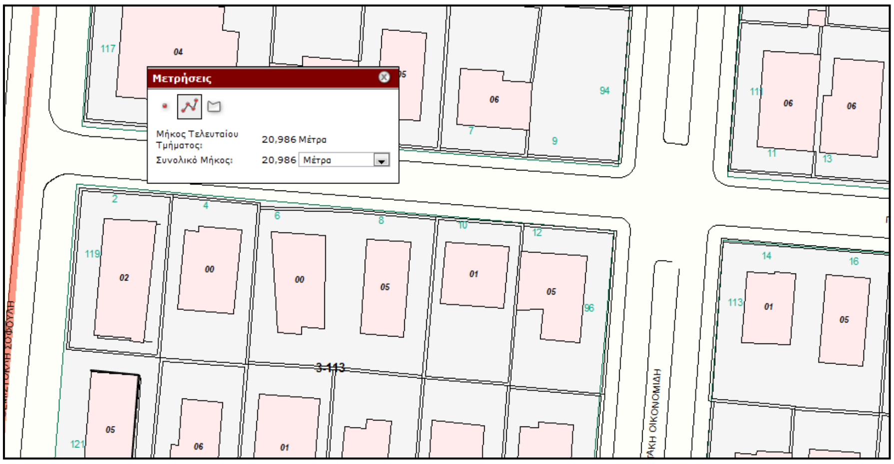


Fig. 5.5 The internal window provides the user with surface area and perimeter length measurement tools

Apparently, the core of the presented methodology includes an efficient classification of typical roofs of MF-buildings, determining all the above construction parameters which influence total solar potential on the buildings' roof areas. Finally, inclined roofs are not examined in this work as they regard a limited fraction of existing roofs in building stock in Greece and can be more straightforwardly classified and elaborated compared to flat roofs.

5.2.1.2 Energy outputs and demands

The estimation of solar utilisation potential in an urban area from the start aims at developing a "solar energy planning" scheme (160), which will allow the energy policy decision makers implement efficient measures for further diffusion of solar systems in building stock as well as optimise the design of newly constructed urban areas to achieve net zero energy consumptions. Still, in order to accomplish this objective, apart from the solar suitable areas, information about the overall energy and power potential of solar resources is needed. Moreover, the degree to which residential baseline energy demands are eventually covered must be determined. For that purpose the four typical MF-buildings presented earlier (Table 4.1) were used. They facilitate the evaluation of the total energy demands for electric appliances, lighting systems and DHW for the whole urban area, by a simple recognition of their typologies in GIS maps. All other prerequisite data for the energy calculations, related to the total built area, exterior surface area, number of storeys and population density per building, are already included in the database of GIS, compensating for individual audits.

As far as PV systems are concerned, the analysis is carried out following a similar approach to Ordonez's et al. (207). In other words, two different installation formulations, namely two overall installation coefficients for PV systems on roofs are assumed, which are based on two roof orientation scenarios (south or southeast/southwest) and the criterion of nil mutual shadowing between parallel PV series at midday during winter solstice, for annually optimal inclination angle and common dimensions assumed for PV panels. Thereafter, the solar suitable areas are multiplied by a hypothetical mean efficiency factor for multi or mono-crystalline silicon PV panels, which are available in the current market, so as to account for the PV potential peak capacity (in kW) per building. Afterwards, by using the well-known online utility tool of PVGIS (208) an average energy output per kWp can easily be exported, taking into consideration set system losses due to wiring, inverter, cell temperature increase and PV panel mismatch. Finally, the results are compared to typical electricity energy demands.

When it comes to the SWH systems, the calculation process until the average efficiency consideration is similar to the PV systems' approach, with one major difference which concerns the higher inclination angle (winter's optimal) of SWH panels. Furthermore, the solar DHW fraction is computed using the widely used f-Chart method (209). The input data for the f-Chart method are the monthly values of incident solar radiation, ambient temperature, water mains temperature and DHW loads, variables all of which are derived from the Technical Directives of Greek Regulation of Energy Efficiency of buildings.

5.2.2 Building envelope

The building's envelope is without doubt the most crucial factor affecting building's energy behaviour. Therefore, primary objective related to the building's envelope is the computation of the average vertical and horizontal surfaces of the built environment based on GIS tools. The proposed procedure allows the determination of the potential retrofit measures as well as the relevant costs produced. More specifically, the available vertical surfaces are defined according to the year of construction and the construction typology. In other words, in correspondence with the building's position (detached or attached to neighbouring buildings), the exterior vertical surfaces are approximated. Similarly, horizontal surfaces are calculated, considering available roof and Pilotis areas. Following the exterior vertical and horizontal surface areas, the total envelope's surface area of the buildings under study is accounted for.

The outcomes of this approach can significantly influence energy efficiency policies, as they provide vital information about the mean amount of the insulation materials needed for buildings' energy refurbishment. Moreover, they can aid the selection of most efficient type of green roof system as well as the specification of appropriate shading technologies and other envelope related energy saving techniques. In this context, a holistic approach of retrofit scenarios and the associated subsidy and implementation expenses can be completed combined with an extensive comparison of the estimated energy conservation outputs.

Table 5.1 The scope of the study regarding the buildings' envelope based on various data sources and evaluation criteria

Result	Evaluation parameters	Data source	Applied method	Depiction format
A/V ratio	buildings' volume	GIS maps	(building's height [number of floors X 3m] + ground floor [height 4.5m]) * building's surface	Table
	construction system (attached or detached buildings)	GIS maps and El. Stat. data	vertical building's surfaces (building's width X height)	
	pilotis or ground floor	GIS maps and El. Stat. data	horizontal building's surfaces (horizontal roofs and pilotis floors)	
mean A/V ratio	as described above			Table
mean energy consumption per building class	correlation of the sample with the typical buildings	chapter 4	according to the buildings': - typology - year of construction	Table and map
CO_2 emissions	correlation of the sample with the typical buildings	chapter 4	according to the buildings': - typology - year of construction	Table and map
available vertical and horizontal surfaces for retrofit measures	for: - green roofs - thermal insulation - openings - PCMs and cool materials	chapter 4	according to the buildings': - typology - year of construction	Table and map

5.2.3 Green roofs

The existence of green areas in the urban space is beyond doubt of great importance. Green is valuable for the atmosphere, whilst it offers cooling comfort during summer, shelter during rainfalls and last but not least improves cities' aesthetics. In this framework, an important aspect is the availability of free space for the planting of green in built-up areas. Given the fact that vegetation can control air pollution, it is often difficult to plant trees in dense cities due to the lack of free spaces (210). Alternatively, green roofs can function as a viable solution to this problem, whereas the cost of such a venture could be justified in the future considering the environmental benefits (210). Similarly, as regards Greek cities, urban density could stifle refurbishment potential by means of green roofs installation. However, above ground level at the level of rooftops, an extreme potential for green roofs installation is revealed. By consequence, green roofs are considered a short and less expensive way of incorporating green into cities, rather than demolishing entire building blocks in order to create larger green areas. Furthermore, the fact that Greek MF – buildings are equipped with balconies has more or less deadened the vital role of rooftops.

Besides architectural perspectives, green roofs are favoured for various reasons such as:

(a) air pollution removal ((210), (211), (212)),
(b) urban reconciliation ecology (213),
(c) sound absorption ((214), (215)),
(d) reduced energy consumption in buildings ((216), (217), (218), (219), (220)),
(e) rainwater runoff solutions ((221), (222), (223)) and
(f) their overall life cycle performance (224).

Hence, as in this case any refurbishment interventions do not only concern the building unit but also the city as a whole. The implementation of green roofs is inevitably a crucial saving energy option. Finally, based on the buildings' age and the corresponding statics of the construction, conclusions can be easily drawn associated with the type of the green roof that can be applied.

5.2.4 Opaque surfaces and openings

Thermal insulation measures are not a new retrofit approach, though popular till today. In particular, the UK Department of the Environment endorsed the 'Homes Insulation Scheme' by promoting improved energy behaviours of loft through thermal insulation technologies (225). Moreover, energy consumption can be highly reduced by the implementation of thermal insulation materials (226), whilst the study concerning the environmental impact of such studies is highly important (227). The exact amount of energy consumption reduction varies according to the optimum thickness of the material that is determined based on the construction characteristics of each building and the respective climatic conditions.

In order to evaluate the effect of this kind of measures and extrapolate the respective energy conservation results to city scale, several base case scenarios were examined, performing in-situ measurements and completing dynamic energy simulations with the aid of Energy Plus software. In this line of thought, thermal insulation, Phase Change Materials (PCMs) as well as cool materials can be studied by means of minimising heat island effect and reducing cooling and thermal loads of buildings (228).

Besides the retrospective implementation of thermal insulation on vertical and horizontal surfaces, the implementation of cool materials can also be assessed. Hence, targeting at the heating loads reduction, cool materials could be applied on roofs and walls, whilst the benefits of thermal insulation and cool coatings could be exploited.

More specifically, based on Table 5.2, the available vertical and horizontal surfaces should be set so as to decide for respective energy interventions. At this point, the estimation of the exposed opaque vertical surfaces of the buildings, besides the width and the height of the facades and the openings to wall ratio is inevitably needed. This information, however, derives from typical buildings. Hence, the calculations are based on the following equation:

$S_{va} = S_v - S_o$ (1)

where

S_{va} is the net vertical surface area (opaque building's surface)

S_v is the total vertical surface area

S_o is the openings' surface

The S_o values for four typical buildings are depicted in Table 5.2.

Table 5.2 Window to wall ratio of the typical buildings

	MF1	**MF2**	**MF3**	**MF4**
window to wall ratio [%]	24.42	21.81	22.41	13.37

With respect to the buildings' openings the approximation of their total surface area, is a complex process, especially when it comes to GIS data analysis. Due to that reason, information associated with the exact surface of the openings is prerequisite in order to be imported to the GIS data base for each building. For that purpose, two methods can be adopted; the first concerns thorough in situ measurements and detailed inspection of the buildings' facades. In turn, the obtained measured data can provide a 3D GIS database, which will reflect the existing façade configuration of buildings. It becomes obvious that this procedure concerns a time-consuming and strict task, which is not related to the character of the proposed flexible methodology whatsoever.

Therefore, for reasons of brevity a second approach is efficiently implemented; after the correlation of the GIS buildings with the already elaborated typical building sample, all information is easily exported based on their analysis, described in the previous section. This method is undoubtedly not as accurate as an in situ detailed survey, but it does lead to representative outcomes regarding retrofit policy making decisions.

5.2.5 Built form and A/V ratio

Apart from ventilation losses, energy losses also occur through the building's envelope that is exposed to the environment. It is well known that the greater the external surface areas are, the higher the energy losses that take place. The A/V ratio was introduced in order to describe the fraction of the total building's envelope surface A to its conditioned volume V. Apparently, it is the best indicator that correlates the structure and form of a building with its energetic behavioural profile (229).

Thus, the building form eventually affects energy consumption; Wright argues that the operation profile of households determines the overall energy behaviour of the building to a higher degree than its built form does. However, he also states that larger houses tend to be less energy efficient (230). Hence, assuming identical operation profiles for two different forms of buildings, the one with a larger A/V ratio, in other words the less compact one, will consume more energy, according to its orientation, the climatic conditions and the surrounding built environment.

Moreover, the relation between urban texture based on the surface-to-volume ratio, by means of its impact on the buildings' energy performance, should always be examined as a part of a built environment and not as "self-defined entities" (231). Within that scheme, indenting to plan large scale intervention measures on a national basis for the existing building stock, residential or not, requires a systematic study of the urban texture and the urban typology. A typical example is the design of retrospective thermal insulation implementation, depending on the urban buildings' envelope and the structure of the built environment. In that sense, this methodological approach aims at integrating an analysis of the stock as regards, detachment, attachment, orientation and height of the buildings, in order to avoid inaccuracies concerning the overall energy performance of the city.

Concerning heating loads, the overall energy performance of the buildings in the densely built Greek city centres, can be positively influenced when constructed in a row-system. In particular, Greek cities are typical for their MF – buildings, constructed in row-system, a parameter, which determines certain A/V ratios as long as it influences energy performance of the buildings under study.

Table 5.3 Maximum allowed mean thermal transmittance of the building's envelope U_m according to the A/V ratio and the climatic zone of Greece [W/m^2K] (18)

A/V ratio [m^{-1}]	Climatic Zone A	Climatic Zone B	Climatic Zone C	Climatic Zone D
≤ 0.2	1.26	1.14	1.05	0.96
0.3	1.20	1.09	1.00	0.92
0.4	1.15	1.03	0.95	0.87
0.5	1.09	0.98	0.90	0.83
0.6	1.03	0.93	0.86	0.78
0.7	0.98	0.88	0.81	0.73
0.8	0.92	0.83	0.76	0.69
0.9	0.86	0.78	0.71	0.64
≥ 1.0	0.81	0.73	0.66	0.60

In Table 5.3 the maximum allowed values regarding the U_m of the building's envelope are depicted, based on the specifications of the Greek Regulation of Energy Efficiency of Buildings.

5.2.6 Overall energy balance

The estimation of the energy behaviour of urban buildings is a complicated and challenging objective. There are numerous examples of fulfilled research efforts each referring to various assessment tools, based on available data since the early 70s ((232),(48), (233), (234), (235), (236), (237), (238),(79), (239), (240)). With respect to the residential building sector, the determination of the energy performance becomes even harder to comprehend due to the various occupancy profiles and the diverse buildings' typologies, factors that are well acknowledged by several researchers (241).

The scope of this thesis is to provide the proper assessment methodological tool for the energy behaviour of building blocks in urban regions. Given the fact that the inhabitant concentration in Greek cities is extremely high, general data regarding the energy consumption cannot contribute to a safe adoption of sustainable energy upgrading measures. This GIS – based approach aims at specifying the urban energy behaviour profile and consequently assisting researchers and public bodies to plan energy refurbishment measures in a more appropriate manner. Hence, taking into consideration the typical MF - buildings, the energy performance of the corresponding building classes is initially defined. Thereafter, the overall energy behaviour of the residential stock is ultimately evaluated so that respective retrofit scenarios can be safely proposed and designed.

5.3 Case study area

The urban fabric of Thessaloniki was chosen as a case study area. Thessaloniki is the second largest city in the country; it is situated in Northern Greece and enumerates 1,100,000 inhabitants. Due to its geographical position and its commercial port, Thessaloniki is Greece's second major economic, industrial, commercial and political centre as well as a major transportation hub of south-eastern Europe and the Balkan area with a very long history. The city was founded around 315 BC by King Cassander of Macedonia and was named after his wife Thessalonike, a half-sister of Alexander the Great. After the era of the Macedonian kingdom Thessaloniki became a city of the Roman Republic in 168 BC and in 379 the capital of the new Prefecture of Illyricum. The byzantine period was followed by the long ottoman rule during the period 1432 – 1912.

With respect to its architectural influences, it is important to notice that the historic centre was completely destroyed in 1917 due to a disastrous fire. Thomas Mawson and Ernest Hebrard undertook to redesign it, based on the city's Byzantine historical influences. Despite the fact that their reconstruction proposals were not fully implemented, they influenced numerous buildings' and urban planning decisions throughout the 20th century, regardless of the inevitable adaptations in order to adjust to the population explosion of the last 50 years. Hence, architecture in Thessaloniki is the direct result of its long history and the various architectural historical origins. Beyond the ancient Greek monuments, several notable Byzantine monuments as well as numerous Ottoman and Sephardic Jewish structures adorn the centre of the city.

Furthermore, apart from the historic monuments in Thessaloniki, 80% of the buildings have an absolute residential use, whilst 90% of the buildings with mixed use refer to MF – buildings with mainly household usage combined with shops or offices on the ground floors and practices in upper floors.

Following the energy efficiency study of typical buildings, the next target to reach is to connect the acquired data with the overall urban environment, based on the methodological approach proposed earlier in this thesis. For that purpose, digital maps of the two largest urban districts of Thessaloniki were analysed using the Arc-GIS program. These maps contained data regarding building unit, plot areas and public spaces (streets, pedestrians, parks, etc.). Data concerning the land use, date of construction, built area and heights were available. Therefore, the analysis focused on all these aspects, which apparently affect the energy performance of Greek MF-Buildings.

The case study area of the greater urban field of Thessaloniki consists of the greater part of the Municipality of Thessaloniki and the second largest Municipality, namely Kalamaria (Fig. 5.6).

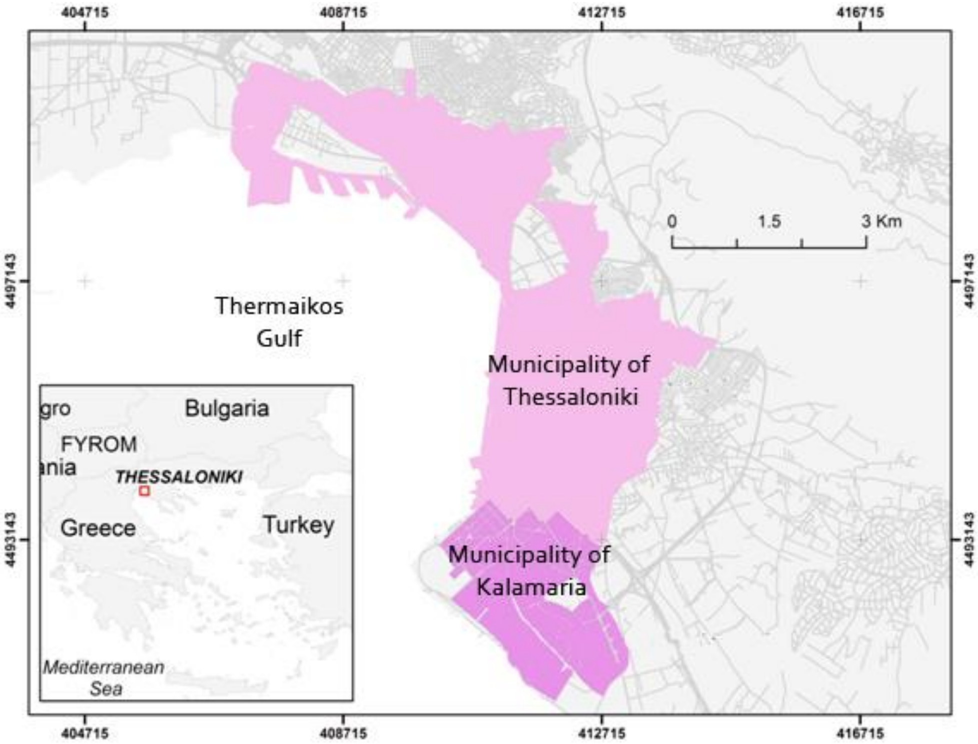


Fig. 5.6 Case study areas

5.3.1 Available data

Data availability combined with accurate digitised GIS urban maps is undoubtedly the most crucial parameter in order to efficiently apply the presented methodology for building's energy behaviour assessment and RES potential examination in urban areas. In this case study all the elaborations, developed in the GIS environment relied on spatial explicit large scale maps of the building footprints and city blocks, which were retrieved by the Municipality of Thessaloniki (242) and the Municipality of Kalamaria (243).

The spatial database of the city plan maps were enriched with census information acquired by National Statistical Authority related to the land use, the height and the construction systems available mostly on building unit level for the Municipality of Kalamaria and on city block level for the Municipality of Thessaloniki.

The ESRI ArcGIS 9.3.1 environment was used at first for processing and analysing the urban datasets. The Trimble eCognition 8.0 mainly employed within the framework of the Geographic Object-Based Image Analysis (GEOBIA), a sub-discipline of GISscience (244), was used for building classification in both municipalities (Fig. 5.7). The recently developed eCognition software exploited so far for segmentation and object-based classification of remote sensing images, is suited and has the potential to be adopted widely by end-users to build landscape level-solutions for environmental and social studies with object based investigation using non-image spatial data (245).

To generate objects corresponding to building footprints, fine resolution (0,1 meter) raster images covering the whole extent of the municipalities were generated with ArcGIS Spatial Analyst. Finally, the classification results were exported in a vector format to the ArcGIS environment and used in the subsequent modelling approach.

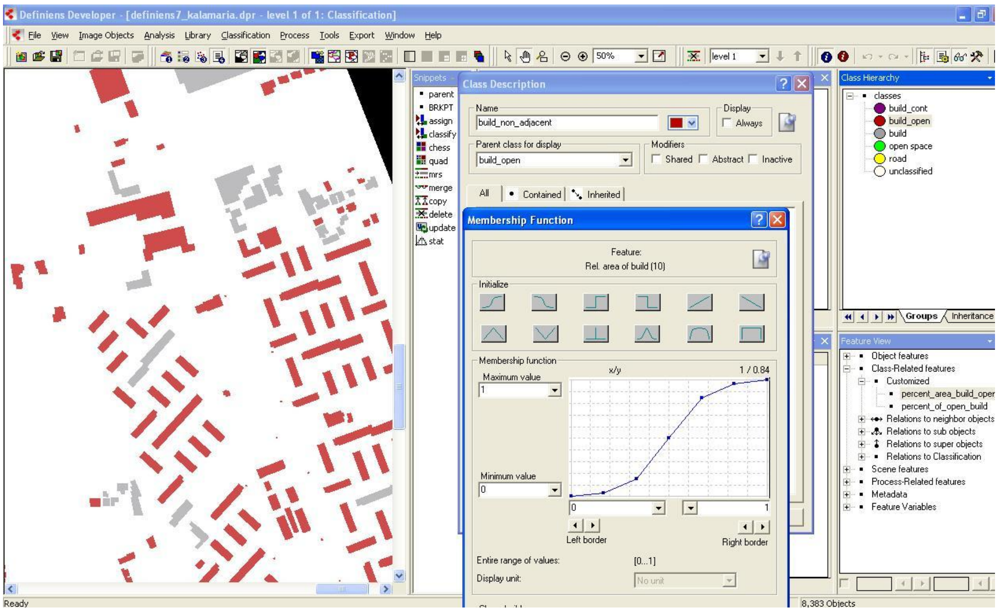


Fig. 5.7 The eCognition software tool

In this framework, this research aims ultimately at presenting a methodological approach that was developed to compensate for inadequate statistical and GIS data and last but not least at giving the opportunity for Authorities, for the first time in Greece, to use GIS systems combined with RES potential estimation, building stock energy behaviour evaluation and optimal retrofitting measures analysis for urban regions.

5.4 Results

5.4.1 RES implementation

5.4.1.1 Assumptions and input data

Concerning PV and SWH, there are two groups of assumptions and input data that are considered initially with respect to the Thessaloniki case study urban area.

The first group concerns the architectural suitable (A_a) roof areas that are already accurately defined for a representative sample of typical MF-buildings in the urban area of Thessaloniki by applying image-roof object recognition using aerial maps (246). The derived unavailable surfaces are then averaged and scaled for the whole urban area. The most important results, expressed as a fraction of gross roof (G_a) areas, are depicted in Table 5.4. At a glance, one can firstly notice the average unavailable area fraction, which reaches nearly 50% of the gross area and secondly the high area fraction covered by perimeter safety area that is mandatory for RES roof applications according to current building regulations.

The remaining results regarding the shading effects and the influence of shaded areas. In particular, the latter are defined when the absolute position for each building is recognised, in order to input the proper shading factor. The state of attachment to higher or lower neighbouring buildings is taken into consideration, in terms of the buildings' near southern ("well-orientated") sides. In Table 5.5 the shading factor as a fraction of architecturally available (A_a) areas is depicted, for four categories of building positions.

Table 5.4 Averaged unavailable roof element areas as a fraction of gross roof (G_a) area, for the examined sample of MF-buildings (246)

Roof unavailable areas	Staircase/elevator shaft and chimney area (Staf) (%)	Perimeter safety area (0.5 m wide across roof perimeter) (Safaf) (%)	Penthouse terrace area (considered only if exists) (Peaf) (%)	Rest of roof element areas: storage rooms; perimeter parapet (REaf) (%)
Mean values	15.0	24.1	5.1	7.1

Table 5.5 Averaged shading factor as a fraction of architecturally available (A_a) areas, according to building's position, for the examined sample of MF-buildings (246)

Building's position	Detached (%)	Attached to one storey higher building* (%)	Attached to two storey higher building* (%)	Attached to at least three storey higher building* (%)
Shading factor (Shf)	71.5	91.9	97.2	98.6

** Typical storey height equals to 3 m*

The second group of input variables that is needed in order to complete solar potential computations for the selected city of Thessaloniki include the electricity and DHW production by the estimated PV and SWH systems as well as the electricity and DHW demands normalised per building area.

As far as PV system electricity production is concerned, a mean PV efficiency of 14.0% for typical PV modules is taken into consideration, as well as for other system losses (cables, inverter etc). Moreover, PVGIS calculations include temperature and angular reflectance losses according to examined location's climatic conditions. Furthermore, roof-top PV panels are considered to be free-standing with optimal inclination (30^o) and south orientation. As regards the roof potential, the actual installed PV surface is assumed to cover approximately 50% of the computed solar suitable (S_a) roof areas, due to the applied criterion of negligible mutual shading losses between parallel PV series. The final PV area is obtained based on the VSA at noon during winter solstice and fixed typical dimensions for PV panels, e.g. 1580x808 mm. Finally, the annual electricity consumptions for electric appliances and lighting systems per building area are derived from MF-building simulation results and attributed to the total built urban area according to their typological characteristics, so as to account for the annual solar electricity fraction provided by the computed PV systems (Table 5.6).

Table 5.6 Annual electrical consumptions for lighting systems and electrical appliances (kWh/m^2) for the examined sample of MF-buildings (246)

MF-building typology	MF1	MF2	MF3	MF4
Annual electrical consumptions for lighting systems and electrical appliances (kWh/m^2)	38.38	39.98	39.61	42.94

Regarding the SWH systems, the actual installation factor for roof areas follows the same estimation pattern compared to PV systems. However, the SWH panels are theoretically installed at an inclination angle of 45^o (optimal for winter), so the required distance in order to avoid shadow effects between parallel series is inevitably longer. Unfortunately, this parameter leads to a reduced overall roof utilisation factor of SWH systems approximately by 7% compared to PV. As for the approximation of the energy loads for DHW and the annual solar DHW solar fraction, the f-chart method is applied. The necessary input data involve monthly incident solar radiation information for fixed inclination and orientation, water mains and ambient temperatures as well as DHW demands per person, for which population density per building block is taken into consideration, acquired from the GIS database. Climatic data along with the other prerequisite data are provided by the national Technical Directives ((18), (20)). Further details are given in Table 5.7.

Table 5.7 Monthly ambient and water mains temperatures, DHW demands per person and solar DHW fraction for one person's needs provided by 1 m^2 south facing SWH panel with 45° inclination angle in the region of Thessaloniki (20).

Months	Ambient temperature (°C)	Water mains temperature (°C)	DHW demands per person (kWh/person)	Solar DHW fraction for one person's demands provided by 1 m^2 south facing SWH panel with 45° inclination angle (%)
Jan	5.3	6.5	75.61	63.72
Feb	6.8	7.3	69.27	70.76
Mar	9.8	9.4	72.92	81.40
Apr	14.3	13.2	63.97	99.50
May	19.7	17.6	58.19	114.47
Jun	24.5	21.9	48.84	128.87
Jul	26.8	24.3	46.16	136.23
Aug	26.2	24.6	45.62	135.06
Sept	21.9	22.0	48.67	122.63
Oct	16.3	17.7	58.01	97.42
Nov	11.1	12.7	64.83	73.92
Dec	6.9	8.6	74.36	61.08
Mean values	15.8	15.5	60.54	98.75

5.4.1.2 Solar potential results

The most significant outcomes regarding solar potential on roof-top areas are formed as follows; initially the estimated PV potential capacity of buildings is presented combined with building stock fractions related to four PV system classes of capacity, namely unsuitable roofs (0.0-1.0 kWp), one phase grid-connected PV systems (1.0-5.0 kWp), three-phase grid-connected PV systems (5.0-10.0 kWp) and PV systems over 10.0 kWp. The latter class refers to PV systems, which are not eligible for obtaining the current tax-free feed-in tariff (0.55 €/kWh) for grid-connected building's applied PV systems, set by a national special PV development program of the Ministry of Environment and Climate Change, as their capacity exceeds the fixed maximum cap of 10 kWp. In current work, all building applied PV systems that are examined, are assumed to be grid-connected in order to be economic profitable, although, the annual solar electricity fraction is estimated as if the PV systems feed MF-buildings' own electricity consumptions for lighting and electrical appliances. In that case, systems over 10 kWp are the most efficient in terms of saving electrical energy and eventually reducing daily peak electrical power.

More specifically, from the following tables (Table 5.8, Table 5.9) it is easily derived that the majority of systems consider either unsuitable roofs or single-phase systems. In the case of Municipality of Thessaloniki over 50% of the available flat roofs are unsuitable, whereas there is a 45.68% which can feed 1 to 5 kWp into the grid, under only optimal operational standard test conditions. Moreover, there is approximately a 2.5% which refers to three-phase PV systems, indicating that the predominant row system in building blocks as well as the miscellaneous heights of adjacent buildings in this specific urban area mitigates significantly solar architecturally suitable top-roof areas. This fact leads, additionally, to a limited annual solar electricity fraction (<5%) for the largest proportion of the building stock (45.56%), given that the shading problems are more intense, the potential capacity is low whilst there are large built areas per building (higher buildings), meaning high overall electrical consumptions per building. On the contrary, when it comes to the Municipality of Kalamaria with the predominant detached construction system, the rate of suitable roofs reaches 64.54%. Respectively, the annual solar electricity fraction is over 10% and it is provided at least by the 35.7% of the examined buildings. The same variable does not exceed 9.94% in the Municipality of Thessaloniki.

Table 5.8. PV potential capacity on roof-top areas

	PV capacity (kWp)	Number of buildings	Building stock fraction
Municipality of Thessaloniki	0.0-1.0 (unsuitable roofs)	9,076	51.88%
	1.0-5.0	7,992	45.68%
	5.0-10.0	382	2.18%
	Over 10.0	44	0.25%
	Total	17,494	100.00%
Municipality of Kalamaria	0.0-1.0 (unsuitable roofs)	2,020	33.74%
	1.0-5.0	3,864	64.54%
	5.0-10.0	103	1.72%
	Over 10.0	0	0.00%
	Total	5,987	100.00%

Table 5.9. Annual solar electricity fraction by roof-top PV systems

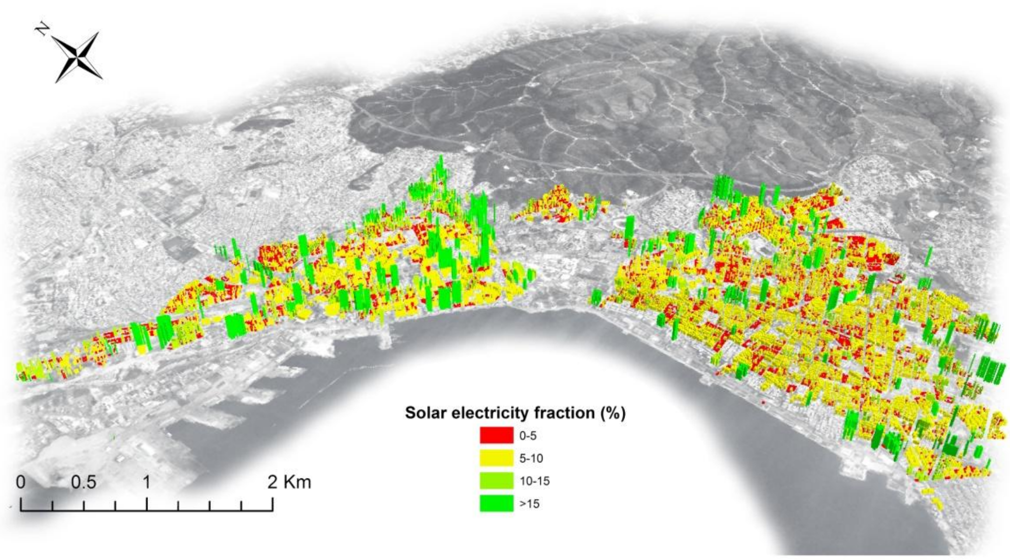
	Annual solar electricity fraction (%)	Number of buildings	Building stock fraction
Municipality of Thessaloniki	0.0-5.0	7,970	45.56%
	5.0-10.0	7,785	44.50%
	10.0-15.0	930	5.32%
	Over 15.0	809	4.62%
	Total	17,494	100.00%
Municipality of Kalamaria	0.0-5.0	1,000	16.70%
	5.0-10.0	2,850	47.60%
	10.0-15.0	1,339	22.37%
	Over 15.0	798	13.33%
	Total	5,987	100.00%

A better aspect of the annual solar electricity fraction is obtained in the following figure (Fig. 5.8). In the case of Thessaloniki, the red coloured buildings (those with low solar fraction) cover a large part of the examined area while the green ones (with fraction over 10%) are remarkably limited. On the contrary, in the Municipality of Kalamaria the green MF-buildings prevail against the red ones. However, in both areas the most widespread type of buildings performs a 5 to 10% annual solar electricity fraction.

Last but not least, as far as PV system potential is concerned, in Table 5.10 some interesting outcomes are shown; at first, the sum of the PV capacity in Thessaloniki reaches 23.0 MWp, whereas in Kalamaria does not exceed 8.7 MWp, justified by the less amount of existing buildings. Ultimately, the aggregated CO_2 emissions reduction accomplished by PVs, accounts for 133,771.35 $tnCO_2$ on an annual basis.

Table 5.10. Annual CO_2 emissions reduction by PV potential roof-top systems

	Values	**PV capacity (kWp)**	**Annual solar electricity production (kWh)**	**Annual CO_2 emissions reduction (0.989 $kgCO_2$/kWh of primary electrical energy)**
Mun. of Thessaloniki	Average	1.35	1,950.00	5,592.80
	Maximum	14.53	20,935.00	60,043.67
	Total	23,685.00	34,107,448.00	97,823,571.61
Mun. of Kalamaria	Average	1.45	2,093.48	6,004.31
	Maximum	9.57	13,784.10	39,534.19
	Total	8,703.93	12,533,657.89	35,947,784.19



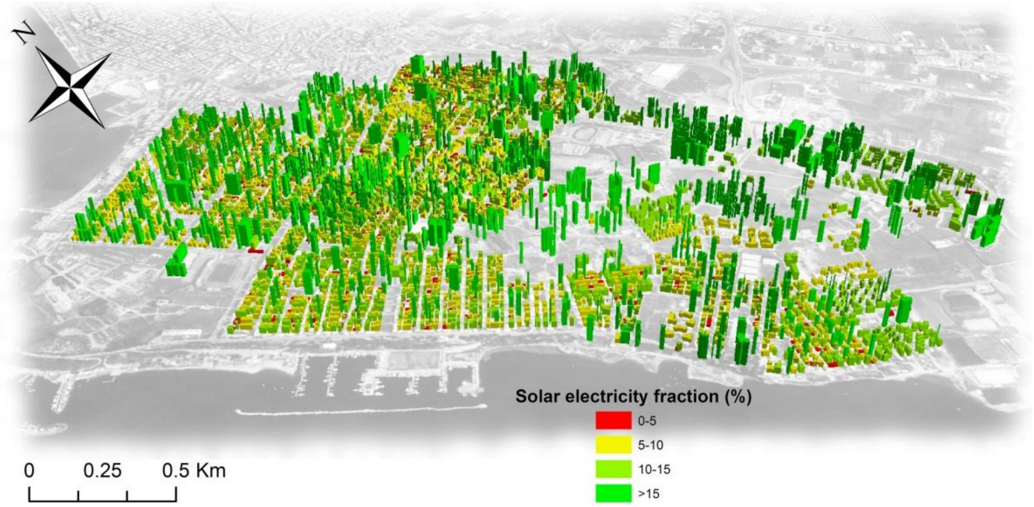


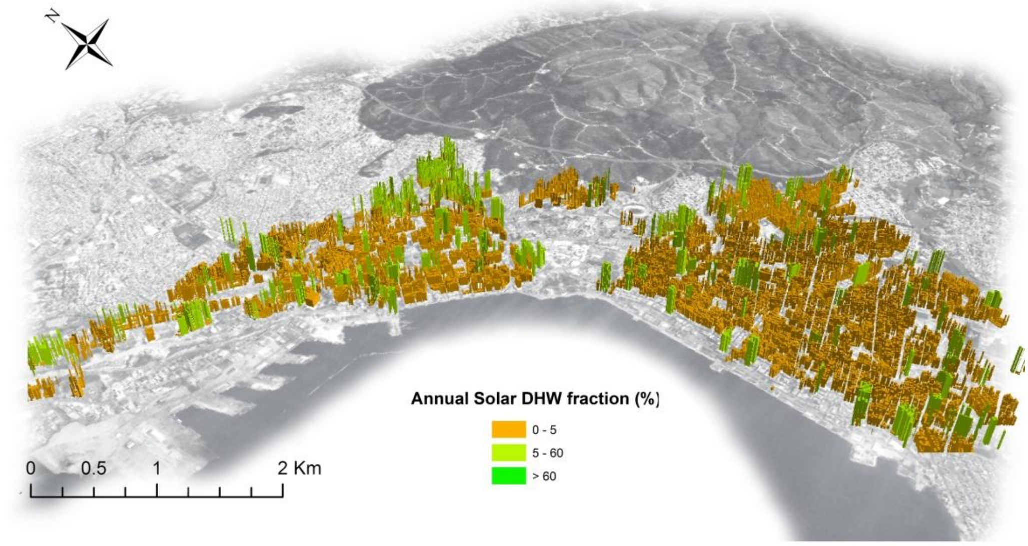
Fig. 5.8. Annual solar electricity fraction by roof-top PV systems depicted in 3d GIS map of Municipalities of Thessaloniki (upper image) and Kalamaria (lower image)[1]

In a pattern similar to the PV potential, the results about SWH systems show the lower annual solar DHW fraction that is estimated for the Municipality of Thessaloniki compared to the Municipality of Kalamaria. In further detail, 81.0% of the building stock in the city centre covers 5.0 to 60.0% of the DHW demands per building (Table 5.11). The 60% minimum solar fraction threshold is set by the national Regulation of Energy Efficiency of Buildings as a standard for newly constructed buildings. Within that context, it is concluded that there is a 10.0% of existing buildings (the 7.67% is represented by SWH systems computed in Kalamaria) that fulfil this obligation.

Table 5.11. Annual solar DHW fraction by roof-top SWH systems

	Annual solar DHW fraction (%)	**Number of buildings**	**Building stock fraction**
Municipality of Thessaloniki	0.0-5.0 (unsuitable roofs)	2,915	16.66%
	5.0-60.0	14,168	80.99%
	Over 60.0% (minimum allowed threshold for newly constructed buildings)	411	2.35%
	Total	17,494	100.00%
Municipality of Kalamaria	0.0-5.0 (unsuitable roofs)	408	6.81%
	5.0-60.0	5,120	85.52%
	Over 60.0% (minimum allowed threshold for newly constructed buildings)	459	7.67%
	Total	5,987	100.00%

[1] Note: the heights of the buildings represent the level of the depicted values of solar electricity fraction rather than the actual height of the buildings



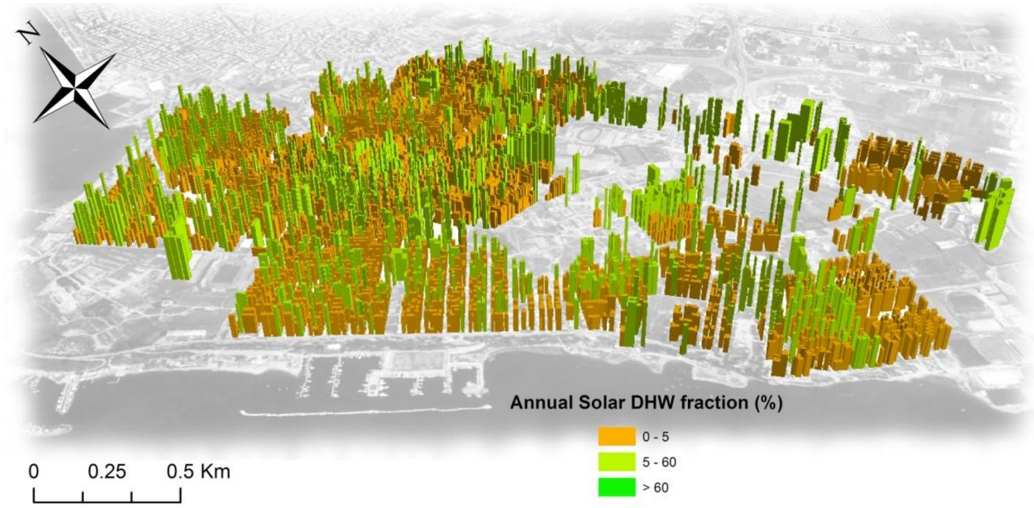


Fig. 5.9. Annual solar DHW fraction by roof-top SWH systems depicted in 3d GIS maps of Municipalities of Thessaloniki (upper image) and Kalamaria (lower image)[2]

In general, the potential outcome is greater in Kalamaria than in Thessaloniki (Fig. 5.9), for the same reasons as those described above concerning PV systems. However, the total annual CO_2 emissions reduction (Table 5.12) in Thessaloniki reaches 285,351.754 $tnCO_2$ and in Kalamaria only 108,702.725 $tnCO_2$, taking into account that the primary energy used for the production of DHW refers to electricity. Instead, when the DHW is provided by fuel oil boilers, the aforementioned levels of CO_2 emission savings are reduced by 90%.

[2] Note: the heights of the buildings represent the level of the depicted values of solar DHW fraction rather than the actual height of the buildings

Table 5.12. Annual CO_2 emissions reduction by SWH potential roof-top systems

	Values	Annual solar DWH production (kWh)	Annual CO_2 emissions reduction (0.989 $kgCO_2$/kWh of primary electricity energy)	Annual CO_2 emissions reduction (0.264 $kgCO_2$/kWh of primary fuel oil energy)
Mun. of Thessalo-niki	Average	5,687	16,310.88	1,651.50
	Maximum	61,069	175,152.00	17,734.44
	Total	99,491,564	285,351,754.71	28,892,350.19
Mun. of Kalamaria	Average	6,330	18,155.07	1,838.23
	Maximum	40,208	115,320.56	11676.40
	Total	37,900,605	108,702,725.20	11,006,335.69

5.4.2 Overall energy balance

5.4.2.1 Assumptions and input data

As mentioned in previous sections, four typical buildings were thoroughly analysed in terms of their energy performance, as real energy consumption data were gathered, whilst the heating energy and cooling consumptions were also exported by Energy Plus simulation software. Further detailed information about the construction and operational characteristics of the examined buildings is given in chapter 4.

For the computation of the annual CO_2 emissions the final energy consumptions for heating, cooling, DHW, lighting and electrical appliances are aggregated based on the kind of primary energy consumed (electricity, diesel oil or natural gas in this case). Then, based on the primary energy factors set by the Regulation of Energy Performance of Buildings (KENAK) and the respective CO2 emission coefficients (Table 5.13), the total CO_2 impact of each building is finally estimated.

Table 5.13. Primary energy factors and respective CO2 emissions coefficients for Greece

Source energy	Primary energy factor	CO_2 emissions factor ($kgCO_2$/kWh)
Natural gas	1.05	0.196
Heating oil	1.10	0.264
Electrical energy	2.90	0.989
Liquefied petroleum gas (LPG)	1.05	0.238
Biomass	1.00	---
District heating	0.70	0.347

5.4.2.2 Overall energy balance

Based on the main features of the aforementioned typical buildings a compatibility test took place, in order to match the buildings of the GIS sample to the typical ones. The comparison referred to the building form (approximate height, A/V ratio, detachment or attachment to neighbouring buildings), year of construction and existence of Pilotis floor. In Fig. 5.10 the three categories of construction typologies under study are depicted. Thus, apart from Class B, Classes C and D categories, the buildings are sub-divided in further categories in order to ensure the link between the maps and the energy behaviour characteristics of the sample.

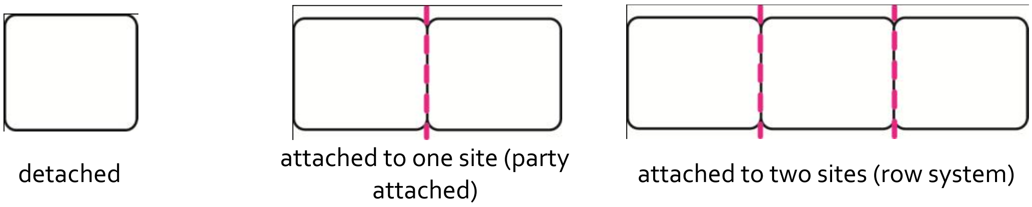


Fig. 5.10 The three types of construction under study

With respect to the buildings' energy behaviour, according to their typology, the annual final energy consumption is depicted in Table 5.14.

Table 5.14 Annual final energy consumption for with the typical constructions

class		**Class B**			**Class C**			**Class D**	
code	**MF1**	**MF1_p.att**	**MF2**	**MF3**	**MF3_p.att**	**MF3_de**	**MF4**	**MF4_p.att**	**MF4_r.sys**
status	row-system	partly attached	detached	row-system	partly attached	detached	detached	partly attached	row-system
final energy consumption [kWh/m²]	**102.07**	**99.01**	**166.33**	**123.56**	**156.28**	**167.08**	**143.14**	**133.62**	**128.36**

It is important to note that the aforementioned final energy consumptions include the energy consumptions for heating, cooling, DHW, lighting and electric appliances.

Table 5.15 Year of construction and typological characteristics for the residential buildings' sample in the Municipality of Thessaloniki

Year of construction [%]				**Pilotis [%]**	**Absolute use – residential [%]**	**Mixed use – main use residential [%]**	**Mixed use – secondary use residential [%]**
till 1960	1960-1980	1980-1990	1990-today				
20.05	53.29	16.80	9.61	10.22	37.81	45.72	1.31%

As shown in Table 5.15 83.53% of the sample represents buildings with residential use, whether an absolute or a mixed one, indicating an obvious consistence with the statistical study's results presented in chapter 3. In this line of thought, the design of retrofitting measures should be consistent with the energy characteristics of the residential building typology. In addition, the majority of the buildings in the Municipality of Thessaloniki, especially those constructed before 1980 (Class B), do not have a Pilotis floor.

Similarly, for the Municipality of Kalamaria the results are presented in Table 5.16. Hence, 93.3% of the studied sample refers to residential use, whilst the percentage of buildings with Pilotis floors rises. Unlike the results concerning the Municipality of Thessaloniki, the majority of the buildings are constructed during 1960 -1990. Therefore, Class C becomes more important, similarly to Class D, which now represents 17% of the sample. Moreover, for the case of Kalamaria, the majority of the detached buildings are referring to semi attachment system (attached to one building). Thus, several MF – buildings of the sample have been constructed in pairs.

Table 5.16 Year of construction and typological characteristics for the residential buildings' sample in the Municipality of Kalamaria

Year of construction [%]				**Pilotis [%]**	**Absolute use – residential [%]**	**Mixed use – main use residential [%]**	**Mixed use – secondary use residential [%]**
till 1960	1960-1980	1980-1990	1990-today				
9.15	37.98	34.32	17.22	41.83	64.77	28.53	0.65

With respect to various typological features, the buildings of each sample are being linked to the 4 proposed constructions and their sub-categories. Table 5.17 and Table 5.17 show the correlation of the sample for the Municipality of Thessaloniki and Kalamaria respectively.

Table 5.17 Residential buildings of the sample linked to typical buildings (Municipality of Thessaloniki)

MF1	**MF1_p.att**	**MF2**	**MF3**	**MF3_p.att**	**MF3_de**	**MF4**	**MF4_r.sys**	**MF4_p.att.**
21.28%	11.13%	20.88%	5.83%	5.77%	5.20%	4.19%	3.60%	1.82%

Table 5.18 Residential buildings of the sample linked to typical buildings (Municipality of Kalamaria)

MF1	**MF1_p.att**	**MF2**	**MF3**	**MF3_p.att**	**MF3_de**	**MF4**	**MF4_r.sys**	**MF4_p.att.**
3.35%	12.50%	22.13%	21.41%	3.24%	9.66%	10.53%	1.61%	5.08%

It becomes evident, that the majority of the residential building typology for the city centre of Thessaloniki can be safely linked to the typological features of buildings MF1 and MF2 as suggested earlier in this thesis. Furthermore, with respect to the energy behaviour, partly attached buildings mainly refer to corner buildings, with a calculated energy consumption increase of only 3%. As regards the area of Kalamaria the majority of the buildings are represented by MF2 and MF3.

Overall, the GIS analysis demonstrates that the typical buildings presented in chapter 4.3 are sufficiently depicting the typological structure of the greater urban area of Thessaloniki. More specifically, buildings MF1 and MF2 are characteristic for the part of the city centre, whilst buildings MF3 and MF4 are representative for the urban area of the Municipality of Kalamaria, which was developed rather lately. In this line of thought, the respective primary energy consumption for each building typology has been calculated and the relevant CO_2 emissions are depicted in Fig. 5.11 and Fig. 5.12 for the two study areas.

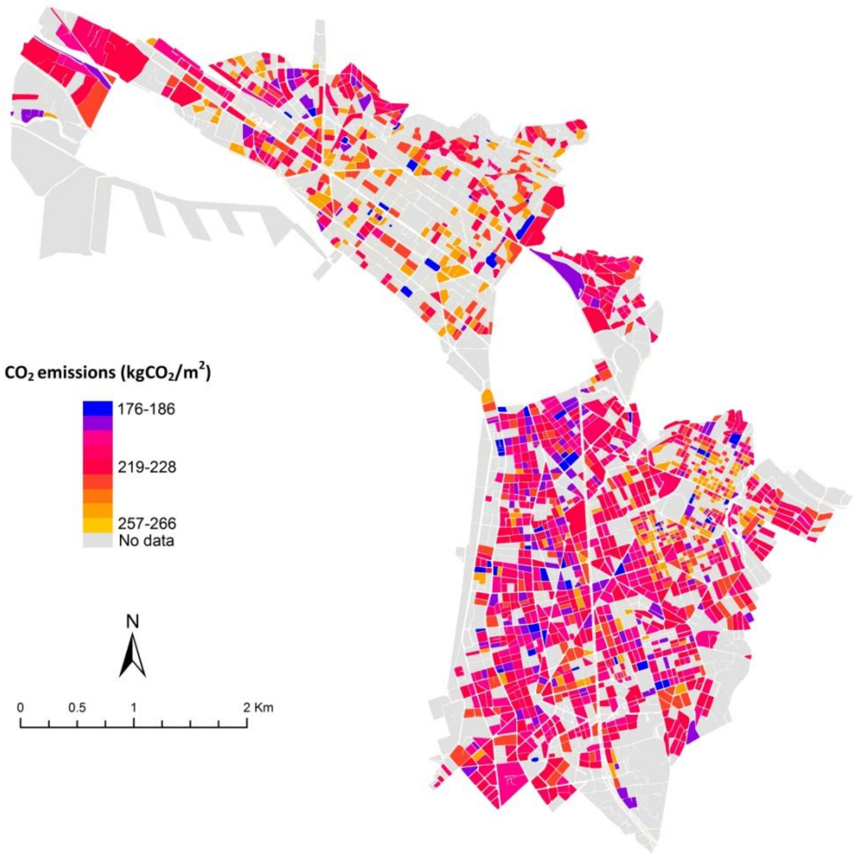


Fig. 5.11 CO_2 emissions per building block in the Municipality of Thessaloniki (residential building use)

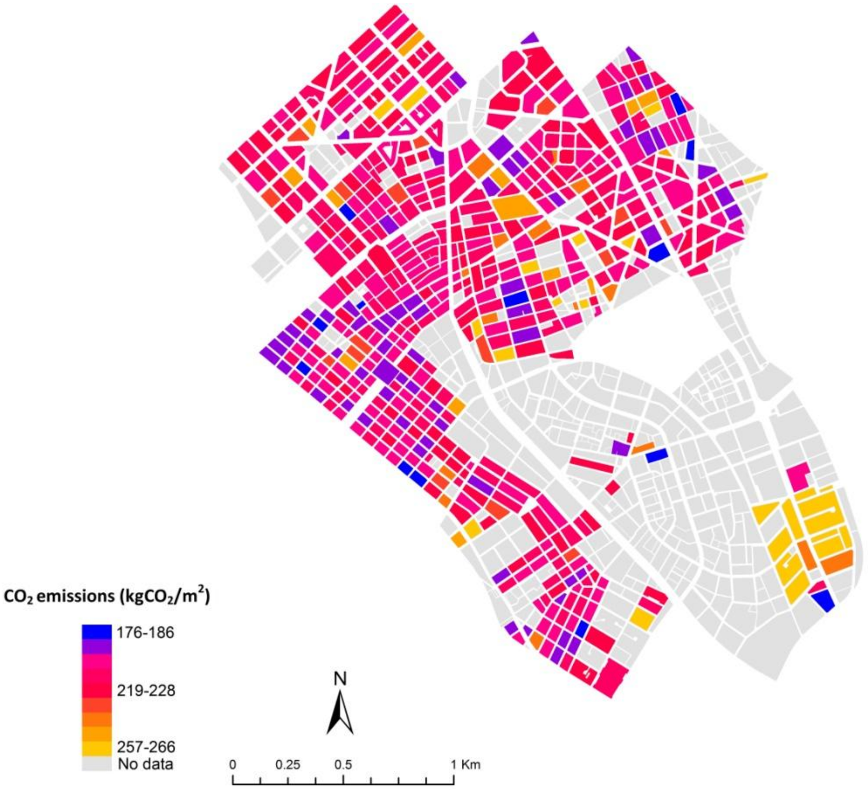


Fig. 5.12 CO_2 emissions per building block in the Municipality of Kalamaria (residential building use)

The most important conclusion drawn from Fig. 5.11 and Fig. 5.12 is that both study areas present rather high emissions with respect to the buildings' energy performance. Thus, although the percentage of buildings constructed before the implementation of the first Thermal Insulation Regulation (1980) in the Municipality of Kalamaria is only 44%, the emissions are rather high, on similar level with the Municipality of Thessaloniki, where 86.43% of the buildings were constructed before 1980.

5.4.3 Buildings' envelope

5.4.3.1 Green roofs

For the calculation of the available roofs area, the same procedure used for the RES implementation was followed, without the corrections due to shading. Namely, approximately 4,772,323 m^2 of available roof areas were calculated according to the GIS maps for the case study area of the city of Thessaloniki.

A major issue concerning green roofs implementation regards the demanding structural standards due to Greece's high seismic activity. Especially as regards existing buildings, this parameter could affect such measures to great extents. More specifically, the first Greek Seismic Code of 1954 was not revised until 1985, whilst the requirements regarding the weight loads of roofs remained the same until the new regulation of 2005.

Table 5.19 shows that the majority of the buildings in the city centre (Municipality of Kalamaria) are constructed before the revised Antiseismic Regulation. In this framework, extensive green roofs are the safer solution for the majority of the existing buildings by means of national retrofitting programs' implementation. In any other case, additional audits and studies are required in terms of each building's static efficiency. Hence, planning energy conservation measures for the existing urban environment presupposes the promotion of the extensive green roof type, especially concerning the urban existing building stock (Table 5.20).

Table 5.19 Available roof areas for the installation of green roofs according to the year of construction [m^2]

	pre 1980	**1980-today**	**sum**
Municipality of Thessaloniki	2,656,991	965,849	3,622,840
Municipality of Kalamaria	412,004	462,183	874,187

Table 5.20 Technical characteristics of green roofs by means of their static load (247)

Type	**Static load**
extensive	80 - 150 kg/m^2
semi- intensive	150 – 280 kg/m^2
intensive	at least 250 kg/m^2

In addition, it is commonly accepted, that due to reduced roofing surface temperatures, green roofs can improve natural cooling of PV modules and their systems' efficiency. Hence, a more pluralistic approach concerning the use of both technologies in tandem, especially with respect to the Greek warm summer periods, could lead to increased PV-system's efficiency (248). In terms of the additional static loads, the values of Table 5.20 would increase by an approximate 15 kg/m^2 for the PV-system's installation, PV-module and mounting device included.

5.4.3.2 Opaque surfaces and openings

As regards solid surfaces, the aforementioned typical buildings provide us with the typical information needed. In the following table the exterior surfaces for the horizontal and vertical exterior surfaces are presented along with the overall openings' area (Table 5.21).

Table 5.21 Window-wall ratio and gross roof area for the building MF1

	total exterior surface [m^2]	percentage exterior glazing [%]	total opaque surfaces [m^2]	total openings' surface [m^2]	roof area [m^2]
MF1	570.53	19.90	457.00	113.54	128.24
MF2	2,438.10	13.40	2,111.40	326.71	205.93
MF3	758.25	13.30	657.40	100.85	228.00
MF4	1,852.80	10.40	1,660.11	192.69	129.99

Based on the information of the above table and the connection of the GIS maps to the relevant typologies, total surface areas regarding openings and vertical wall, flat roof and Pilotis areas can be approximated and efficient retrofit measures can be proposed. Hence, based on the analysis of the sample for the Municipality of Thessaloniki, the majority of the residential buildings were constructed before 1980 and are therefore categorized in Class B. As a result, they were constructed before the implementation of the first Thermal Insulation Regulation, whereas the buildings located in the area of Kalamaria refer to more recent construction dates. More specifically, the overall exposed vertical and horizontal opaque surfaces for the Municipality of Thessaloniki and Kalamaria are presented in Table 5.22 and Table 5.23.

Table 5.22 Available exposed opaque vertical and horizontal surfaces for the implementation of thermal insulation (Municipality of Thessaloniki)

	Horizontal exposed opaque surfaces [m^2]	Vertical exposed opaque surfaces [m^2]	Total
total	3,787,233	7,194,569	10,981,802
until 1980	2,777,557	5,276,497	8,054,054
1980-present	1,009,677	1,918,072	2,927,749

Table 5.23 Available exposed opaque vertical and horizontal surfaces for the implementation of thermal insulation (Municipality of Kalamaria)

	Horizontal exposed opaque surfaces [m^2]	Vertical exposed opaque surfaces [m^2]	Total
total	1,270,448	2,612,477	3,882,925
until 1980	598,762	1,231,260	1,830,023
1980-present	671,686	1,381,217	2,052,902

With respect to retrospective thermal insulation implementation measures, the surfaces of buildings constructed before 1980 are of vital importance. In this line of thought, according to the respective Technical Directive of the KENAK, which are in accordance with the European EPBD Guidelines, the mean U-value of the bearing structure for buildings constructed before 1980 is 3.4 W/m^{2}K, whereas for the brick walls the respective value ranges between 2.2 -3.05 W/m^{2}K (18). Similarly, for horizontal surfaces, the U-value is 3.05 W/m^{2}K and 2.75 W/m^{2}K for flat roofs and Pilotis floors respectively (18).

For a moderate scenario of targeted energy upgrading retrofitting national plan, aiming at heating energy mitigation, thus improvement of the buildings' envelope, the minimum necessary width of thermal insulation material was calculated. More specifically, Table 5.24 shows these minimum widths for insulation materials with a thermal conductivity rate of 0.035 W/mK, which comply with the minimum requirements according to the new legislative framework of KENAK for the Climatic Zone C.

Table 5.24 Calculated minimum thermal insulation widths for each construction element (Climatic Zone C)

	Pilotis floor	Flat roof	Brick walls	Bearing structure
Thermal insulation width [m]	0.08	0.08	0.06	0.07

In the case of an ETICS system the thermal insulation is assumed to be applied with the same insulation material used for the vertical exposed surfaces. In this line of thought and based on the official pricing for thermal insulation materials, defined by national funding programmes (249) the average total costs for retrospective thermal insulation of existing buildings for the Municipality of Thessaloniki and Kalamaria are presented (Table 5.25). Hence, an overall thermal insulation retrofitting initiative by the state, would eventually inquire the partial or full capital funding of 508,606,98 Euros in order to achieve better energy behaviour for the urban residential building stock with respect to a large part of the city of Thessaloniki.

Table 5.25 Average total expected costs for retrospective thermal insulation measures for the Municipality of Thessaloniki and Kalamaria*

	Vertical surfaces [m^2]	price [€/m^2]	Expected costs	Horizontal surfaces [m^2]	price [€/m^2]	Expected costs	Total costs
Municipality of Thessaloniki	5,276,497	50	263,824,850	2,777,557	40	111,102,280	374,927,130
Municipality of Kalamaria	1,231,260	50	61,563,000	598,762	40	23,950,480	85,513,480
total	**6,507,757**		**325,387,850**	**3,376,319**		**135,052,760**	**460,440,610**

*refers to retrofitting measures for all buildings constructed before 1980.

Moreover, these costs would raise more in the case of a larger sample, which will include buildings constructed during 1980-1990, a rather dull period as regards the degree in which thermal insulation was implemented according to the TIR Regulation's requirements (80). It is obvious that greater widths of thermal insulation could be studied as for their implementation's costs and would assuredly lead to better energy conservation results.

As far as cool materials' retrofitting applications are concerned, it is important to note that the respective implementation's costs would drop drastically, though the eventual cooling energy reduction, would not be as significant as the one succeeded with the implementation of thermal insulation. This is being verified in chapter 7, where various retrofit scenarios are assessed in terms of their energy, economic and environmental efficiency. Moreover, it is worth mentioning that the implementation of cool coatings, particularly of cool roofs, makes more sense when endorsed within the frame of large scale retrofit; a related building unit implementation, according to the respective outcomes is not considered viable.

5.4.3.3 Built form and A/V ratio

According to the assessment tool the mean A/V ratio for the Municipality of Thessaloniki is 0.42 and 0.53 for the Municipality of Kalamaria. Moreover, the U_m values of the existing buildings are presented in Table 5.3. Hence, in the case of energy refurbishment and retrospective insulation of the building the respective Um values should drop to 0.95- 0.86 m^{-1} respectively in order to comply with the minimum requirements. More specifically, it becomes obvious that the Municipality of Thessaloniki consists of more compact buildings, a fact that explains the relative low energy consumption, regardless the lack of thermal insulation on the buildings' envelope (59). On the other hand, detached MF – buildings domain the Municipality of Kalamaria and are connected to higher energy consumption rates. In the case of large scale retrofitting, such details may play a crucial role; as the buildings are more compact, smaller widths of insulation could be used in order to achieve the minimum requirements of KENAK concerning the mean U_m value. In terms of economic feasibility, and based on the relevant assumptions in the previous chapter, these figures could determine, by and large, factors such as the quality of the materials in terms of their thermal conductivity properties, specific widths and even the nature of the state's funding supports. In this framework, urban density could influence respective retrofit strategies to a great extent.

5.5 Overview of the results

In this chapter a brief overview of the GIS analysis results is carried out. As it was concluded in the previous sections, all results concerning solar potential, overall energy performance and CO2 emissions of the building stock sample, show a direct strong connection to the construction typology and the respective density factors. Thus, energy conservation studies and the design of respective policies should be planned in terms of a city scale approach and not, as up to now, on a building unit basis.

5.5.1 Solar potential

Given the higher density in the Municipality of Thessaloniki, shading problems are more intense as far as roof solar suitability is concerned; the buildings' fraction with potential single-phased systems (1 - 5 kWp) does not exceed 46%, whereas over 50% of the buildings are evaluated as unsuitable for PV installations. On the other hand, higher ratio of built area per building in the city centre leads overall to high electrical consumptions per building. On the contrary, in the Municipality of Kalamaria, where the ratio of built area per building is lower, combined with the predominant detached construction system, the capacity outcomes seem more optimistic for solar applications; the roof solar suitability for instance increases up to 66% of the overall building stock, whilst the solar electricity fraction per building is noticeably improved. Finally, the total PV potential capacity in Thessaloniki can reach 23.0 MWp, whereas in Kalamaria only 8.7 MWp, given the smaller amount of existing buildings. As a consequence, the aggregated CO_2 emissions' reduction provided by PV roof-top systems can account aggregately for 133,771.35 tnCO_2 on an annual basis.

In the same line of thought, the results concerning SWH systems are better compared to PVs, given that an annual solar DHW fraction of 5 to 60% is provided by the 81% of buildings in Municipality of Thessaloniki and 85% in Municipality of Kalamaria. More importantly, in case of large scale retrofit programs, the "60% minimum solar fraction" threshold set by the national Regulation of Energy Efficiency of Buildings can be succeeded by a 10.0% of the existing buildings.

5.5.2 Overall energy balance and CO2 emissions

Overall, the GIS analysis proved that the typical MF - buildings chosen for this large scale analysis are suitable for the typological structure of the broader urban area of Thessaloniki. More specifically, buildings MF1 and MF2 are representative for area of the city centre and buildings MF3 and MF4 are representative for the area of Kalamaria. The link to the respective energy balance profile of each typical building provides us with a comprehensive overall illustration of the city's energy performance.

As regards the potential in retrofit actions, approximately 4,497,027 m^2 of available roof areas were calculated according to the GIS maps for the implementation of green roof systems. In addition, by means of retrospective thermal insulation measures, for all buildings constructed before 1980, approximately 9,884,077 m^2 of vertical and horizontal surfaces were estimated for both municipalities. Moreover, the fact that the Municipality of Thessaloniki consists of more compact buildings, explains the relative low energy consumption, regardless the lack of thermal insulation on the buildings' envelope. On the other hand, detached MF – buildings domain the Municipality of

Kalamaria and are related to higher energy consumption rates. It is important to underline the obvious agreement between the results of this GIS study and the statistical analysis presented in chapter 3.2.

Furthermore, in terms of economic feasibility, urban density could influence respective retrofit strategies to great extents. In other words, in the case of the city centre, the Municipality of Thessaloniki, the expected costs of intervention works in order to reach the minimum requirements set by KENAK concerning the buildings' envelope U-values were estimated at a sum of 374,927,130 Euros. Additionally, the expected costs for thermal insulation measures regarding horizontal and vertical opaque surfaces in both municipalities rise up to 460,440,610. It is obvious that if these retrofit actions were to be applied also to buildings constructed after 1980 the costs would rise dramatically. Similarly, if all Municipalities of Thessaloniki's urban region are taken into consideration as well.

Finally, by means of CO2 emissions, both areas under study present rather high amounts of CO2 emissions, although the percentage of buildings constructed before the implementation of the first Thermal Insulation Regulation (1980) in the Municipality of Kalamaria are lower (47%) compared to the Municipality of Thessaloniki (74%).

5.5.3 General results

"God made the country, and man made the town" said William Cowper in 1785. Given the fact that over 200 years have passed, and the structure of cities has changed dramatically, this saying is more relevant than ever. Over this time, cities grew, expanded in height and width, with less environment friendly materials, less green and more inhabitants. Thus, energy efficiency is now a part of a holistic sustainable management approach for urban environments. Great efforts towards this direction have to be made, whilst single solutions cannot offer the covetable results. The need to connect urban topography, typologies of buildings, indoor air quality and urban free spaces of high quality, within a framework of urban sustainable development, is immense.

This research showed that GIS based assessment tools can significantly contribute to energy efficiency management. Hence, the proposed methodology aims at the systematic collaboration of available data, regarding buildings, occupants, urban topography, climatic conditions and many more, in order to better serve this purpose. In this line of thought, besides the hereby presented research parameters, the proposed scheme allows the further elaboration of information input, concerning shading control in buildings, the estimation of CO_2 reduction in the urban built environment according to various retrofit scenarios as well as the implementation cool materials, the potential of RES on vertical building elements and many more.

Conclusively, GIS – maps can become a powerful mechanism during the process of retrofit policy planning in a city scale and provide vital information as regards urban energy efficiency. The bottom line is, as Ben Stein said, "somewhere there is a map of how it can be done".

6 Retrofit scenarios

Energy efficiency of urban buildings is affected by numerous aspects. Most of these parameters are strongly connected to urban density and structure as well as to respective derivatives, such as attachment to other buildings, solar radiation and A/V ratio, strongly influencing cooling, heating and ventilation loads as well as indoor air quality and thermal comfort. Hence, in the proposed methodology, urban buildings are examined by means of their built environment and classified accordingly. Specific buildings are studied as typical examples of various building blocks, which in turn, reflect a common urban typology structure. Each of the aforementioned parameters, are strongly connected to the energy performance of the buildings under study, thus they determine the energy profile of typical city areas.

With respect to energy efficiency management of the building stock several studies were developed over the past years. More specifically, there are six prominent bottom-up methodological approaches based on building physics evaluation that are applied for the UK housing stock, which share the same evaluation tool named BRE Domestic Energy Model (BREDEM) and study the CO_2 emissions reduction (121). In addition, as regards the residential stock, Míguez et al. deliver analytical information concerning the energy policies implemented in 15 European countries, a state-of-the-art referring to the year 2004, though describing a tendency that still remains strong in Europe as well as worldwide. In this framework, energy certification became a prominent tool for the improvement of the buildings' energy behaviour since the early 1990s (250).

Furthermore, several researchers dealt with the energy performance of residential buildings, for various climates and used different approaches; Filippín et al. study the energy performance of MF - buildings in a temperate-cold climate in Argentina (251), whereas Papadopoulos et al. present a feasibility study for energy conservation measures for various building typologies among which residential buildings (80). In particular, for the evaluation of the respective results, criteria such as the A/V ratio, the building form, the heating systems and the year of construction are taken into consideration. Moreover, with respect to Jordan's energy sectoral consumption of electricity, the residential stock demonstrates the highest percentage up to 35% followed by industry with 29% and other usages (140). Likewise, Al-Ghandoor et al. use multivariate regression analysis in order to examine and classify the parameters that determine fuel and electricity consumption (140). In addition, Wang et al. use multi-criteria decision analysis (MCDA) in order to determine sustainability factors of retrofit policies and show that CO_2 emissions are a common comparison tool for technical, economic, environmental and social aspects (252). Similarly, as simple retrofitting is a rather outdated goal for many EU-members; Xing et al. study various retrofit scenarios focusing on the UK building stock in order to meet zero-carbon energy refurbishment standards proposing a hierarchical implementation of the respective technologies (253). On the same wavelength, Hernandez and Kenny state that crucial assessment criterion is the life cycle energy use thus proposing a relevant methodology applied to the EU Building Energy Rating method concerning Irish residential buildings (254). In the same line of thought, Sivaraman suggest an integrated life cycle assessment model in order to evaluate energy conservation measures for heritage buildings in Australia, studying specific intervention scenarios (255).

The aforementioned studies reflect the current research state-of-the-art, leading to a very important conclusion; energy refurbishment of buildings is a matter of classification, evaluation criteria and priorities, assessment procedure, data availability, whilst the issue of flexibility and easy application of the proposed methodologies are of vital importance in order to ensure efficient energy conservation policies concerning the building sector.

6.1 Proposed retrofit measures

Energy efficiency policies have been a subject of research for several decades, especially with respect to the residential sector. Recently, in addition to such policies concerning energy conservation and reduction of CO_2 emissions, the overall environmental assessment of such actions is of vital importance. Hence, the impact of retrospective interventions by means of materials and building technologies, their implementation, the respective expected energy savings and their overall life cycle assessment, outline integrated energy conservation policies.

With respect to the urban Greek residential stock an evaluation of typical energy conservation measures was studied, in terms of their economic, energy and environmental feasibility. Based on the outcomes of this study, energy interventions' scenarios can be planned according to the evaluation criteria and their importance. Thus, the scope of this thesis is to present the most beneficial interventions for the Greek urban built environment in terms of their energy, economic and environmental efficiency and, as a consequence, to propose specific measures that will provide the suitable framework for future energy policies. For this purpose, various interventions are being studied and evaluated according to energy simulations and the environmental assessment tool ib3at (256).

More specifically, an integrated assessment of retrofitting scenarios is of vital importance, when aiming at sustainable measures planning. In this line of thought, the methodology adopted for the evaluation criteria of the intervention scenarios has been carefully determined. The main issues relating to the proposed interventions can be summed in the following question "*is there one optimum solution with respect to energy, environmental and economic aspects?*". This question is the subject of this chapter as well as of this thesis. The respective answer largely determines the shaping of policies involving large scale energy conservation measures. Consequently, four basic questions have to be answered, with respect to the retrofitting evaluation criteria:

A. <u>Minimum Requirements</u>

Which interventions satisfy the minimum requirements of the current legislative framework with the least costs involved?

B. <u>Maximum energy savings</u>

Which interventions lead to the maximum energy savings?

C. <u>Feasibility</u>

Which interventions are the most feasible ones?

D. <u>Environmental aspects</u>

Which interventions have the smallest environmental impact?

Apart from the above, the architectural upgrading of the retrofitted buildings should not be ignored. This aspect of retrofitting will be analysed in chapter 7.

These issues describe the evaluation criteria of this work. Further sub-criteria determining the retrofitting strategies are:

(a) technical issues,

(b) the least-cost approach and

(c) special requirements.

The relation between these parameters is depicted in Fig. 6.1.

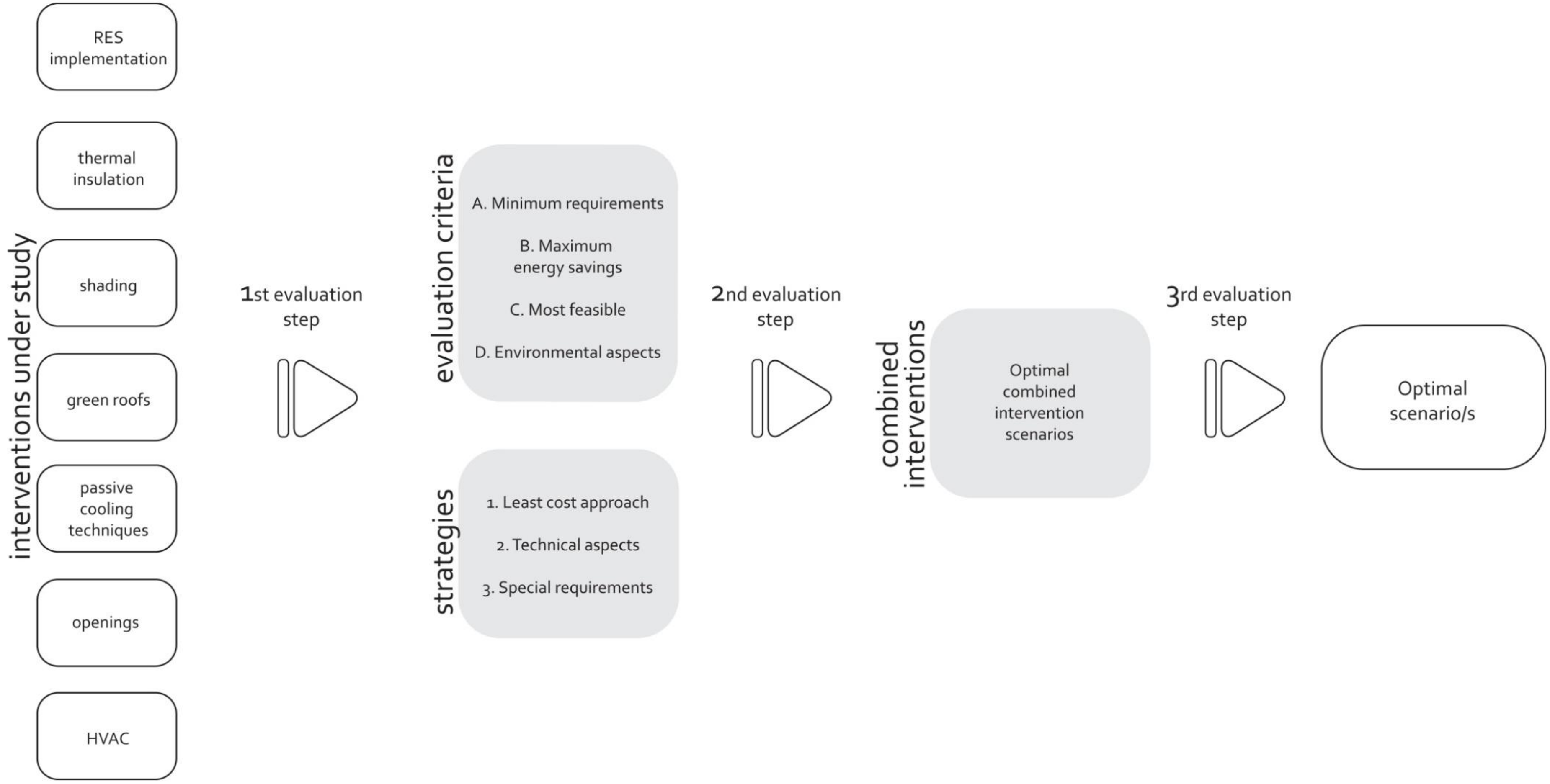


Fig. 6.1 Methodological approach for the development of the optimal intervention scenarios

As depicted in Fig. 6.1, each intervention is studied according to specific evaluation criteria. Meanwhile matters related to financial, technical and other special requirements are being assessed.

For the evaluation procedure the ib3at© tool was used (227). It is an integrated building energy, environmental and economic assessment tool, which can also be used separately in order to optimise the materials and systems used in the various phases of a building's life time.

The basis of the ib3at lies in the analytical calculation of the desirable assessment factors during the life cycle of a building. The life cycle consists of four distinct stages namely the construction, the operation, the demolition and the end-of-life management. Primary energy consumption, environmental impact and financial cost are the three main assessment factors that were chosen to be studied. The methodology that is embodied in ib3at is analytically presented elsewhere (227), (256).

It has to be noted that the environmental impact assessment implemented in ib3at is based on the Life Cycle Analysis (LCA) methodology. LCA offers a comprehensive analysis, which links actions with environmental impacts. At the same time, it provides quantitative and qualitative results and enables the effortless identification of the issues with improvement needs, by taking into consideration the link between system's functions and environmental impacts is (257).

There are several environmental impacts categories that are thoroughly examined like climate change, acidification, eutrofication, photochemical oxidation, etc. Every category is characterised by certain emissions (such as CO_2 equivalent, SO_2 equivalent, PO_4 equivalent, C_2H_4 equivalent) that stem from specific procedures within the life cycle of a building.

The economic feasibility of a retrofitting scenario for the energy upgrade of existing buildings is examined by comparing the long-term economic performance of the different alternative solutions. It can be determined with the Net Present Value (NPV) method or the Life Cycle Costing (LCC). The NPV is defined as the total present value of a time series of cash flows and it is a well-established method for appraising long-term projects taking into consideration the time value of money (81). The LCC is an estimation of the monetary costs of the funding, design, construction, operation, maintenance and repair, component replacement, and demolition of a building. It may be applied to new designs or to existing structures, in the latter case enabling residual life and value to be estimated. As different maintenance and repair and replacement operations take place at different times, incremental costs are converted to present-day value using a discounted cash flow approach (258). The LCC makes it possible for the whole life performance of buildings and other structures to be optimised. The two methods mentioned above are both incorporated in the ib3at tool.

More specifically, for an evaluation period of 30, years various interventions have been studied according to following aspects; these interventions refer to:

- Thermal insulation of vertical surfaces, such as brick cavity walls, concrete walls and the bearing structure
- Thermal insulation of horizontal surfaces, such as flat roofs and Pilotis floors
- Replacement of openings
- Improvement of the HVAC systems
- RES implementation for DHW and electricity production
- Shading
- Passive cooling techniques
- Green roofs implementation

The exact specifications of each scenario are presented in the following sections.

6.2 Determining typical intervention scenarios

Based on the description of Thessaloniki's climatic conditions in chapter 4.4.1, the intervention measures should firstly focus on the reduction of the heating loads and secondly on the minimisation of the cooling loads.

As a consequence, the intervention scenarios mainly concern the buildings' envelope, shading interventions as well as upgrading of the HVAC systems. They are planned in order to:

- Minimise or even efface heating loads

- Reduce cooling loads to minimum

- Ensure high thermal comfort indoor conditions

These three aspects are then analysed based on the aforementioned methodology, namely with an overall LCA assessment. The specific scenarios for each building are examined thoroughly in following chapters. It should be underlined though that these criteria could/should vary according to the climatic zone of each case study area. In this case, Thessaloniki belongs to the 3rd climatic zone, the second coldest zone one in Greece heating degree day values between 1,700 and 2,300 HDD, demonstrating climatic similarities to cities like Toulon in France and Stuttgart in Germany (43).

6.2.1 Building's envelope

6.2.1.1 Thermal insulation

Regarding the thermal insulation scenario, all vertical and horizontal building elements are examined as insulated by means of an External Thermal Insulation Composite System (ETICS) concerning vertical surfaces and retrospective thermal insulation of flat roofs and Pilotis floors. Three insulation materials are studied:

- Extruded polystyrene

- Expanded polystyrene

- Stonewool

It is important to note that, in contrary to Germany and other European countries, extruded polystyrene represents a very large market share in Greece, unlike stonewool and expanded polystyrene (Fig. 6.2).

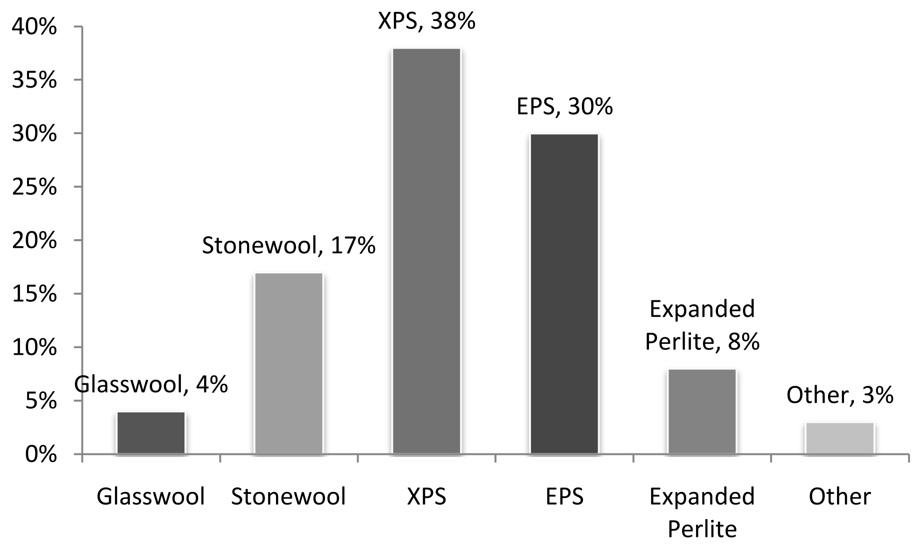


Fig. 6.2 Market share of the insulation materials in Greece (42)

As regards the LCC analysis of the insulation materials, the environmental impact during the production, transportation, operation and their waste management options at the end of their life cycle were taken into consideration. Furthermore, with respect to the maximum requirements of the Energy Performance of Buildings Regulation (KENAK) (Table 6.1), various widths of insulation were evaluated.

Table 6.1 Maximum U-values of the building's envelope for all four Climatic Zones in Greece [3]

Structural element	Symbol	Maximum allowed U value [W/m²K]			
		Climatic Zone A	Climatic Zone B	Climatic Zone C	Climatic Zone D
Exterior horizontal and sloped roofs	U_R	0.50	0.45	0.40	0.35
Exterior walls	U_T	0.60	0.50	0.45	0.40
Exterior floors (Pilotis floors)	U_{FA}	0.50	0.45	0.40	0.35
Exterior walls attached to ground and unconditioned rooms	U_{TU}	1.50	1.00	0.80	0.70
Floors attached to ground and unconditioned rooms	U_{FU}	1.20	0.90	0.75	0.70
Windows and openings	U_W	3.20	3.00	2.80	2.60
Glazed façades	U_{GF}	2.20	2.00	1.80	1.80

The specific thermal insulation scenarios are depicted in the following tables (Table 6.2, Table 6.3, Table 6.4 Table 6.5). In the first columns the various widths for each insulation materials according to their λ – thermal conductivity values are presented. In the right part of the tables, the new U-values of the construction materials are depicted. The widths and the selected λ-values are in correspondence with the Greek market, in order to support reasonable and feasible intervention scenarios.

It is important to note that for buildings MF1 and MF2 larger insulation widths are applied, due to the absence of thermal insulation in the buildings' envelope. Building MF3 was constructed after the introduction of TIR in 1979. However, the thermographic control and the energy consumption data have shown that the implementation of TIR was inadequately carried out and the bearing structure remained uninsulated. As a result, although smaller insulation widths are sufficient for the brick walls, larger widths are necessary for the concrete construction elements, so as to comply with the minimum standards of KENAK. In addition, MF4 building can reach the minimum standards with smaller insulation widths. Finally, the horizontal surfaces by means of the Pilotis floors were also examined in terms of their thermal insulation scenarios, particularly for buildings MF2, MF3 and MF4.

The coding used for these scenarios is:

EPS: expanded polystyrene

XPS: extruded polystyrene

SW: stonewool

Table 6.2 Scenarios for the implementation of retrospective thermal insulation for building MF1

expanded polystyrene		Walls		Flat roofs		new U-values [W/m²K]		
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs
EPS_1	1st scenario	7	0.035	8	0.035	0.4	0.43	0.37
EPS_2	2nd scenario	10	0.035	10	0.035	0.3	0.31	0.26
EPS_3	3rd scenario	15	0.035	15	0.035	0.21	0.22	0.21
EPS_4	4th scenario	6	0.031	7	0.031	0.41	0.38	0.37
EPS_5	5th scenario	10	0.031	10	0.031	0.27	0.28	0.27
EPS_6	6th scenario	15	0.031	15	0.031	0.19	0.19	0.19
					current	1.58	3.13	3.06
extruded polystyrene		**Walls**		**Flat roofs**		**new U-values [W/m²K]**		
Code		**width [cm]**	**λ [W/mK]**	**width [cm]**	**λ [W/mK]**	**brick walls**	**concrete walls**	**roofs**
XPS_1	1st scenario	7	0.035	8	0.035	0.4	0.43	0.37
XPS_2	2nd scenario	10	0.035	10	0.035	0.3	0.31	0.26
XPS_3	3rd scenario	15	0.035	15	0.035	0.21	0.22	0.21
XPS_4	4th scenario	6	0.031	7	0.031	0.41	0.38	0.37
XPS_5	5th scenario	10	0.031	10	0.031	0.27	0.28	0.27
XPS_6	6th scenario	15	0.031	15	0.031	0.19	0.19	0.19
					current	1.58	3.13	3.06
stonewool		**Walls**		**Flat roofs**		**new U-values [W/m²K]**		
Code		**width [cm]**	**λ [W/mK]**	**width [cm]**	**λ [W/mK]**	**brick walls**	**concrete walls**	**roofs**
SW_1	1st scenario	8	0.038	8	0.038	0.38	0.41	0.38
SW_2	2nd scenario	10	0.038	10	0.038	0.32	0.34	0.32
SW_3	3rd scenario	15	0.038	15	0.038	0.22	0.23	0.22
					current	1.58	3.13	3.06

Table 6.3 Scenarios for the implementation of retrospective thermal insulation for building MF2

expanded polystyrene		Walls		Flat roofs		Pilotis		new U-values [W/m²K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
EPS_1	1st scenario	7	0.035	8	0.035	8	0.035	0.4	0.43	0.37	0.37
EPS_2	2nd scenario	10	0.035	10	0.035	10	0.035	0.3	0.31	0.26	0.26
EPS_3	3rd scenario	15	0.035	15	0.035	15	0.035	0.21	0.22	0.21	0.21
EPS_4	4th scenario	6	0.031	7	0.031	7	0.031	0.41	0.38	0.37	0.37
EPS_5	5th scenario	10	0.031	10	0.031	10	0.031	0.27	0.28	0.27	0.27
EPS_6	6th scenario	15	0.031	15	0.031	15	0.031	0.19	0.19	0.19	0.19
							current	1.58	3.13	3.06	2.76

extruded polystyrene		Walls		Flat roofs		Pilotis		new U-values [W/m²K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
XPS_1	1st scenario	7	0.035	8	0.035	8	0.035	0.4	0.43	0.37	0.37
XPS_2	2nd scenario	10	0.035	10	0.035	10	0.035	0.3	0.31	0.26	0.26
XPS_3	3rd scenario	15	0.035	15	0.035	15	0.035	0.21	0.22	0.21	0.21
XPS_4	4th scenario	6	0.031	7	0.031	7	0.031	0.41	0.38	0.37	0.37
XPS_5	5th scenario	10	0.031	10	0.031	10	0.031	0.27	0.28	0.27	0.27
XPS_6	6th scenario	15	0.031	15	0.031	15	0.031	0.19	0.19	0.19	0.19
							current	1.58	3.13	3.06	2.76

stonewool		Walls		Flat roofs		Pilotis		new U-values [W/m²K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
SW_1	1st scenario	8	0.038	8	0.038	8	0.038	0.38	0.41	0.38	0.4
SW_2	2nd scenario	10	0.038	10	0.038	10	0.038	0.32	0.34	0.32	0.33
SW_3	3rd scenario	15	0.038	15	0.038	15	0.038	0.22	0.23	0.22	0.23
							current	1.58	3.13	3.06	2.76

Table 6.4 Scenarios for the implementation of retrospective thermal insulation for building MF3

expanded polystyrene		Walls		Flat roofs		Pilotis		new U-values [W/m²K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
EPS_1	1st scenario	7	0.035	8	0.035	8	0.035	0.4	0.43	0.37	0.37
EPS_2	2nd scenario	10	0.035	10	0.035	10	0.035	0.3	0.31	0.26	0.26
EPS_3	3rd scenario	15	0.035	15	0.035	15	0.035	0.21	0.22	0.21	0.21
EPS_4	4th scenario	6	0.031	7	0.031	7	0.031	0.41	0.38	0.37	0.37
EPS_5	5th scenario	10	0.031	10	0.031	10	0.031	0.27	0.28	0.27	0.27
EPS_6	6th scenario	15	0.031	15	0.031	15	0.031	0.19	0.19	0.19	0.19
							current	0.80	3.13	3.06	2.76

extruded polystyrene		Walls		Flat roofs		Pilotis		new U-values [W/m²K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
XPS_1	1st scenario	7	0.035	8	0.035	8	0.035	0.4	0.43	0.37	0.37
XPS_2	2nd scenario	10	0.035	10	0.035	10	0.035	0.3	0.31	0.26	0.26
XPS_3	3rd scenario	15	0.035	15	0.035	15	0.035	0.21	0.22	0.21	0.21
XPS_4	4th scenario	6	0.031	7	0.031	7	0.031	0.41	0.38	0.37	0.37
XPS_5	5th scenario	10	0.031	10	0.031	10	0.031	0.27	0.28	0.27	0.27
XPS_6	6th scenario	15	0.031	15	0.031	15	0.031	0.19	0.19	0.19	0.19
							current	0.80	3.13	3.06	2.76

stonewool		Walls		Flat roofs		Pilotis		new U-values [W/m²K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
SW_1	1st scenario	8	0.038	8	0.038	8	0.038	0.38	0.41	0.38	0.4
SW_2	2nd scenario	10	0.038	10	0.038	10	0.038	0.32	0.34	0.32	0.33
SW_3	3rd scenario	15	0.038	15	0.038	15	0.038	0.22	0.23	0.22	0.23
							current	0.80	3.13	3.06	2.76

Table 6.5 Scenarios for the implementation of retrospective thermal insulation for building MF4

expanded polystyrene		Walls		Flat roofs		Pilotis		new U-values [W/m^2K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
EPS_1	1st scenario	3	0.035	2	0.035	2	0.035	0.41	0.45	0.38	0.38
EPS_2	2nd scenario	6	0.035	6	0.035	6	0.035	0.31	0.31	0.27	0.26
EPS_3	3rd scenario	10	0.035	10	0.035	10	0.035	0.23	0.23	0.2	0.2
EPS_4	4th scenario	15	0.035	15	0.035	15	0.035	0.17	0.17	0.16	0.16
EPS_5	5th scenario	3	0.031	2	0.031	2	0.031	0.4	0.41	0.37	0.37
EPS_6	6th scenario	6	0.031	6	0.031	6	0.031	0.29	0.29	0.25	0.25
EPS_7	7th scenario	10	0.031	10	0.031	10	0.031	0.21	0.21	0.19	0.19
EPS_8	8th scenario	15	0.031	15	0.031	15	0.031	0.16	0.16	0.15	0.14
							current	0.66	0.71	0.50	2.87

extruded polystyrene		Walls		Flat roofs		Pilotis		new U-values [W/m^2K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
XPS_1	1st scenario	3	0.035	2	0.035	2	0.035	0.41	0.45	0.38	0.38
XPS_2	2nd scenario	6	0.035	6	0.035	6	0.035	0.31	0.31	0.27	0.26
XPS_3	3rd scenario	10	0.035	10	0.035	10	0.035	0.23	0.23	0.2	0.2
XPS_4	4th scenario	15	0.035	15	0.035	15	0.035	0.17	0.17	0.16	0.16
XPS_5	5th scenario	3	0.031	2	0.031	2	0.031	0.4	0.44	0.37	0.37
XPS_6	6th scenario	6	0.031	6	0.031	6	0.031	0.29	0.33	0.25	0.25
XPS_7	7th scenario	10	0.031	10	0.031	10	0.031	0.21	0.24	0.19	0.19
XPS_8	8th scenario	15	0.031	15	0.031	15	0.031	0.16	0.18	0.15	0.14
							current	0.66	0.71	0.50	2.87

stonewool		Walls		Flat roofs		Pilotis		new U-values [W/m^2K]			
Code		width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	width [cm]	λ [W/mK]	brick walls	concrete walls	roofs	pilotis
SW_1	1st scenario	3	0.038	2	0.038	2	0.038	0.43	0.44	0.39	0.39
SW_2	2nd scenario	6	0.038	6	0.038	6	0.038	0.32	0.33	0.27	0.27
SW_3	3rd scenario	10	0.038	10	0.038	10	0.038	0.24	0.24	0.21	0.21
SW_4	4th scenario	15	0.038	15	0.038	15	0.038	0.18	0.18	0.17	0.17
							current	0.66	0.71	0.50	2.87

For each insulation material the appropriate widths according to the respective λ-value were calculated, in order to reach the minimum requirements set by KENAK. Particularly, the 1st scenario of each insulation material represents the least necessary implementation's solution in order to fulfil KENAK's standards.

6.2.1.2 Replacement of windows and glass doors

With respect to the openings of the four buildings, emphasis is laid both on the material of the frame and the U-value of the overall construction. Hence, three frame material types are studied, wooden, synthetic and metal frames. As concerns the U-values, three types are evaluated, namely:

a. U-value 2.80 W/m^2K (minimum requirement of KENAK for Climatic Zone C),
b. U-value 1.80 W/m^2K and
c. U-value 1.10 W/m^2K

Based on the previous analysis of the climatic conditions and the Greek market lower U-values would not be considered as feasible measures. This statement is verified by the outcomes of the overall evaluation in the following chapter. Moreover, as regards the infiltration rates of the buildings under study, they were re-evaluated according to Table 4.7.

The coding of the scenarios concerning the openings is organised as follows:

W1: U-value 2.80 W/m^2K

W2: U-value 1.80 W/m^2K

W3: U-value 1.10 W/m^2K

Wood: Wooden frame and dividers

Aloum: Aluminium frame and dividers

PVC: Synthetic frame and dividers

6.2.1.3 Green roofs

For the implementation of the green roofs three types were studied:

- the extensive type

- the semi-intensive type and

- the intensive type of green roof construction.

In terms of the implementation of the green roof system and the data input in the Energy Plus software, the following aspects were considered:

a. The height of plants
b. The thickness of the soil layer
c. The density of the foliage
d. The operational schedule of the irrigation

In this framework, each green roof type was combined with specific features as depicted in the following table (Table 6.6). It is important to note that the simulation software allows the use of the so called "smart irrigation schedule", combined with the annual input of the irrigation for the green roof. In other words, the software has the ability to turn the standard irrigation schedule off, in case of rainfall and eventually sufficient humidity of the soil layer.

Table 6.6 Width of the soil layer and the overall construction (247)

	Width of construction [cm]	**Width of the soil layer [cm]**
extensive type	13	10
semi-intensive type	20	15
intensive type	33	25

Moreover, information regarding the reflectivity and emissivity of the leaves as well as the thermal conductivity and specific heat of the dry soil, assure more accurate results concerning the green roof systems.

The plants were determined according to climatic zone of the case study area, with medium to high demand concerning daylight and minimum demands as regards irrigation. The data input were also based on the National Requirements determined by the Geotechnical Chamber of Greece concerning green roofs (247).

The codes that were used for the three types of green roofs are:

GR_ext: extensive type of green roof

GR_semi: semi intensive type of green roof

GR_int: intensive type of green roof

6.2.1.4 Cool materials

Cool materials were also studied in terms of their contribution to the cooling loads' reduction. The main technical properties of the materials, associated with their reflectance and emittance coefficients for the selected cool materials assessed in retrofitting scenarios of the examined MF-buildings, were defined based on EU Cool Materials Council's database (259). Furthermore, information about the installation costs of cool materials in the Greek market was obtained from the same online database. In Table 6.7 a comparison between common hot and cool roof systems in terms of solar reflectance and infrared emittance values is shown. In current work, for cost-benefit reasons, only white and tinted roof coatings were evaluated. These materials contain transparent polymeric materials, such as acrylic and a white pigment, with high reflectivity values up to 70%-90%. These coatings absorb approximately 5 % of the sun's energy which falls in the ultraviolet range, despite the white appearance. In this manner, the pigments help protect the polymer material and the substrate underneath from UV damage.

Table 6.7 Comparison between usual hot and usual cool roofs systems: solar reflectance and infrared emittance values (259)

Roof Type	Reflectance	Emittance	Roof Type	Reflectance	Emittance
Built-up Roof With dark gravel	0.08-0.15	0.80-0.90	Built-up Roof With off-white gravel and/or cementitious coating	0.50-0.70	0.80-0.90
Single-Ply Membrane Black (PVC)	0.04-0.05	0.80-0.90	Single-Ply Membrane White (PVC)	0.70-0.78	0.80-0.90
Single-Ply Membrane Black (PVC)	0.04-0.05	0.80-0.90	Single-Ply Membrane painted with coloured cool coating	0.30-0.80	0.80-0.90
Modified Bitumen With mineral surface cap-sheet (SBS, APP)	0.10-0.20	0.80-0.90	Modified Bitumen White coating over a mineral surface (SBS, APP)	0.60-0.75	0.80-0.90
Concrete Tile Dark colour with conventional pigments	0.05-0.35	0.80-0.90	Cool Concrete Tile coloured	0.40-0.65	0.80-0.90
Metal Roof unpainted, corrugated	0.30-0.50	0.05-0.30	Metal Roof painted with coloured cool coating	0.05-0.80	0.80-0.90

The respective code for the cool material scenarios is CoolMat.

6.2.2 HVAC systems

A significant option for the retrofitting measures proposed in the examined MF-Buildings, concerns the replacement of the poorly maintained current heating and DHW production systems as well as the insulation of the existing distribution networks and last but not least the substitution of the old cooling split unit devices with new more efficient ones.

In Table 6.8 and Table 6.9 the overall efficiency of the existing and the newly proposed heating and DHW systems of the examined MF-buildings are presented. Each system's overall efficiency, as it is remarked also in chapter 4.4.1.4, is estimated based on the boiler's efficiency measured during annual maintenance adding also the losses due to its over-dimensioning, the status of the insulation on its shell and the heating distribution network as well. The input data needed to calculate the individual loss factors are obtained by the Technical Directives.

Concerning the cooling systems, it is assumed that the new split units have a seasonal effective energy ratio exceeding 3.0, considering the standards set by KENAK and the respective Technical Directives for newly constructed buildings, whilst the existing devices perform with a ratio of 2.0.

Table 6.8 Current heating system of the examined MF-buildings and the proposed one with better overall efficiency

	Heating boiler Fuel	**Overall efficiency [%]**	**Proposed system's overall efficiency [%]**
MF1	Diesel oil	57.0	83.0
MF2	Natural gas	66.0	90.5
MF3	Diesel oil	70.0	88.0
MF4	Natural gas	65.0	88.0

Table 6.9 Current DHW system of the examined MF-buildings and the proposed one with better overall efficiency

	DHW heater Fuel	**Overall efficiency [%]**	**Proposed system's overall efficiency [%]**
MF1	Electricity	81.0	93.0
MF2	Natural gas (during winter)	56.0	82.5
	Electricity (during summer)	81.0	93.0
MF3	Electricity	81.0	93.0
MF4	Natural gas	60.0	81.5
	Electricity (during summer)	93.0	93.0

These scenarios are coded as follows:

BB: Heating system/boiler and DHW interventions

AC: A/C split unit replacement

6.2.3 RES

Regarding the implementation of solar systems on the examined MF-buildings, two technologies are examined; the first one concerns photovoltaics (PVs) applied on the roofs, whereas the second one refers to solar water heating (SWH) applications in order to cover the domestic hot water (DHW) demands.

Initially, the estimation of solar utilisation potential for the examined buildings is carried out by computing the shaded areas and eventually the overall solar architecturally suitable areas (S_a) and solar utilisation factor (SU_f) per gross roof areas. In this process, the common criterion of optimal operation of solar systems for at least a four hour interval during winter solstice is applied. Thereafter, two different installation formulations, more specifically two overall installation coefficients for PV and SWH systems on roofs are assumed. They are based on two roof orientation scenarios (south or southeast/southwest) and on the criterion of least mutual shadowing between parallel PV or SWH series at midday during winter solstice, for an annually optimal inclination angle and common dimensions for the solar panels.

Following, the solar suitable areas are multiplied by a hypothetical mean efficiency factor for multi and mono-crystalline silicon PV panels, which are available in the current market, so as to account for the final PV potential peak capacity (in kW) per building. Afterwards, by using the well-known online utility tool of PVGIS (208) an average energy output per kWp can easily be exported, taking into consideration set system losses due to wiring, inverter, cell temperature increase and PV panel mismatch. Finally, the results are compared to each building's electricity energy demands. When it comes to the SWH systems, the calculation process until the average efficiency consideration is similar to the PV systems' approach, with one major difference which concerns the higher inclination angle (winter's optimal) of SWH panels. Furthermore, the solar DHW fraction is accounted for using the widely used f-Chart method (209). The input data for the f-Chart method are the monthly values of incident solar radiation, ambient temperature, water mains temperature and DHW demands, variables that derived from the Technical Directives and the simulation process.

In detail, as far as PV systems' electricity production is concerned, a mean PV efficiency of 14.5% and 15.5% for polycrystalline and monocrystalline PVs respectively is taken into consideration. Additionally, further system losses (cables, inverter etc) up to 14,0% are assumed, while PVGIS calculations include temperature and angular reflectance losses according to examined location's climatic conditions. Moreover, roof-top PV panels are considered free-standing with optimal inclination (30^o) and south orientation, whereas regarding the roof potential, the actual installed PV surface is assumed to cover approximately 50% of the computed solar suitable (S_a) roof areas, due to the applied criterion of negligible mutual shading losses between parallel PV series. Regarding the SWH systems, the actual installation factor for roof areas follows the same estimation pattern compared to PV systems, although the SWH panels are theoretically installed in 45° inclination angle (optimal for winter), so the required distance to avoid shadow effects between parallel series is inevitably longer. This parameter leads to a reduced overall roof utilisation factor of SWH systems approximately by 7% compared to PV. As for the approximation of the energy loads for DHW and the annual solar DHW solar fraction, the f-chart method is applied while the main input data are presented in Table 6.10.

Table 6.10 Monthly ambient and water mains temperatures, DHW demands per person and solar DHW fraction for one person's needs provided by 1 m2 south facing SWH panel with 450 inclination angle in the region of Thessaloniki (20).

Months	Ambient temperature [°C]	Water mains temperature [°C]	DHW demands per person [kWh/person]	Solar DHW fraction for one person's demands provided by 1 m^2 south facing SWH panel with 45° inclination angle [%]
Jan	5.3	6.5	75.61	63.72
Feb	6.8	7.3	69.27	70.76
Mar	9.8	9.4	72.92	81.40
Apr	14.3	13.2	63.97	99.50
May	19.7	17.6	58.19	114.47
Jun	24.5	21.9	48.84	128.87
Jul	26.8	24.3	46.16	136.23
Aug	26.2	24.6	45.62	135.06
Sept	21.9	22.0	48.67	122.63
Oct	16.3	17.7	58.01	97.42
Nov	11.1	12.7	64.83	73.92
Dec	6.9	8.6	74.36	61.08
Mean values	15.8	15.5	60.54	98.75

Based on the aforementioned methodological approach, interesting results are produced which show that the solar electricity fraction varies between 9.63% to 35.79%, whilst the solar DHW fraction is much higher, over 100%, and thus the solar systems can totally cover the buildings' demands on a yearly basis (Table 6.11, Table 6.12 and Table 6.13).

Table 6.11 Annual electrical consumptions per MF-building typology and solar electricity fraction covered by polycrystalline PV systems

Building	Electrical consumptions [kWh/m^2/year]	Gross roof area [m^2]	PV area [m^2]	Roof solar utilisation factor [%]	PV capacity [Wp]	Annual solar electricity production [kWh/kWp]	Solar electricity fraction [%]
MF1	56.76	157	62	39%	8,973	1,449	18.65%
MF2	44.95	335	79	23%	11,395	1,369	9.63%
MF3	58.75	240	108	45%	15,708	1,445	35.79%
MF4	44.43	279	54	19%	7,841	1,365	16.88%

Table 6.12 Annual electrical consumptions per MF-building typology and solar electricity fraction covered by monocrystalline PV systems

Building	Electrical consumptions [kWh/m²/year]	Gross roof area [m²]	PV area [m²]	Roof solar utilisation factor [%]	PV capacity [Wp]	Annual solar electricity production [kWh/kWp]	Solar electricity fraction [%]
MF1	56.76	157	62	39%	9,592	1,449	19.93%
MF2	44.95	335	79	23%	12,181	1,369	10.29%
MF3	58.75	240	108	45%	16,792	1,445	38.25%
MF4	44.43	279	54	19%	8,381	1,365	18.04%

Table 6.13 Annual DHW demands per MF-building typology and solar DHW fraction covered by SWH systems

Building	Domestic hot water demands [kWh/year] calculated using f-chart method	Gross roof area [m²]	SWH area [m²]	Roof solar utilisation factor [%]	Solar DHW production [kWh/year]	Solar DHW fraction [%]
MF1	25,063	157	62	39%	31,969	97.70
MF2	54,485	335	79	23%	50,433	117.22
MF3	18,525	240	108	45%	52,961	320.89
MF4	26,153	279	54	19%	29,381	131.48

Following codes refer to the aforementioned RES scenarios:

SC: Solar Collectors

PV_MonoSi: Monocrystalline Silicon Photovoltaic systems

PV_MultiSi: Multicrystalline Silicon Photovoltaic systems

6.2.4 Shading

Shading plays a very important role when aiming at the cooling loads reduction. As already stated, *Polykatoikies* are characteristic for their shading systems, consisting of the horizontal projections, namely balconies, equipped with awnings, made either by metal or by fabric materials.

Although awnings are present in most cases, there are three main aspects, which lead us to the reassessment of this shading system:

1. The actual performance of the awnings is, by and large, depending on the actual length of the balcony and the orientation of the façade. In addition, they are almost never automatically controlled, a fact that does not guarantee maximum efficiency.
2. Their deterioration is evident, especially in older buildings, as their maintenance and cleanliness is extremely difficult, altering the image of the building.

3. Their minimal to zero transmittance to solar radiation, reduces natural ventilation and day-lighting.

As a result the replacement of old existing awnings is assessed, along with alternative external surface shading, by means of vertical and horizontal louvers, according to the buildings' orientation.

Both shading solutions were studied as static systems and as controlled based on the solar tracking provided by the Energy Plus software engine. Prior to the evaluation of their influence on the energy balance of the building, a quality control was conducted. Thus, all four buildings were studied in terms of the incidence of solar radiation for three typical days and day-hours as foreseen by KENAK (17). In this framework, shading is planned only for the parts of facades that are highly exposed to solar radiation, in order to avoid useless installation costs. It should be noted though, that as regards the awnings, this approach has great effect on the architectural image of the facades, a fact that must be taken into consideration. On the contrary, vertical and horizontal louvers, could contribute significantly to the aesthetics of the building, by creating clear volumes and lines.

In the following table (Table 6.14) the daily time intervals during which each exterior side of the examined buildings needs shading protection are presented. More specifically shading calculations are presented for summer and winter solstice and autumn equinox.

Table 6.14 Daily time intervals during which exterior buildings' surfaces are exposed to direct solar radiation; presented for summer/winter solstice and autumn equinox.

MF-buildings	**21st June (summer solstice)**	**21st December (winter solstice)**	**21th September (autumn equinox)**
MF1			
South side	09:00 - 16:00	11:00-15:00 except from 1st and 2nd floor	08:00 - 17:00
North side	17:00-19:00	None	None
MF2			
North - east side	08:00 - 10:00	08:00 - 09:00	08:00 - 10:00 (the first, second and third floor are shaded from 9:00-10:00)
South - west side	13:00 - 19:00 (the first, second and third floor are shaded from 13:00-19:00)	13:00 - 15:00 (the first, second and third floor are shaded from 13:00-15:00)	12:00 - 17:00 (the first, second and third floor are shaded from 13:00-17:00)
North - west side	16:00 - 19:00	None	17:00 - 18:00
South - east side	08:00-15:00 (periodically shaded parts of the facade due to surrounding buildings)	08:00-11:00	08:00-11:00
MF3			
South side	11:00-15:00	09:00-16:00 (the west half part of the side - until 14:00 the 1st floor) - 12:00-16:00 (the east half part of the side)	10:00-15:00 (the west half part of the side) - 12:30-18:00 (the east half part of the side)
North side	08:00-09:30 (the first and second floor on the west half part of the side since 06:50)	None	None
MF4			
South - east side	08:00-11:00	08:00-15:00 (the first, second, third and fourth floor are shaded from 9:00-10:00)	08:00-13:00
South - west side	13:00-18:00 (the first four floors are periodically shaded due to surrounding buildings)	11:00-16:00 (the first four floors are periodically shaded due to surrounding buildings)	13:00-18:00 (the first four floors are periodically shaded due to surrounding buildings)
North - east side	08:00-09:00 (the last three floors)	None	None
North - west side	16:00-19:00	None	None

Additionally in the following figures shaded areas are depicted during summer solstice for each of the four examined buildings (Fig. 6.3, Fig. 6.4, Fig. 6.5, Fig. 6.6).

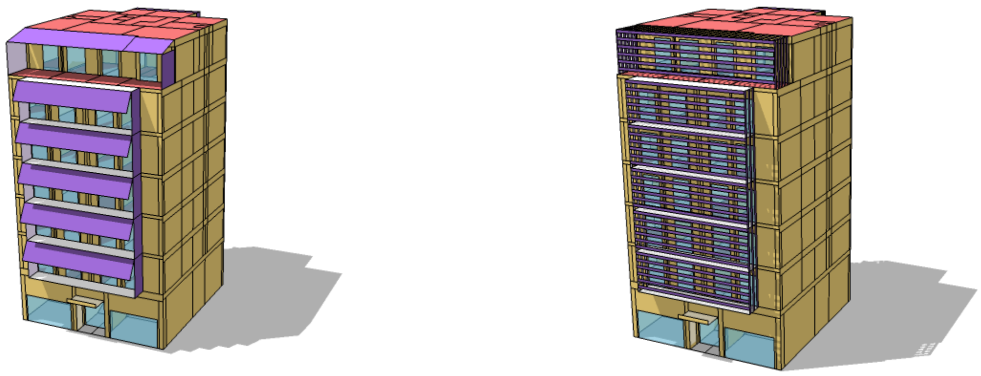


Fig. 6.3 Shading modelling of the south side of building MF1 in the Energy Plus engine (as depicted with the Open Studio tool of Google Sketchup software for 21th June - 14:00 hours

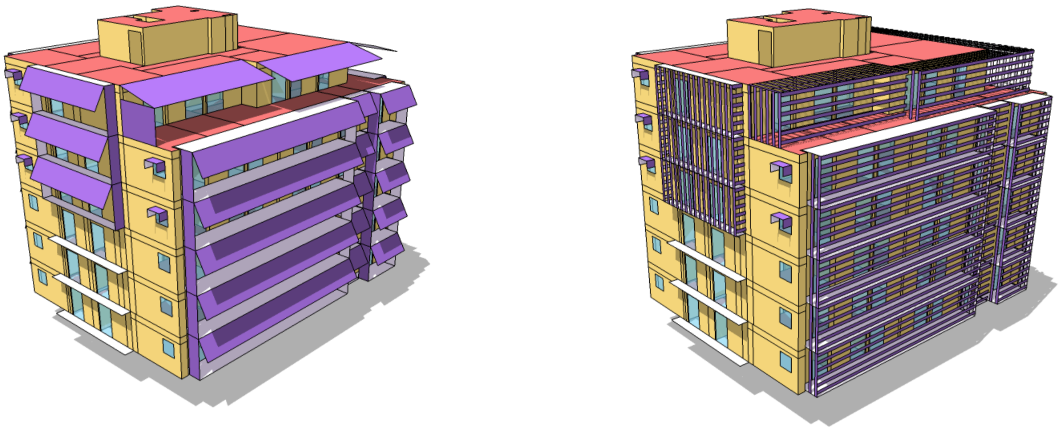


Fig. 6.4 Shading modelling of the south-east and south-west side of building MF2 in the Energy Plus engine (as depicted with the Open Studio tool of Google Sketchup software for 21th June - 14:00 hours)

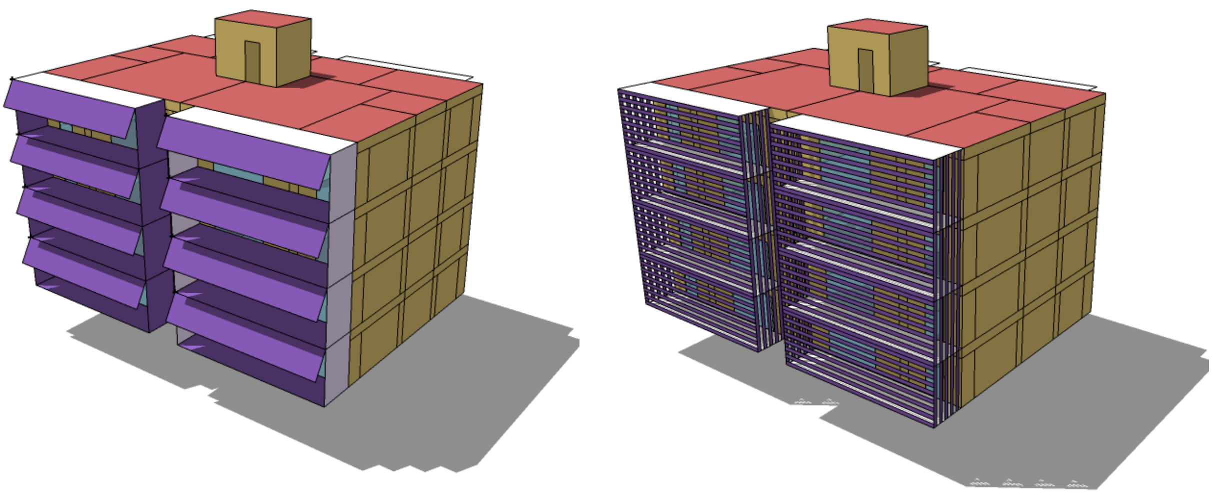


Fig. 6.5 Shading modelling of the south side of building MF3 in the Energy Plus engine (as depicted with the Open Studio tool of Google Sketchup software for 21th June - 14:00 hours)

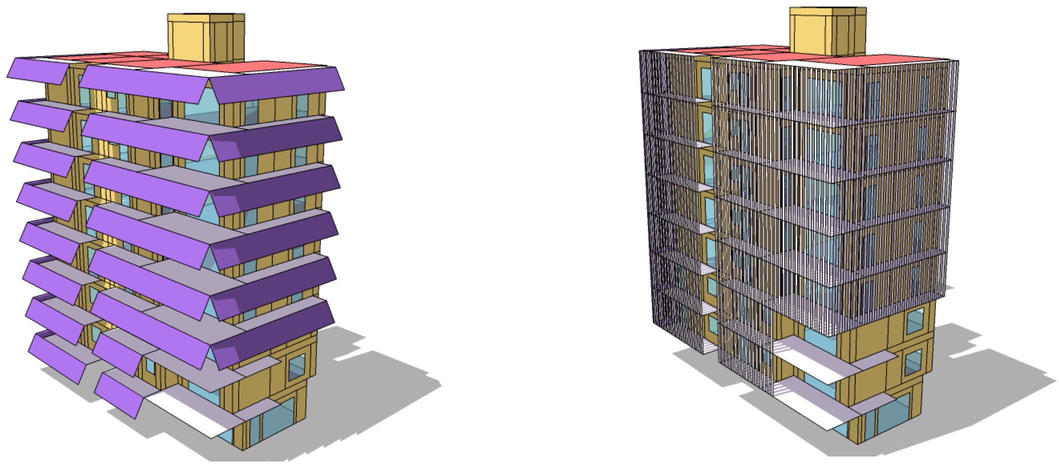


Fig. 6.6 Shading modelling of the south-east and south-west side of building MF4 in the Energy Plus engine (as depicted with the Open Studio tool of Google Sketchup software for 21th June - 14:00 hours)

The shading devices are coded as follows:

Aw_con: Awnings with automatic control

Aw_unc: Awnings without automatic control

Louvre_con: Louvers with automatic control

Louvre_uncon: Louvers without automatic control

6.2.5 Night ventilation

Besides shading control, passive cooling techniques can contribute drastically to the reduction of cooling loads. Due to their heavy construction type, Greek buildings have high thermal mass; as a consequence, heat is stored in the construction elements throughout the day, and radiated in the interior spaces during the night. Within this framework, night ventilation could efficiently dissipate excess heat from the building during the night hours.

In the proposed retrofitting scenarios, certain night ventilation schedules were evaluated. Initially, applicability and fan schedules were defined, with which the seasonal application of night ventilation and the daily operation of central fans of modelled air system were set (Table 6.15). Following limitations related to the temperature set-point of each thermal zone, the temperature difference between the internal and outdoor temperature and a minimum threshold for the zone temperature were assumed, in order to restrict the night ventilation only to absolutely necessary and efficient operation.

Table 6.15 Night ventilation schedules and system's proposed operational conditions

Schedules - Operational conditions	
Applicability schedule	01 May - 13 Oct 24 hours/day
Thermal zone temperature set-point	26 °C
Indoor / outdoor temperature difference	2 °C
Temperature lowest threshold	18 °C

The code for the night ventilation implementation is NC.

6.3 Alternative intervention scenarios

The aforementioned retrofit approach builds on the idea of the building's envelope enhancement. Alternative measures were also considered; in this case, the building's envelope is not a permanent element of the construction, whilst its function depends on the climatic conditions. Hence, the envelope consists of light, moveable elements. During the heating period, these elements are used to protect the inhabitants from the low temperatures. There are no separately conditioned thermal zones; the core of each apartment is the kitchen, both by means of the thermal zones' organisation, as well as of the apartment's uses and functions. The floor plan is characterised by free space and thus, increased flexibility as regards secondary usages. In addition, during the cooling period, this solution increases natural ventilation.

In the following figure, the scheme of this concept is depicted (Fig. 6.7). The kitchen functions as the central room, hence as a starting point of all other uses. The exposure to the external environment is controlled by flexible, moveable structures, which can vary by means of their transparency, weight, physical properties and functional role.

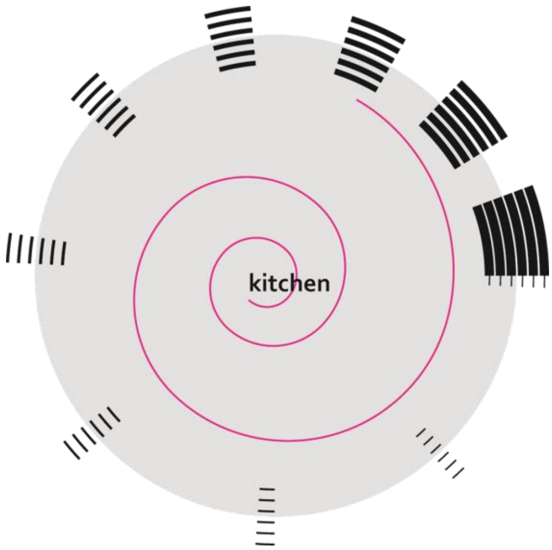


Fig. 6.7 Scheme for the alternative approach by means of *Polykatoikia* retrofitting actions

The Greek kitchen has always been a strong element of the residential architecture. Especially as regards traditional houses, both in insular, mountainous and continental areas, the kitchen functioned not only as the meeting spot of the family, but also as the main heating source of the house, as no other mechanical systems were used. Thus, cooking and heating had a synonymous meaning. The kitchen was placed either in a central position functioning as the core of the house, or separately, often even detached as the main room of all secondary uses (cooking, cleaning, laundry). The kitchen and the living-room were practically one open space characterised as "the daily room" (so called "*kathimerino*" in Greek).

Fig. 6.8 Typical floor plan of an mountain house in Little Papigko (260)

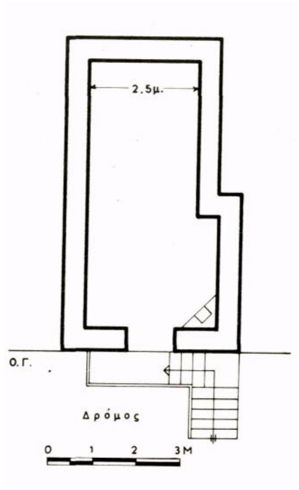


Fig. 6.9 Typical floor plan of an Cycladic house "*monochoro*" (261)

After the end of the First World War the role of the kitchen changed radically; the rooms were now separately heated and the apartments became the dominant residential element, especially in the urban areas. In the aftermath of the Second World War, the rapid urbanisation, along with the large numbers of refugees in the cities who needed immediate sheltering, led to the new residential type of the Greek *Polykatoikia*. The apartments started to shrink, in order to accommodate as many per floor as possible. Kitchens no longer functioned as the main room of the apartment; on the contrary they were now built as a separate room with the smallest possible dimensions, having a "secondary usage". This scheme continued to rule Greek apartments in the urban *Polykatoikies*.

It is important to compare the existing structure of each building under study with the new structure of an "open floor plan" scenario; the concept's realisation regarding the kitchen as the core of each apartment would transform the program of the floors radically. In this framework, following aspects should be considered concerning this intervention implementation:

a. Thermal mass

The thermal mass of the building is now reduced to its minimum, referring only to the horizontal construction elements. If applied in Climatic Zones with cold winters and rather warm summers, this fact could lead to low thermal comfort levels and, in the case of translucent materials, to overheating during summer periods and low temperatures during winter. On the other hand in warmer climates with rather small annual temperature variations and high relative humidity values this intervention could prove to be rather efficient. In this case, the climatic conditions of Thessaloniki do not assure thermal comfort conditions and therefore can be considered to be rather inappropriate for such interventions.

b. Soundproofing

In order to avoid low acoustic comfort levels, as *Polykatoikies* are mostly located in a dense urban environment, materials with high soundproofing properties should be used.

c. Privacy issues

Due to the dense urban environment, the new envelope material should enable solutions that will ensure the privacy of the owners.

d. Natural daylight

In the case of translucent or semi-translucent materials, the daylighting will decrease electricity needs for lighting of the apartments. Moreover, in case of non-residential use, such as offices this could be a very energy efficient intervention. If properly studied the loads could drop significantly. Albeit it is important to prevent possible glare problems and overheating during summer.

e. End of life treatment (Dismantling-demolition)

The implementation of this measure presupposes a large scale demolition and construction material waste management, which will improve the environmental impact of such interventions.

f. Static issues

Radical changes concerning the load-bearing structure of the *Polykatoikia*, refer to a very sensitive topic, due to Greece's high seismic activity. Consequently, interventions regarding the buildings' envelope, concerning whether demolition of brick walls, or other construction elements, should be planned very carefully.

g. Economic feasibility

In terms of economic viability, it is difficult to achieve a positive benefit/cost ratio, especially if the demolition and the new envelope's implementation costs are considered. On the other hand, if the architectural solution ensures energy efficiency and thermal, acoustic and visual comfort and the demolished materials are to be recycled this could be an overall environmental and economic feasible intervention.

h. Large scale retrofit

By means of energy conservation policy planning, it is rather difficult to determine specific requirements and to achieve their actual implementation, due to the complexity and diversity of the *Polykatoikies*. The solutions require high architectural quality combined with accurate interventions planned for specific groups of typologies.

i. Usages

Polykatoikies have proven to function both as residential and commercial buildings. Mixed usage in city centres is a common phenomenon related to urban MF – buildings (64), (59). A reformation of the floor plan could support solutions related to specific occupancy profiles. Hence, apartment types can be re-formed in order to cover the needs of specific owners' profiles for each area of the cities.

In general, the implementation of such interventions could, or rather should, be studied in terms of a redefinition of *Polykatoikia's* function and actual design, under the provision of specific climatic conditions and the resolving of relevant technical issues. It appears to be an interesting challenge, as main part of some further research.

6.4 Optimal intervention scenarios for the Greek Polykatoikia

Greek *Polykatoikia* reflects without doubt a complex residential typology. Although differing in shape, height, number of apartments per floor, density, program, openings, their attachment status, orientation and structure of the ground floor, they present a similarity; they are all constructed based on a repetitive grid, in order to adjust to the antiseismic requirements. This grid always consists of a number of columns and the main circulation core (64), whilst the basic construction materials of the urban *Polykatoikia* consist of reinforced concrete and brick. In addition, as underlined earlier, the quality of the building envelope in terms of energy behaviour is rather poor, at least regarding the majority of the existing building stock.

Based on these characteristics and following the global tendency by means of retrofitting measures, the commonly used and studied energy conservation interventions are:

- retrospective thermal insulation of the building envelope

- interventions concerning the operation of the HVAC systems

- integration of passive cooling and heating techniques in order to reduce the respective loads

- implementation of RES systems

This thesis deals with the energy, environmental and economic evaluation of such measures as a part of an integrated methodological approach. In chapter 7, a set of intervention scenarios are studied and their overall efficiency is assessed. The diversity of the results indicates the potential for several combinations under the scope of architectural creativity. Hence, although most of the retrofit policies are limited to the thermal insulation of the envelope, a mix of techniques could drastically improve the energy performance of the *Polykatoikia*.

In addition, according to the current climatic conditions, alternative and original intervention scenarios could be studied. *Polykatoikia* functions as a living organism; although there is a rule, which defines the similarities among the *Polykatoikies*, each building is different than the others by means of their façade, their program, their floor plan organisation. Hence, this residential typology is appropriate for the exploring of new ideas regarding energy conservation measures. Consequently, the *Polykatoikia* gives the planer the opportunity to become creative, even in the framework of typical interventions as well as beyond. This fact is considered to be one of the main perspectives for further research as indicated in chapter 8.3.

Concluding, this Thesis examines a broad spectrum of typical interventions combining them according to their energy, economic and environmental feasibility. Besides these evaluation parameters, architectural aspects are discussed in order to propose interventions that will ensure the integrity of this complex residential typology. In this line of thought, both the interventions and their evaluation are assessed through an architectural prism.

7 Results

Based on the methodological approach concerning the retrofit measures in chapter 6.1, each intervention was studied according to its specific features. Hence, overall 154 simulations have been performed for all MF – buildings under study, namely 65 for the thermal insulation scenarios, 36 for the openings, 12 for the green roofs, 4 for the cool materials, 8 for the HVAC systems, 8 for the renewable energy systems, 16 for the shading and 4 for the night ventilation scenarios. After the first evaluation of each intervention scenario, specific combinations have been designed and new simulation controls were performed, according to the scheme illustrated in Fig. 6.1. Afterwards, the evaluation of these combined scenarios, led to the development of specific intervention measures, which could form the foundation of large scale intervention scenarios for the urban area of Thessaloniki. The complete progress of the outcomes' evaluation is thoroughly analysed in the following chapters and illustrated in detailed Tables in the Appendix chapter (Table 10.1 - Table 10.36).

7.1 General results

In order to obtain the outcomes a flexible evaluation matrix was created. This matrix allows the targeted combination of various scenarios according to specific evaluation parameters, as described in chapter 6.1. In this framework an overview is enabled for each intervention. Following symbols are used:

↑ Positive impact assessment compared to the other solutions

↓ Negative impact assessment compared to the other solutions

o Neutral impact assessment compared to the other solutions

More specifically, based on the tables in the appendix (Table 10.1 - Table 10.36) a generalised, qualitative assessment was performed. Hence, the main criteria of minimum requirements, maximum energy savings, overall feasibility and environmental impact were analysed according to second series of criteria, such as the least cost, technical issues and specific requirements. The degree to which these criteria apply varies for each intervention and it is explained in the following chapters.

In the following Tables (Table 7.1 - Table 7.20) the evaluation of each intervention reflects its comparison to the rest of the interventions of the same category. In the cases of cool materials and night ventilation, with only one scenario per intervention category and no further sub-criteria applicable, their overall evaluation is performed by comparing them to the rest of the presented interventions. In other words, each of the following tables demonstrates the relation of the basic evaluation criteria and the secondary sub-criteria analysed in chapter 6.1 and depicted in Fig. 6.1.

7.1.1 Thermal insulation

The first obvious conclusion is that extruded polystyrene illustrates the worst score overall, which, considered its large share in the Greek market, is a significant output (Table 7.1, Table 7.2, Table 7.3). On the other hand, expanded polystyrene is the undisputed winner, whilst stonewool performs relatively well. By means of technical issues, emphasis is laid on the width of insulation materials. In particularly, large insulation widths would lead to shrinked balconies and therefore ergonomic problems, especially for buildings constructed before the revision of the first Greek Seismic Code of 1954 in 1985 since they have shorter overhangs, mainly due to static reasons. Hence, besides space issues, the additional static load is also an important parameter, concerning the retrospective thermal insulation of vertical surfaces. In this framework, the weight and widths of stonewool led to its negative evaluation (technical issues). On the contrary, smaller widths can be achieved with both extruded and expanded polystyrene due to their low λ-value of 0.031 W/mK. Furthermore, under the term of "specific requirements" high soundproofing and fireproofing are to be understood, especially for the case of stonewool, although no legislative framework exists to set specific standards, especially when it comes to the residential sector. In addition, high vapour permeability is also a positive characteristic concerning stonewool, especially for humid cold areas. For both expanded and extruded polystyrene, specific requirements concern smaller installation widths (λ-value 0.031 W/mK) due to the aforementioned restrictions as regards balcony widths.

In the following Tables (Table 7.1,Table 7.2, Table 7.3) a combinatorial evaluation is presented. More specifically the positive, negative or neutral evaluation reflects the performance of each material compared to the other two.

Table 7.1 Evaluation matrix for stonewool

	Stonewool	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↓	↓	O	↑
	Technical issues	O	↓	O	O
	Specific requirements	↑	↑	↑	↑

Table 7.2 Evaluation matrix for expanded polystyrene

Expanded polystyrene		Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↑	↑	↑	O
	Technical issues	↑	↑	↑	↑
	Specific requirements	↓	↓	↓	↓

Table 7.3 Evaluation matrix for extruded polystyrene

Extruded polystyrene		Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	O	O	↓	↓
	Technical issues	↑	↑	O	O
	Specific requirements	↓	↓	↓	↓

In terms of life cycle costing (LCC), expanded polystyrene performs better, according to the primary and final energy results (Table 10.1, Table 10.10, Table 10.19 and Table 10.28). Hence, based on the LCC analysis and the environmental score, the overall LCA analysis ("Feasibility"), the most feasible scenario for the majority of the typical buildings is EPS_4, namely 6cm expanded polystyrene with a thermal conductivity rate 0.031 W/mK. It should be underlined, that in cases of small demand on U-value improvement, and eventually small thicknesses of material required, the economic feasibility is not improved significantly concerning all the insulation materials considered.

7.1.2 Replacement of windows and glass doors

In the following tables the assessment for the openings' interventions is depicted. Besides the U-value parameter, the glazing type remains the same for all three scenarios. On the contrary the infiltration rate changes drastically, affecting the heat losses of the building (chapter 6.2.1.2).

Under the term specific requirements one cannot fail to consider architectural aspects. Thus, in case of specifications regarding the façade design, wooden or metallic framed openings could be preferred instead of PVC frames. It is important to note that according to the latest statistics aluminium framed openings hold the largest market share by 72%, followed by wooden (16%) and PVC frames (12%), at least as regards new constructions (262). The results of the overall evaluation are presented in the following tables (Table 7.4, Table 7.5, Table 7.6).

Table 7.4 Evaluation matrix for wooden frames

	Wooden frame	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	O	↓	O	↑
	Technical issues	↓	↓	↑	↑
	Specific requirements	↓	↓	O	↑

Table 7.5 Evaluation matrix for PVC frames

	PVC frame	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↑	↑	↑	O
	Technical issues	↑	↑	O	O
	Specific requirements	↓	↓	O	↑

Table 7.6 Evaluation matrix for aluminium frames

	Metal frame	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↓	O	↓	↓
	Technical issues	O	O	↓	↓
	Specific requirements	↑	↑	O	↓

Moreover, it is important to underline that the outcomes of a life cycle assessment strongly depend on the assumptions and the system boundary (263). In particular, various LCA studies concerning the operational phase of window frames, underline its dominant role as regards greenhouse effect (264). In this line of thought, recent reviews argue that no material has advantages in every impact category, whilst optimisation of the frame structures can lead to a better overall performance, such as:

(a) improvement of the U-values,
(b) increase of secondary and recycled material during the production phase
(c) minimisation of the amount of material needed for the same purpose (263)

Thus, recycling can lead to reduction of primary energy as well as resources by means of all window frames and in particular for non renewable materials such as PVC and aluminium (263). Hence, although the embodied energy for the aluminium frame is considered to be the highest, if the production of aluminium frames is based on recycled materials, the embodied energy drops significantly. In addition, the long estimated service life as well as the low maintenance demands and high durability should also be considered, which confer the aluminium window frames a competitive advantage to PVC frames (265). This is also the reason for the rising market share of al-clad wood frames. In our case, according to the LCC results (Table 10.1 - Table 10.36), the PVC-frame scenario with an opening U-value of 2.8 W/m^2K is overall the second most feasible intervention after wooden frames (Table 10.2, Table 10.11, Table 10.20 and Table 10.29). However, it is important to notice that with better U-values (compared to the KENAK limitation of 2.8 W/m^2K) the investment cost of wooden frames rises. Hence, as regards the least costs aspect one should take into serious consideration the rather poor U-value requirements set by the current legislation framework.

In addition, as the LCA analysis was performed for the 30 year life span of the building, the beneficial long time estimated service life of aluminium frames is not reflected in the current results. In this framework, the scenario of the overall environmental score for the aluminium frame could be significantly improved, if the life time was raised up to 15 years and, in addition, larger amounts of recycled products were to be used. As a result, and only from a cost effective point of view, the PVC window frames were chosen, by means of their low investment cost.

7.1.3 Green roofs

As regards green roofs, static issues are of great importance. Hence, although the extensive type, does not offer the best energy efficiency results, it was preferred for the combined scenarios. It is important to note that these results would differ to a great extent if the additional costs for static loads were also included in the LCC evaluation, leading to a better cost benefit rate for the extensive green roof type (Table 10.5, Table 10.14, Table 10.23, Table 10.32). These costs however are very difficult to determine and were not considered to be within the scope of this thesis. The following tables demonstrate this fact by means of "specific requirements" and "technical issues" (Table 7.7, Table 7.8, Table 7.9).

In this framework, the first term "specific requirements" refers to static matters, whilst "technical issues" is used to describe the need for irrigation and all relevant maintenance factors. In addition, it is important to underline the fact that no thermal insulation layer was added to the green roof construction, in order to obtain the actual benefits of this intervention by means of their energy performance.

Table 7.7 Evaluation matrix for the extensive green roof type

	Extensive type	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↓	↓	O	↑
	Technical issues	↑	↑	↑	↑
	Specific requirements	↑	↑	↑	↑

Table 7.8 Evaluation matrix for the semi-intensive green roof type

	Semi-intensive type	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	O	O	↑	↑
	Technical issues	O	O	↑	↑
	Specific requirements	O	O	↓	↑

Table 7.9 Evaluation matrix for the intensive green roof type

	Intensive type	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↑	↑	O	↑
	Technical issues	↓	↓	↓	↑
	Specific requirements	↓	↓	↓	↑

Larger widths of soil and foliage density lead to higher energy performance, as expected. Consequently, intensive green roofs perform better in terms of maximum energy savings, however their maintenance needs are high. Further issues, mainly concerning static loads, lead to a better performance of the extensive green roof types. In the same line of thought semi-intensive green roofs provide a midway solution.

7.1.4 Cool materials

With respect to cool materials' implementation, their overall performance is rated as very efficient (Table 10.3, Table 10.12, Table 10.21, Table 10.30). In this line of thought, they have been used for both vertical and horizontal building surfaces in order to achieve further cooling load reduction (Table 7.10).

Table 7.10 Evaluation matrix for cool materials

	Cool materials	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↓	O	↑	↑
	Technical issues	↓	O	↑	↑
	Specific requirements	↑	↑	↑	↑

In this case, the term "Technical issues" describes issues related to the need for scaffolding at the building's façade. On the other hand, specific requirements reflect their flexibility as regards the architectural enhancement of the building, due to their large variety in colours and finishing solutions in general. Hence, in case of a retrospective thermal insulation implementation on the vertical construction elements of the building, matters linked to Technical issues are automatically eliminated and the implementation of cool materials is considered to be feasible again. It is worth mentioning that the positive evaluation regarding the environmental impact does not refer exclusively to the materials' environmental footprint, rather than its overall environmental performance compared to other interventions as indicated above.

7.1.5 HVAC systems

The HVAC systems refer to the heating and cooling systems of the MF – buildings under study (Table 7.11, Table 7.12, Table 7.13). Since the heating loads are in all cases higher than the cooling loads, and the central heating systems also cover fraction of the DHW demands, the results were as expected (Table 10.6, Table 10.15, Table 10.24, Table 10.33); More specifically, if one should chose between these two HVAC interventions, the heating systems' replacement is of higher priority regarding the building's overall energy performance, compared to the upgrade of the A/C, especially in terms of economic feasibility. It should be noted that this conclusion is strongly related to the climatic conditions of Thessaloniki, located in the second coldest Greek Climatic Zone. However, it is important to underline the fact that the latent cooling loads of Thessaloniki are high due to the high humidity levels and can only be managed with mechanical cooling systems.

Table 7.11 Evaluation matrix for the heating systems

	Heating systems	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↑	↑	↑	↑
	Technical issues	↓	↑	↑	↑
	Specific requirements	O	↓	↑	↑

Table 7.12 Evaluation matrix for the cooling systems

	Cooling systems	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↓	↓	↓	↓
	Technical issues	↑	o	o	↓
	Specific requirements	o	↑	↓	↓

In the case of the heating system, technical issues refer to the complicated procedure of retrospective thermal insulation concerning the distribution network, due to limited access. Moreover, specific requirements concern the ventilation needs of boiler rooms, hence openings are required; in any other case, wall mounted gas-boilers could be used, though having negative effect on aesthetics and safety (technical issues).

As regards cooling systems, specific requirements refer to energy class A+ and A/C split units' compressors equipped with inverters, leading to a rise in costs. Again the parameters of aesthetics should be taken into account. Relative topics have been thoroughly discussed in chapter 2.2.2.

Finally, as concerns primary energy consumptions, it is worth mentioning that the primary energy factor for electricity is 2.9, thus almost 3 times higher than that for natural gas (1.05) and for oil (1.10). Therefore, A/C units' replacement eventually leads to noticeable savings regarding primary energy consumptions.

7.1.6 Renewable energy systems

In terms of renewable energy systems' implementation, solar collectors undoubtedly reflect the best case scenario. Not only do they perform better than the PV-systems in the overall rating matrix, they are also particularly more efficient compared to all scenarios under study (Table 10.7, Table 10.16, Table 10.25, Table 10.34). As regards PV- systems, monocrystalline panels achieve a greater annual energy production and overall LCA rate, due to their higher module efficiency and eventually installed capacity. On the contrary, polycrystalline PVs reach a satisfying performance only in terms of environment impact.

Table 7.13 Evaluation matrix for solar thermal systems

Solar thermal		Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↑	↑	↑	↑
	Technical issues	O	O	↑	↑
	Specific requirements	↑	↑	↑	↑

Table 7.14 Evaluation matrix for monocrystalline PV - systems

Monocrystalline PV		Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↓	O	↓	↓
	Technical issues	O	O	O	↓
	Specific requirements	O	O	O	↓

Table 7.15 Evaluation matrix for polycrystalline PV - systems

Polycrystalline PV		Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↓	↓	↓	O
	Technical issues	↓	↓	↓	O
	Specific requirements	↓	↓	↓	O

According to the above tables, the RES feasibility combined with the least costs is proved to be profitable only for the option of SWH systems, given the lower investment cost required as well as their efficient coverage of buildings' hot water demands. As regards PV systems they are assumed to be off-grid, thus not being eligible for high state's feed-in tariff provisions granted for residential grid-connected systems. Overall they prove not to be economically beneficial, among other reasons, also due to the current electricity retail prices that are still relative low and inadequate to ensure a long-term viability for off-grid PV applications.

As far as" technical issues" are concerned, they refer to the actual installation and operation of the RES systems applied on roof-top surfaces. More specifically, at first they are associated with the lack of solar suitability of available roof surfaces, as long as intensive shading effects are occurred by opposite and adjacent buildings in typical Greek dense urban environment and last but not least by the roof configurations itself. Other technical limitations include mounting device applications on existing roofing insulation; particularly for the case of solar collectors, a retrospective hot water distribution network installation is a complex task, especially for the MF – buildings' typology, where such interventions had not been foreseen initially by the contractor. When it comes to PVs, "technical issues" lead to respective negative evaluation due to reduced coverage of building's own electricity consumptions ("minimum requirements"). Still, monocrystalline PV systems perform better in certain scenario than polycrystalline ones, due to the greater installed capacity.

Interesting outcomes are also obtained for "specific requirements" that concern legislated and regulated restrictions and standards for RES building applications. Roof installation restrictions, reduce to a great extent the available areas. For instance, solar thermal and PV - system should not exceed the legal virtual volume of the building, or should be installed at fixed distance from the perimeter of the roof (158). As concerns particularly solar thermal systems, "specific requirements" set also by KENAK, foresee a 60% minimum threshold ("requirements") for annual solar DHW fraction in the case of newly constructed buildings or, as in this case, retrofitting of existing buildings (17).

Finally, analysing environmental issues the electricity consumed to manufacture framed PVs is estimated higher for single-crystal silicon modules compared to polycrystalline ones (266).

By means of the combination scenarios and the respective retrofit actions proposed in chapter 7.2, the combination of SWH with PV systems was not efficient in terms of economic feasibility. Hence, as priority should be laid on the DHW demands, due to 60% regulative threshold of KENAK for retrofitting, an additional installation of PVs would result in low installed PV capacity and apparently less beneficial intervention. Conclusively, the optimum option should include particularly only SWH systems.

7.1.7 Shading

With respect to the shading systems' implementation, four scenarios were studied; the two first concern controlled and uncontrolled awnings and two last scenarios refer to controlled and uncontrolled louvers (Table 7.16, Table 7.17, Table 7.18, Table 7.19). It is a fact that both the construction and installation of louvers requires higher investment cost. On the other hand, from an architect's point of view, louvers can become a significantly more flexible tool both for the shading requirements of the building and the reformation of its façade. Consequently, technical issues are mainly associated with the realisation of such measures and the construction works' procedure; for instance, in the majority of the Greek residential buildings, awnings already exist. On the other hand, vertical and horizontal louvers require extensive works, regarding their mounting and a respective adaptation of the railing. Hence, although a louver installation with a solar tracking system influence energy performance of the buildings at a higher level, technical issues as well as their economic feasibility, lead to an overall poorer performance compared to awnings systems. Last but not least, special requirements reflect aesthetics and design necessities, underlining the "clear lead" of such systems in contrast to awnings.

In this framework, based on the results of the computations concerning shading systems, the most feasible solution is the one of the controlled awnings (Table 10.4, Table 10.13, Table 10.22, Table 10.31).

Table 7.16 Evaluation matrix for controlled awing systems

	Awnings controlled	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↓	O	↓	↑
	Technical issues	O	O	↑	↑
	Specific requirements	O	↓	O	↑

Table 7.17 Evaluation matrix for uncontrolled awing systems

	Awnings uncontrolled	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	O	O	↑	↑
	Technical issues	↑	↑	↑	↑
	Specific requirements	↓	O	O	↑

Table 7.18 Evaluation matrix for controlled louvers

	Louvers controlled	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↓	↑	↓	↑
	Technical issues	↓	↓	O	↑
	Specific requirements	O	O	O	↑

Table 7.19 Evaluation matrix for uncontrolled louvers

	Louvers uncontrolled	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	Least costs	↓	O	↓	↑
	Technical issues	↓	↑	↓	↑
	Specific requirements	↑	↑	↑	↑

7.1.8 Night ventilation

With respect to night ventilation, the overall efficiency of this intervention is rather high (Table 7.20). The minimal intervention cost compensates for the relative low energy savings, by means of cooling loads' reduction (Table 10.8, Table 10.17, Table 10.26, Table 10.35). Once again the low reduction of the cooling energy consumption is a result of the lower sensible cooling loads in the area under study, which falls within Climatic Zone C. It should be noted that in warmer areas (Climatic Zone B and A) the results would differ accordingly.

Table 7.20 Evaluation matrix for night ventilation

	Night ventilation	Minimum requirements	Maximum energy savings	Feasibility	Environmental impact
		scenarios			
strategies	**Least costs**	↑	o	↑	↑
	Technical issues	↓	o	↑	↑
	Specific requirements	↓	↓	↓	↑

In the case of night ventilation the term "Technical issues" reflects matters of security, whilst special requirements describe the case of an automatic control. As a consequence the implementation costs would rise and the overall feasibility would not be as positively evaluated as in the case under study.

7.2 Combinations

Based on the above assessment of each intervention solution and their analytic evaluation illustrated in the tables of the appendix, certain combinations were determined. They are prioritised starting with the buildings' envelope, followed by two extra separate scenarios. The first aims at the maximum possible heating consumption reduction and the second to the respective cooling load minimisation. Thereafter, a full combination is evaluated, as depicted in Fig. 7.1.

Furthermore, apart from the aforementioned evaluation of each proposed retrofit action, each building is studied in detail, whilst the respective combinations fit to their special energy requirements. These are presented in the following chapters.

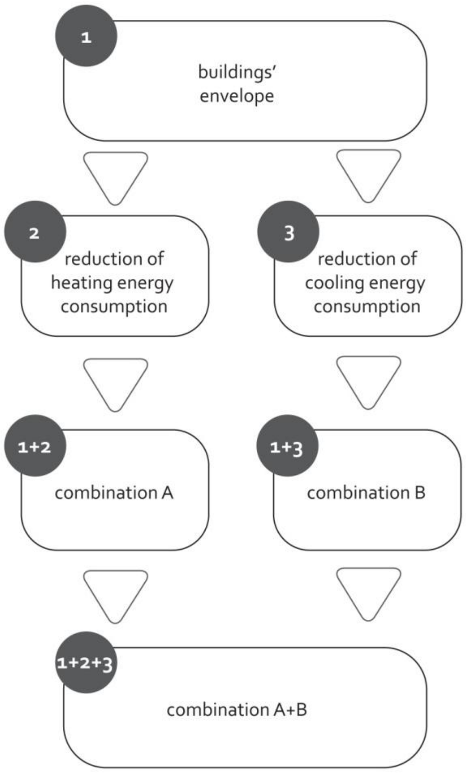


Fig. 7.1 Combination of the intervention scenarios

7.2.1 Building MF1

Based on the outcomes for each retrofit scenario, 13 combinations were tested in terms of their overall efficiency (Table 10.9). In Table 7.21 a summarised depiction of the results can be obtained.

Table 7.21 Summarised depiction of the results for the combined interventions' scenarios - building MF1

Scenario	LCC	Env. Score	Score	Final Energy Consump-tion
	[€]	[pt]	[pt]	[kWh/m^2]
Thermal insulation + windows replacement	476,054	136.43	221.11	56.39
Thermal insulation + boiler & A/C replacement	400,516	125.47	196.94	53.15
Thermal insulation + Green Roof + Controlled shading + Night ventilation+ Cool materials	457,831	139.11	222.90	64.90
Thermal insulation + boiler & A/C replacement + Green Roof + Controlled shading + Night ventilation+ Cool materials	427,818	115.73	183.42	45.11
Thermal insulation + boiler & A/C replacement + Solar collectors	270,500	57.73	84.84	21.61
Thermal insulation + boiler & A/C replacement + PV-system	359,332	97.34	148.85	37.18

Initially, they are organised with respect to their main scope. For instance, the basic envelope interventions were combined (MF1_EPS_4+W1). The evaluation of this scenario shows that changing the openings would not contribute to the overall energy balance as expected given the relative high investment cost. Comparing the base case scenario with the scenario of the thermal insulation implementation (MF1_EPS_4) and this combined scenario, it becomes evident that the improvement of both the LCC and the LCA scores is mainly achieved due to the ETICS system's implementation. Hence, the thermal insulation scenario was chosen for further combination with HVAC interventions (MF1_EPS_4+BB+AC), which performed well, as expected.

Furthermore, a full "cooling load" oriented scenario was tested that led to positive overall scores, though not as energy efficient as expected. Thereafter, the building's behaviour after the implementation of thermal insulation combined with a green roof system was assessed, performing rather poorly, especially compared to the rest of the combinations. In addition, the worst environmental and LCC rates can be observed for the case of the mixed implementation involving awnings, thermal insulation and night ventilation (MF1_EPS_4+Aw_Con+NC). The second worst performance was achieved by another "cooling load" oriented scenario combining all related interventions, HVAC systems excluded (MF1_EPS_4+GR_ext+Aw_Con+NC+CM). Finally, in line with the results of the individual outcomes concerning RES implementation, as presented in the previous section, their combination improves the energy, environmental and economic feasibility of the building to a great extent. In particular, SWH are combined with the best scenario in terms of environmental and overall scores, thus scenario MF1_EPS_4+BB+AC. The results show a drastic minimisation of the LCC and the environmental indicators, consequently a better overall performance, with a relative low initial investment cost.

7.2.2 Building MF2

In the case of building MF2 the evaluation of the results is not as easy as expected, unlike the case of building MF1. An overview of the most important intervention combinations is depicted in Table 7.22.

Table 7.22 Summarised depiction of the results for the combined interventions' scenarios - building MF2

Scenario	LCC	Env. Score	Score	Final Energy Consump-tion
	[€]	[pt]	[pt]	[kWh/m^2]
Thermal insulation + windows replacement	752,670	156.16	254.88	16.21
Thermal insulation + windows, boiler & A/C replacement	723,984	129.81	205.54	11.11
Thermal insulation + windows, boiler & A/C replacement + Solar collectors	743,732	134.16	210.30	10.83
Thermal insulation + windows, boiler & A/C replacement + PV-system	667,929	92.25	141.47	5.86
Thermal insulation + windows, boiler & A/C replacement + Green Roof + Controlled shading + Night ventilation	788,436	117.12	188.01	10.58
Thermal insulation + Green Roof + Night ventilation+ Cool materials	692,815	144.50	235.10	15.28

It is very difficult to simultaneously deduce an optimum scenario from an environmental, economical and energy efficiency point of view for this building type. The results significantly differ from those of building MF1, although they both refer to the same Building Class (chapter 4.3 and Table 4.1). This is due to the higher external surface area (detached building type), which in turn increases the openings' surface, leading to diverse results as regards the scenario concerning the upgrading of windows and glass doors.

Secondly, the overall assessment of the RES is not as efficient as in all other buildings. This is due to the fact that MF2 is the largest building, apparently with the highest domestic hot water demands. Moreover, analogous to the high DHW demands, only 10% of the electricity demands are covered. It is important to note that the DHW and electricity demands do not rise proportionally to the available roof surface area, as they depend on total built areas and the number of occupants. In addition, the initial investment cost is amplified, leading to relatively poor results concerning the LCC evaluation of these interventions, although the environmental and overall score are noticeably improved.

More specifically, given that the retail electricity rates are rather low (267), the life cycle cost of SWH systems prove to be rather high. As regards the PV - systems they are assessed as off grid, thus the respective benefits linked to the profitable, current Greek granted feed in tariff do not affect the LCC analysis. Nevertheless, their evaluation is plausibly good. However, the initial investment cost is so high that such an implementation cannot be promoted straightforwardly. Concluding, as the rest of the implementations seem to have similar outcomes, as for MF1, the most beneficial retrofit is MF2_EPS_5+NC+GR_ext+CM, at least from a cost benefit point of view. On the other hand, if the same scenario is evaluated in terms of ecological aspects, its implementation is not recommended due to its poor environmental performance.

7.2.3 Building MF3

For building MF3 the results are very similar to the ones of building MF1. Due to the low window to wall ratio and the lack of thermal insulation (uninsulated load bearing structure, badly insulated cavity walls), ETICS is overall feasible, dissimilar to the glass doors' improvement. The most beneficial retrofit scenario is MF3_EPS_T4+BB+AC+NC+SC (Table 10.27), which includes thermal insulation, improvement of the HVAC systems, night ventilation and solar collectors. The LCC, environmental and overall scores are very satisfying, compared to the relative initial high investment cost (Table 7.23).

Table 7.23 Summarised depiction of the results for the combined interventions' scenarios - building MF3

Scenario	LCC	Env. Score	Score	Final Energy Consump-tion
	[€]	[pt]	[pt]	[kWh/m^2]
Thermal insulation + boiler replacement	337,935	95.42	152.50	35.44
Thermal insulation + boiler & A/C replacement	332,117	90.92	144.00	32.52
Thermal insulation + windows, boiler & A/C replacement + Green roofs + Cool materials + Night ventilation	395,404	86.65	139.57	29.27
Thermal insulation + boiler & AC replacement + Night ventilation+ Solar collectors	252,535	44.45	65.33	11.32
Thermal insulation + boiler & A/C replacement +Night ventilation+ PV systems	259,295	41.32	59.22	7.43

7.2.4 Building MF4

Unlike all other buildings under study, in the case of MF4 thermal insulation implementation is not profitable. This is an absolutely comprehensible outcome, as the building is relatively new and insulated according to TIR (Table 10.36). Table 7.24 shows the main interventions that represent most of the combination scenarios based on the analytical Table 10.36.

Table 7.24 Summarised depiction of the results for the combined interventions' scenarios - building MF4

Scenario	LCC	Env. Score	Score	Final Energy Consump-tion
	[€]	[pt]	[pt]	[kWh/m^2]
Thermal insulation + boiler replacement	446,736	112.54	184.64	54.16
Thermal insulation + boiler & A/C replacement	436,760	104.69	169.76	49.76
Thermal insulation + boiler & A/C replacement + Night ventilation	433,382	103.04	167.06	49.21
Thermal insulation + boiler & A/C replacement + Night ventilation+ Cool materials	442,102	102.62	166.61	48.82
Boiler & A/C replacement + Night ventilation+ Cool materials	446,734	131.07	215.18	75.42
Boiler & A/C replacement + Night ventilation+ Cool materials + Solar collectors	406,177	107.65	170.87	47.80
Boiler & A/C replacement + Night ventilation+ Cool materials + PV-systems	414,577	108.36	176.21	65.36

Apart from the results concerning thermal insulation, the high rated interventions are similar to the ones of the aforementioned buildings. The combination of HVAC systems upgrade along with night cooling, cool materials and solar collectors for DHW, seems to represent the most reasonable intervention from all points of view. Furthermore, solar collectors combined with upgrading of the HVAC system and interventions concerning the cooling load limitation are performing proportionally well in terms of energy efficiency, environmental assessment and life cycle costing.

7.2.5 Overview of the optimal scenarios according to the buildings' typology

7.2.5.1 Parameter Architecture

Based on the precept of "combined refurbishment" presented in chapter 2.2.2 as well as the findings that were described above that were analysed in chapter 6.1 (Fig. 6.1), an overview of the outcomes is presented in this chapter. More specifically the three sub-criteria that are used for the assessment of the retrofitting strategies are:

(a) technical issues,

(b) the least-cost approach and

(c) special requirements

The respective technical issues have been described for each intervention category in the previous chapters. Moreover, special requirements are mainly linked to architectural aspects. In this framework, Table 7.25 depicts the relation of these two parameters for each building typology. Thereafter, architectural aspects are linked to each intervention in order to underline the importance of this sub-criteria.

Table 7.25 Architectural and economic aspects for each intervention



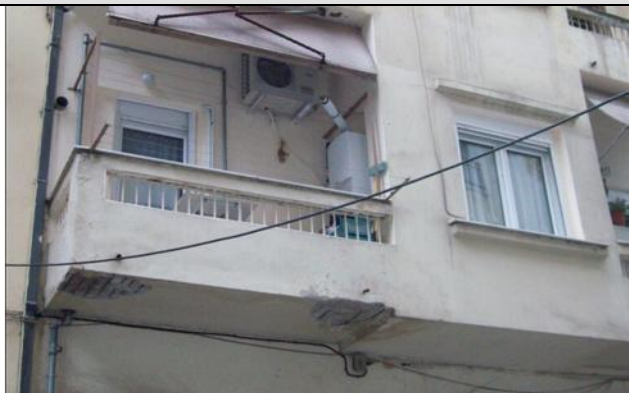

	MF1		MF2		MF3		MF4	
	architecture	cost benefit	architecture	cost benefit	architecture	cost benefit	architecture	cost benefit
Thermal insulation	↑	↑	↑	↑	↑	↑	↑	↓
Windows replacement	↑	↓	↑	O	↑	↓	↑	↓
Green roof	↑	O	↑	↑	↑	↓	↑	↓
Cool materials	↑	O	↑	↑	↑	O	↑	↑
HVAC systems	↓	↑	↓	↑	↓	↑	↓	↑
RES	↑	↑	↑	↑	↑	↑	↑	↑
Shading	↑	↓	↑	↓	↑	↓	↑	↓
Night ventilation	O	↑	O	↑	O	↑	O	↑

The evaluation of envelope related interventions is considered to be positive overall, under the condition that they are properly and carefully applied. The negative evaluation of the HVAC replacement reflects the often randomly installed AC-split unit systems on the buildings' façades.

This is a problem that can easily be solved in terms of clever and imaginative design and innovative ideas with respect to their integration in the *Polykatoikia* façade. Furthermore, RES systems are in most cases economically feasible if associated with DHW reduction due to the installation of solar thermal systems.

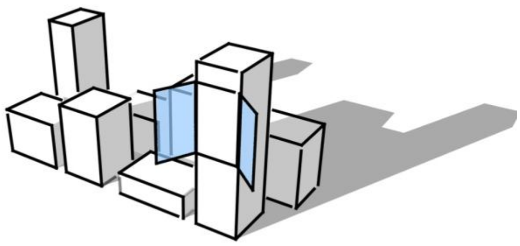
Hence, the effect of these interventions on the architecture of the building cannot be quantified. It is an absolutely qualitative characteristic that can only be assessed separately. Apart from the improvement of the energy efficiency, the urban Greek residential buildings are aesthetically upgraded and this is depicted in the pictures bellow.

1. Thermal insulation / possible combination with cool materials



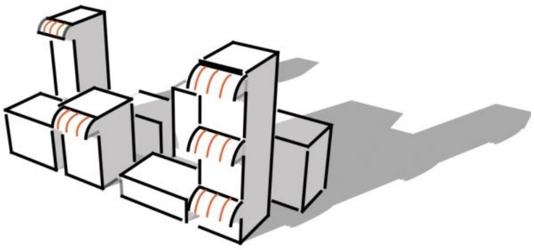
It was already underlined that the majority of the Greek urban buildings and in particular those of residential use were constructed before 1980. Besides issues of thermal insulation this fact implies a long process of aging that was accelerated by the unfriendly urban environment. The retrospective implementation of thermal insulation can solve issues of façade deterioration. Such actions can easily be combined with cool coatings for the improvement of the buildings' energy behaviour.

2. Replacement of openings / possible combination with night ventilation



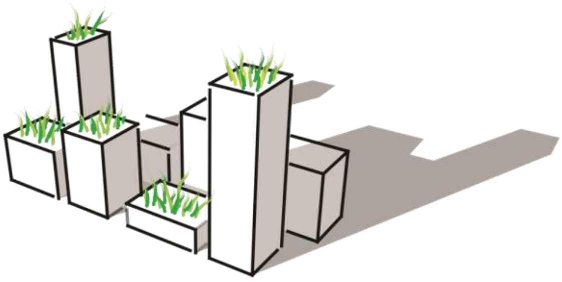
A problem that comes along with the high tenure percentage as regards Greek households is the difficulty to reach unanimous decisions especially when it comes to energy upgrading measures. The legislation framework has always made provision for restrictions concerning façade uniformity and consistency, which unfortunately were rarely considered by the owners in the past. This resulted in a random installation of windows and glass doors, with wooden frames that mix with PVC frames of various colours and types, leading to a complete deformation of the building's envelope, especially in older buildings. Therefore, a holistic assessment of energy conservation policies foreseeing stricter regulations concerning openings is of high importance in order to preserve the character of the Greek *Polykatoikia* and the cities.

3. Shading



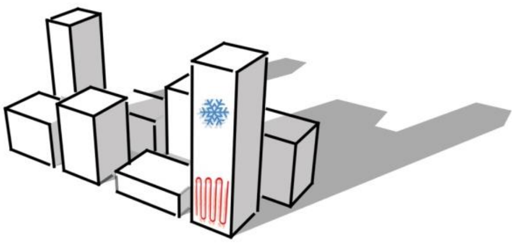
Along with the replacement of windows and glass doors the shading systems changed as well. The figure describes a typical *Polykatoikia* downtown, where each apartment has its own shading system; an awning metallic or fabric, wooden or PVC shutters of various colours and sizes. As indicated for the case of the openings' replacement, shading interventions should be carefully planned in order to achieve maximum energy conservation and additionally reform the MF – buildings. Although their economic feasibility proved to be rather poor, at least for the Climatic Zone C, shading systems represent a powerful tool in the hands of an architect; they can reform and regenerate the buildings' façades and simultaneously allow the harmonic integration of HVAC systems.

4. Green roofs



Similarly to shading systems green roofs are not an economic profitable investment. The benefits of their installation, as regards *Polykatoikies*, concern only the upper floor. As a consequence it is hardly likely that green roofs will be promoted only by private initiatives. Moreover, the problem of additional static loads restricts the variety of green roof types that can be installed. On the other hand, their undeniable positive effects in the urban built environment are widely proven. Thus, a funding program for mass installation, would not only create green space in the enormously dense Greek cities, but would also drastically contribute to the improvement of the urban microclimate.

5. HVAC installation



The high tenure percentage in *Polykatoikies* is also affecting retrofit actions, discouraging any attempt for energy upgrade of HVAC systems to a great extent. Particularly, common owners' disagreements on the operational schedule of the heating systems, lead often to the solution of wall mounted autonomous gas boilers' application. Thus, along with the random installation of A/C – systems, the façades of *Polykatoikia* are altered drastically. A targeted retrofit could harmonically integrate HVAC systems into the building's façades and eventually protect the aesthetics of the Greek city centres.

The following tables (Table 7.26 - Table 7.29) indicate the immense role of evaluation criteria, especially the sub-criteria that was thoroughly discussed in this chapter, as concerns the overall evaluation of each intervention. Prior to obtaining the respective results, a brief presentation of the best case scenarios according to each building typology is illustrated below.

<u>Building MF1</u>

Table 7.26 Overview of the retrofit scenarios according to the evaluation criteria – MF1

Year of construction	1969			
Typology	row-system			
Built environment	very dense			
Main features	south orientation, two sides attached, commercial use in the ground floor			
	Best LCC	**Best environmental score**	**Best (aesthetics included)**	**Best least-cost approach**
Combination scenario	MF1_EPS_4+BB+AC+SC	MF1_EPS_4+BB+AC+SC	MF1_EPS_4+BB+AC+GR_ext+Aw_Con+NC+CM	MF1_EPS_4+BB

Building MF2

Table 7.27 Overview of the retrofit scenarios according to the evaluation criteria – MF2

Year of construction	1976			
Typology	detached			
Built environment	medium dense			
Main features	north-west orientation, fully detached, Pilotis floor			
	Best LCC	**Best environmental score**	**Best (aesthetics included)**	**Best least-cost approach**
Combination scenario	MF2_EPS_5+W1_PVC+BB+AC+PV	MF2_EPS_5+W1_PVC+BB+AC+PV	MF2_EPS_5+W1_PVC+BB+AC+Aw_Unc +NC+GR_ext	MF2_EPS_5+NC+GR_ext +CM

Building MF3

Table 7.28 Overview of the retrofit scenarios according to the evaluation criteria – MF3

Year of construction	1985			
Typology	row-system			
Built environment	dense			
Main features	south orientation, two sides attached, Pilotis floor			
	Best LCC	**Best environmental score**	**Best (aesthetics included)**	**Best least-cost approach**
Combination scenario	MF3_EPS_T4+BB+AC+NC+SC	MF3_EPS_T4+BB+AC+NC+PV	MF3_EPS_T4+BB+AC+GR_ext +CM+NC	MF3_EPS_T4+BB+AC

Building MF4

Table 7.29 Overview of the retrofit scenarios according to the evaluation criteria – MF4

Year of construction	1998			
Typology	detached			
Built environment	low density			
Main features	south west orientation, partially commercial use in the ground floor, Pilotis floor			
	Best LCC	**Best environmental score**	**Best (aesthetics included)**	**Best least-cost approach**
Combination scenario	MF4_BB+AC+NC+CM+SC	MF4_EPS_T4+BB+AC+NC+CM	MF4_EPS_T4+BB+AC+NC+CM	MF4_BB+AC+NC+CM

As indicated in chapters 7.2.1 - 7.2.4 the typology of each building is the most crucial factor for intervention scenarios' planning. Nevertheless, based on the above tables certain conclusions can be drawn:

a. As regards best LCC and environmental scores, MF1 and MF2 share the same results, whilst the respective results for MF3 are kept at the same levels.
b. Regardless the building's typology the replacement of the boilers is beyond any doubt beneficial.
c. In case of retrospective thermal insulation and replacement of windows, related interventions such as cool materials and night ventilation are positively evaluated due to the low additional implementation costs included.
d. The best scenario from an architectural point of view, is not always the most economically viable solution. This amplifies the strong necessity for subsidy programs' enactment that will be accompanied by strict design specifications, which will ensure an overall aesthetically acceptable implementation result of the retrofit scenarios.
e. The evaluation criteria for these implementations should be set very carefully. The goal of a holistic energy conservation intervention should clearly lead to the most feasible retrofit scenario, based on the building's typology.
f. Climatic conditions also affect the interventions to great extents. Thessaloniki is located in Northern Greece, where the heating degree days are relatively high compared to the rest of the country. Thus, the intervention scenarios would be altered radically, if these typologies were to be studied in another Climatic Zones of Greece.

7.3 Outcomes

The numerous outcomes of this in depth retrofit action's assessment are discussed in this section. Firstly, in order to implement retrofit policies buildings need to be classified according to these policies. Especially as regards buildings constructed before 1980, which are currently the main target group in Greece in terms of energy conservation policies, it is proven that their construction typology can affect the optimal interventions significantly. More specifically, the detachment and attachment state of a building influences the window to wall ratio, which in turn drastically affects relevant retrofit actions, apart from the envelope's thermal losses.

Furthermore, assigning specific weighting factors could affect retrofit scenarios to a great extent; setting exact goals and prioritising them according to detailed criteria, is a procedure that would influence the design and the structure of respective funding programs considerably. In this line of thought, the first step in terms of the evaluation procedure, is to specify the scope of such policies; national incentive programs with environmental friendly background, assuredly demand a different way of handling the existing building stock, and, as a consequence, the determination of analogous analysis factors. In that sense, the results showed us that, primary energy oriented assessment of intervention scenarios, can notably differ from the corresponding final energy consumption results. In addition, the role of the initial investment cost, and its great significant during the evaluation procedure can lead to solutions with lower environmental scores.

Furthermore, heating loads are easier to moderate, as the overall feasibility of the respective improvement scenarios is better, unlike the ones concerning cooling loads reduction. This is of course also a matter of the climatic conditions of the study area; it was already underlined that the case study area favours for heating loads' limitation measures.

Economic efficiency proves to be an issue that needs further attention when it comes to RES and their diffusion. This is due to the limited potential capacity of roof-top solar systems combined with the fact that no capital subsidies are provided for SWH systems. In the case of SWH systems, the low electricity retail rates for DHW consumptions do not aid the feasibility of this technology, unless certain financial incentives are granted. In the case of PVs, the feed-in tariff system for grid-connected residential systems seems to be a successful diffusion scheme, but only when the systems' capacity exceeds 1 to 2 kWp. Smaller scale systems, which unfortunately dominate in the existing building stock, need additional incentive measures to be set, as proven by the unsuitability of the existing available roof areas. In the current thesis the PV systems are examined as off-grid, in order to cover buildings' electricity demand. Eventually, due to the current low electricity retail prices, such investments prove to be unviable especially for MF – buildings occupants.

As a result, the presented methodological approach mainly allows a quality based multi-criteria analysis at each stage of the evaluation procedure; it can be easily applied to numerous case study areas, providing safe and valid outcomes based on the respective climatic conditions.

8 Outlook

8.1 Utilisation prospect of the Dissertation

Implementing a European Directive is not an easy task, as it was proven even in countries with long experience in energy standards. The implementation of the urgently needed energy renovation policies will not be an easy task, given the complexity of the Greek building sector, the rather limited interest shown by the buildings' owners, at least until the energy price increase in 2010, and a series of legal and administrative hurdles considering energy renovation measures. A detailed knowledge and a sound understanding of the prevailing technical and socioeconomic boundary conditions are prerequisites.

More specifically, analysis of official data regarding the existing building stock as well as specifically designed surveys can provide the respective vital information concerning the required measures nature in order to achieve energy efficiency in the building sector. In this context, this study showed that attention should be laid upon all legal barriers, which may discourage and prevent owners from the implementation of energy renovation measures. Moreover, the occupants' income and the quality of the building's envelope, HVAC and RES systems should be taken into consideration when designing measures and developing economic and other support policies and tools. The relationship between actual energy consumption and energy pricing should be re-examined, also on the basis of the national GDP per capita.

Furthermore, clear definitions for building energy standards should be made that refer to specific categories of buildings and provide the respective support tools. Otherwise, the risk of prescribing standardized interventions for all typologies is high, without taking important parameters of differentiation into account, resulting in less than optimum results.

In this framework, the New Greek Regulation on the energy performance of buildings aims to improve buildings, especially newly built ones, in terms of their energy performance and in turn to reduce resulting CO_2 emissions. This is a fair aim and a given necessity, however, as this study demonstrates, the existing Greek building stock needs drastic energy renovation interventions to off-set the poor quality of construction practiced until the 1990's. Furthermore, the actual consistency of the Greek building stock indicates the particular need for the implementation of such measures especially in the residential sector. As the Greek economy is going through the deepest recession since WW2, capital intensive investments in the building sector have to be carried out thoughtfully, ensuring the most cost-effective results. Specific measures have to be endorsed, under the perspective of improving the energy behaviour of each building class presented in this thesis. Moreover, these measures also have to be optimised according to their energy and environmental impact. This presupposes an in-depth knowledge of the building stock's features, a well calculated evaluation of the feasibility of various measures and a thoughtful elaboration of financing and marketing tools in order to address the already stretched by the recession building owners. The complexity of the building stock, the legal and administrative frame of Greek multi-family buildings as well as the socioeconomic effects of energy policies, have to be kept in mind, when utilising the analysis of the building stock. On this base, the quantification of the impact of specific energy renovation measures in terms of their economic, energy and environmental impact, were assessed and discussed, as the next reasonable step towards an efficient and effective energy conservation policy.

By means of energy efficiency strategies and in order to conduct the necessary overview concerning the energy performance of the Greek building sector, the following questions are raised: Can we afford retrofit planning solely for the buildings' energy behaviour improvement? Shouldn't these measures be part of an overall sustainability upgrading plan? As indicated, numerous parameters should be taken into consideration in order to form the proper answers to the aforementioned questions. The proposed methodological approach regarding retrofitting in the existing residential building stock is based on a thorough research concerning all parameters involved with this task. Based on the restricted available data, this methodology aims at developing a flexible evaluation assessment tool of energy conservation measures in the existing urban residential sector, which will be affected by social, economic and environmental aspects of the Greek reality. Inevitably, the attention is drawn to the *Polykatoikies*; they determine the urban architecture, the indoor air quality, the energy performance of the building stock and the Greek cities in general. Thus, this building typology is unquestionably dominant and retrofitting should be carefully planned with respect to this distinctive architecture.

Concluding, one of the most vital outcomes of this study is the matter of the actual evaluation process, rather than the results themselves. Hence, this research has shown that the application of the proposed methodology can lead to optimal intervention scenarios, as long as specific evaluation criteria are set. In this framework, efficient energy conservation policies can be implemented. In order to achieve this, a thorough analysis of the existing urban building stock was carried out, which indicated the fact that residential buildings are the optimum field for such interventions. Thereafter, the actual structure and nature of the residential building stock was determined, by means of an analytical statistical and building physics bottom-up research. *Polykatoikia* was the core of this research, as it is the core of Greek cities. In this framework, this significant urban residential typology shouldn't be studied under the scope of a building unit approach; on the contrary it is important to expand the present narrow research field and connect the revival of *Polykatoikia* with the subject of urban sustainable development. The benefits of such actions are numerous and, as a consequence, retrofit actions would lead not only to energy conservation and the respective economic and environment benefits, but also to better living conditions in buildings and in cities in general; redefinition of the dense Greek urban areas, along with improved thermal comfort conditions can positively affect the urban network socially.

Consequently, architecture proved itself to be a powerful tool, linking retrofitting policies with urban sustainability. It provided us with the important background that was required for the process of understanding the physis of *Polykatoikia* as well as the linkage of its energy behavioural patterns to the built environment.

8.2 Innovative features of the Thesis

Up to now most studies regarding the energy efficiency evaluation of the Greek building stock were based on statistical and/or calculated results as produced by field research and building energy software tools, similar to the European trend. The typological evaluation of the existing building sector mainly refers to the year 1980 that marks the implementation of the first Thermal Insulation Regulation, based on a pre and post classification. The strategic planning of energy upgrading measures is mainly based on the building unit regardless the built environment. Moreover, the commonly proposed evaluation of such measures is only based on the cost effective parameter in terms of NPV analysis; only in rare cases environmental factors and the overall LCA of such interventions are discussed. Furthermore, architectural aspects are almost never discussed, along with the effects of such measures on the urban fabric, especially in the typical 'hard-engineering' approach.

Although individual studies are rather analytical and thoroughly performed, there are restrictions concerning their implementation due to the lack of linkage to various parameters, such as buildings' typologies, urban fabric, environmental aspects and architectural design. In addition, they mainly suggest the implementation of typical retrofit measures, regardless the climatic conditions, their environmental impact and their effect on the urban fabric. This is the result of a non cohesive evaluation tool that builds on a multivariable methodological procedure.

This Thesis proposes an integrated assessment methodology that can easily be applied to several European cities and the urban built environment in general. Based on the climatic conditions and the typological features of the area under study, specific retrofit actions can be planned according to the nature of the urban fabric. The proposed methodological approach offers a broader, multivariate evaluation scheme taking into account several factors, such as economic, energy, environment, and LCA aspects as well as technical issues and architectural quality matters.

This tool was applied to a typical Greek city in the Mediterranean area and showed that the complexity of the urban fabric strongly determines energy efficiency policies. In this line of thought, this tool can be used by researches, engineers or local authorities in order to examine and promote energy upgrading measures for the urban built environment.

The methodological approach of the Thesis as well as the results produced by implementing it, have been published in the following journal papers:

- Theodoridou I., Papadopoulos A.M. and Hegger M., (2011), A typological classification of the Greek building stock, Energy and Buildings 43, 10, 2779-2787.
- Theodoridou I., Papadopoulos A.M. and Hegger M., (2011), Statistical analysis of the Greek residential building stock, Energy and Buildings 43, 10, 2422–2428.
- Anastaselos D., Theodoridou I., Papadopoulos A.M. and Hegger M., (2011), Integrated evaluation of radiative heating systems for residential buildings, Energy 36, 4207-4215

Furthermore the following papers presented in conference included some of the Thesis' findings:

- Theodoridou I., Papadopoulos A.M., (2011), Energy conservation in existing residential buildings – a different approach, Proceedings of the National Conference on Architecture, Energy and Environment in buildings and cities (ARENEP 2011) (A.M. Papadopoulos, ed), Athens, Greece, 3-4 May (in Greek).
- Theodoridou I., Karteris M., Papadopoulos A.M., Tzortzi T.N., Karteris A., (2009), Integrated study of green roof applications in office and residential buildings, Proceedings of the National Conference of Environment Council 2009 - Climate change, Sustainable Development and Renewable Energy Sources, Thessaloniki, Greece, 9 October (in Greek).
- Theodoridou I., Karteris M., Oxizidis S., Mantadakis M., Papadopoulos A.M., (2009), Study of zero energy residential building, Proceedings of the 9^{th} Conference of Solar Techniques Institute, Pafos, Cyprus, 28-29 (in Greek).
- Theodoridou I., Papadopoulos A.M., (2009), Analysis of the Greek building stock and potential retrofit scenarios, Pafos, Cyprus, 28-29 (in Greek).

- Theodoridou I., Papadopoulos A.M., (2008), Impact of energy pricing on buildings' energy design, Poster at 7th European Conference Solar Energy I structure on their energy behaviour, Proceedings of the 2nd International Workshop – Energy Performance and Environmental Quality of Buildings, Milos Island, Greece, 12-13th July 2007.

8.3 Suggestions for further research

This Thesis showed that improving the energy performance of residential buildings in the urban built environment is not a simple, straight-forward task. Using large scale evaluation tools, an interacting relation can be achieved based on the fact that the construction typology of the urban building sector affects the urban microclimate, which in turn influences the energy performance of the buildings. Moreover, energy efficiency measures should be planned according to the cities' overall energy performance profile that is determined mainly by the buildings' typologies. Hence, retrofitting policies should be designed according to numerous parameters, regarding urban texture, economic feasibility, environmental aspects and architectural factors, in order to achieve the most profitable interventions concerning energy performance improvement of urban buildings.

In this line of thought the following fields are suggested for future research:

I. <u>Application of the proposed methodology to further building typologies other than residential ones</u>

This methodological approach can easily be applied to urban areas, where the dominant use of buildings is not residential. The study of commercial use buildings could be of interest. Mixed use buildings are also a very remarkable field of research as regards the implementation of energy upgrading measures.

II. <u>Incorporation of the methodological steps in terms of a software tool</u>

The tools used for this evaluation procedure could be linked to each other in terms of a combining software tool; a flexible interface could help users follow each step of the methodological procedure in order to achieve an overall assessment of urban retrofit policies. Hence, large scale maps based on GIS data, commonly possessed by local authorities could be linked to energy simulation software. Several intervention scenarios could be tested in turn. An integrated evaluation tool could allow their assessment according to energy, economic and environmental aspects. Moreover, the effects of such measures on the urban climate can be calculated by using an attached micro-scale urban climate model. It becomes obvious that there is great potential in this direction.

III. Optimisation of retrofit measures according to climatic conditions

If applied on other urban areas, the retrofit scenarios will be re-evaluated according to the climatic conditions of the area under study. Hence, alternative interventions as presented in chapter 6.3, could be developed for warmer climates, such as the southern Mediterranean area. Thus, the actual nature of the interventions and their respective architectural effect can vary considerably, influencing the overall energy, economic and environmental assessment.

Overall, this Thesis has shown that the evaluation of the energy behaviour of buildings, under the scope of urban sustainability, is a complex and difficult task. The analysis of the buildings' typologies, the study of their energy performance, their relation to the urban built environment and the design of energy conservation measures, require long, hard and interdisciplinary work. It was also shown that architecture can play the main role, by coordinating all interactions and linking the various parameters to the most favourable result, of high efficiency and of course high aesthetics.

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10 Appendix

In this chapter the tables of the results of the LCC analysis are presented. The respective discussion of the outcomes is presented in chapter 7.

<u>List of tables in this chapter:</u>

Table 10.1 Evaluation of the thermal insulation scenarios – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF1_XPS_1	700,104.15	426,626.58	149.12	236.51	61.99	161.35	22,212.41	42,256.12
MF1_XPS_2	694,786.36	428,742.55	149.60	237.36	60.83	160.42	19,855.60	45,824.96
MF1_XPS_3	691,847.19	433,901.40	151.35	240.15	59.69	159.51	14,671.51	52,180.54
MF1_XPS_4	699,812.59	425,391.77	148.65	235.77	62.09	161.42	23,392.97	40,985.00
MF1_XPS_5	692,122.67	428,181.41	149.22	236.54	60.44	160.11	20,252.84	45,824.96
MF1_XPS_6	690,055.81	433,543.26	151.10	238.96	59.43	159.32	12,287.99	52,180.54
MF1_SW1	699,498.21	428,936.26	148.16	234.89	61.97	161.40	21,320.19	43,103.53
MF1_SW2	694,570.85	448,774.20	147.94	234.71	61.11	160.65	18,708.34	46,672.37
MF1_SW3	689,076.88	436,942.53	148.42	234.73	59.89	159.67	13,624.28	53,027.95
MF1_EPS_1	696,488.66	425,725.14	146.15	233.02	61.99	161.35	23,059.82	41,408.71
MF1_EPS_2	689,757.94	427,813.99	145.46	232.12	60.83	160.42	20,703.01	44,977.55
MF1_EPS_3	684,303.62	432,929.01	145.13	231.87	59.69	159.51	15,518.92	51,333.13
MF1_EPS_4	**696,700.13**	**424,499.09**	**146.09**	**232.88**	**62.09**	**161.42**	**24,240.38**	**40,137.59**
MF1_EPS_5	687,094.25	427,252.85	145.08	231.57	60.44	160.11	21,100.25	44,977.55
MF1_EPS_6	682,512.25	432,570.87	144.88	231.59	59.43	159.32	13,135.40	51,333.13

Table 10.2 Evaluation of the openings scenarios – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF1_W1_Aloum	1,025,905.16	602,298.39	199.13	314.57	96.02	197.54	-139,841.45	159,232.00
MF1_W1_PVC	973,360.33	502,778.39	194.25	305.63	96.02	197.54	-40,321.45	59,712.00
MF1_W1_Wood	960,778.63	591,109.61	191.20	299.39	96.02	197.54	-122,851.68	128,181.76
MF1_W2_Aloum	947,331.63	629,464.39	189.60	299.32	93.18	192.36	-169,537.15	195,059.20
MF1_W2_PVC	936,584.72	531,138.63	186.55	294.69	93.18	192.36	-71,211.39	96,733.44
MF1_W2_Wood	934,749.93	641,641.90	184.72	293.12	93.18	192.36	-180,518.19	203,140.22
MF1_W3_Aloum	929,549.34	563,901.36	187.03	296.46	90.66	190.23	-199,645.71	227,900.80
MF1_W3_PVC	916,967.64	658,445.36	183.98	293.00	90.66	190.23	-105,101.71	133,356.80
MF1_W3_Wood	918,417.89	714,583.80	182.08	290.37	90.66	190.23	-254,618.78	280,049.28

Table 10.3 Evaluation of the cool materials' implementation – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF1_CoolMat	909,093.12	440,242.64	175.88	278.01	91.58	193.20	19,906.78	4,890.60

Table 10.4 Evaluation of the shading systems – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF1_Louvre_Con	1,077,544.81	518,926.08	199.29	313.23	116.37	211.02	-49,036.04	50,400.00
MF1_Louvre_Uncon	1,098,415.43	503,515.26	202.01	316.52	119.61	212.80	-32,600.73	31,500.00
MF1_Aw_Con	**1,116,306.39**	**486,014.33**	**204.49**	**319.51**	**122.25**	**214.68**	**-14,072.39**	**10,500.00**
MF1_Aw_uncon	1,080,786.92	486,239.80	200.13	313.67	116.48	212.28	-15,773.17	15,750.00

Table 10.5 Evaluation of the green roofs – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF1_ GR_ext	**860,104.12**	**434,756.66**	**167.91**	**266.02**	**85.48**	**185.28**	**21,464.61**	**13,040.00**
MF1_ GR_semi	857,955.77	437,223.03	166.04	265.47	85.27	184.80	14,944.61	16,300.00
MF1_ GR_int	849,683.48	437,778.89	165.74	263.26	84.35	183.18	18,204.61	19,560.00

Table 10.6 Evaluation of HVAC – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF1_BB	862,311.49	410,469.74	164.25	257.89	89.76	175.44	41,590.39	3,000.00
MF1_HP	1,059,141.78	478,795.66	199.51	309.30	112.05	202.00	-13,263.40	25,200.00

Table 10.7 Evaluation of RES – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF1_SC	669,710.03	315,187.08	121.20	183.00	89.87	148.97	44,292.65	18,600.00
MF1_PV_MonoSi	895,241.99	421,758.63	167.98	258.77	96.38	170.68	24,515.61	34,098.64
MF1_PV_MultiSi	911,805.50	429,285.63	170.95	263.84	98.86	175.06	19,187.04	34,098.64

Table 10.8 Evaluation of Night ventilation– MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF1_NC	1,071,154.73	468,174.12	198.67	311.04	115.17	210.97	1,616.11	0.00

Table 10.9 Evaluation of combined scenarios – MF1

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF1_EPS_4+W1	646,604.83	476,053.73	136.43	221.11	56.39	156.41	-30,067.12	100,697.00
MF1_EPS_4+W1+BB	569,347.61	442,231.53	119.55	192.96	51.05	133.05	-7,209.40	104,217.00
MF1_EPS_4+BB+AC+GR_ext+Aw_Con+NC+CM	531,366.32	427,818.43	115.73	183.42	45.11	118.88	1,372.10	113,070.60
MF1_EPS_4+BB+AC	593,335.03	400,515.86	125.47	196.94	53.15	128.08	32,391.12	69,705.00
MF1_EPS_4+ GR_ext	679,417.00	435,854.76	140.99	226.39	61.22	159.88	12,032.47	54,025.00
MF1_EPS_4+BB+AC+Aw_Con	591,939.18	425,422.49	124.97	196.78	53.24	127.20	7,090.05	95,955.00
MF1_EPS_4+BB+AC+ GR_ext	586,907.92	411,506.86	124.35	195.56	52.42	126.87	20,798.49	82,745.00
MF1_EPS_4+Tente_Con s+NC	704,158.99	444,690.50	141.74	226.29	67.43	156.15	1,912.36	67,235.00
MF1_EPS_4+BB+AC+Aw_Con+NC	588,635.08	424,062.49	124.30	195.70	52.95	126.37	8,050.72	95,955.00
MF1_EPS_4+ GR_ext +Aw_Con +NC+CM	686,141.06	457,830.85	139.11	222.90	64.90	153.95	-12,395.21	84,350.60
MF1_EPS_4+BB	676,156.27	425,915.56	140.91	225.97	60.54	159.71	21,848.58	44,505.00
MF1_EPS_4+BB+AC+SC	**240,167.63**	**270,500.23**	**57.73**	**84.84**	**21.61**	**128.08**	**60,769.99**	**88,305.00**
MF1_EPS_4+BB+AC+PV	430,155.52	359,331.86	97.34	148.85	37.18	128.08	51,474.22	103,791.00

Table 10.10 Evaluation of the thermal insulation scenarios – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF2_XPS_1	1,236,335.41	759,564.84	280.26	422.07	28.82	52.76	323,533.51	147,982.53
MF2_XPS_2	1,191,223.17	756,277.25	278.34	416.17	26.14	50.43	322,970.91	159,928.48
MF2_XPS_3	1,153,728.13	764,750.98	281.28	416.81	23.40	48.07	311,354.21	183,088.71
MF2_XPS_4	1,244,210.71	756,502.47	282.64	425.36	29.05	52.95	327,239.24	143,350.48
MF2_XPS_5	1,166,476.59	750,160.53	272.26	407.09	25.22	49.63	326,886.89	159,928.48
MF2_XPS_6	1,116,514.78	758,695.64	265.64	395.78	22.74	47.51	314,080.18	183,088.71
MF2_SW1	1,216,677.36	679,612.53	267.07	403.33	28.85	52.84	320,090.94	151,070.56
MF2_SW2	1,180,155.45	679,986.41	264.39	396.82	26.81	51.03	316,978.37	163,016.51
MF2_SW3	1,130,810.22	687,206.39	262.20	389.56	23.87	48.47	306,290.99	186,176.74
MF2_EPS_1	1,222,756.93	756,336.58	269.17	408.72	28.82	52.76	326,621.54	144,894.50
MF2_EPS_2	1,172,922.05	752,985.13	263.36	398.18	26.14	50.43	326,058.94	156,840.45
MF2_EPS_3	1,126,275.65	761,354.05	258.82	389.87	23.40	48.07	314,442.24	180,000.68
MF2_EPS_4	1,228,935.33	753,313.44	270.20	410.39	29.05	52.95	330,327.27	140,262.45
MF2_EPS_5	**1,151,201.21**	**746,971.50**	**259.81**	**392.11**	**25.22**	**49.63**	**32,9974.91**	**156,840.45**
MF2_EPS_6	1,101,239.39	755,506.61	253.20	380.81	22.74	47.51	317,168.21	180,000.68

Table 10.11 Evaluation of the openings scenarios – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF2_W1_Aloum	2,777,959.44	1,411,462.75	460.67	785.87	108.91	132.38	-225,706.91	311,928.00
MF2_W1_PVC	2,753,312.48	1,216,507.75	454.69	773.66	108.91	132.38	-30,751.91	116,973.00
MF2_W1_Wood	2,724,068.05	1,350,636.79	446.09	767.08	108.91	132.38	-164,880.95	251,102.04
MF2_W2_Aloum	2,592,662.86	1,421,120.55	432.48	738.80	101.17	123.44	-253,042.71	382,111.80
MF2_W2_PVC	2,568,015.90	1,228,505.01	426.51	726.65	101.17	123.44	-60,427.17	189,496.26
MF2_W2_Wood	2,538,771.47	1,290,110.79	417.90	718.01	101.17	123.44	-122,032.95	251,102.04
MF2_W3_Aloum	2,488,030.36	1,388,935.32	417.72	712.58	96.33	118.74	-230,257.91	382,111.80
MF2_W3_PVC	2,463,383.40	1,196,319.78	411.75	700.43	96.33	118.74	-37,642.37	189,496.26
MF2_W3_Wood	2,434,138.97	1,555,426.89	403.14	700.27	96.33	118.74	-396,749.48	548,603.37

Table 10.12 Evaluation of the cool materials' implementation – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy	Primary Energy	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF2_CM	2,529,961.29	998,954.87	437.86	719.91	92.27	116.17	26,086.05	10,408.10

Table 10.13 Evaluation of the shading systems – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF2_Louvre_Con	3,334,978.60	1,655,776.64	550.63	932.41	129.81	152.11	-430,482.32	420,941.56
MF2_Louvre_Uncon	3,421,944.55	1,568,991.50	561.86	949.69	134.25	155.70	-336,366.96	309,191.56
MF2_Aw_Con	3,328,045.80	1,432,469.76	549.67	924.38	129.48	151.80	-20,7794.07	199,741.56
MF2_Aw_uncon	3,494,719.28	1,452,418.80	569.85	961.17	138.54	158.29	-214,368.93	174,141.56

Table 10.14 Evaluation of the green roofs – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF2_GR_ext	2,721,270.44	1,049,321.19	458.38	759.66	103.73	122.83	117,673.42	26,140.00
MF2_GR_semi	2,387,005.72	954,871.20	412.31	677.44	87.84	108.13	145,293.85	32,530.00
MF2_GR_int	2,574,495.91	1,008,864.63	438.51	724.03	96.61	116.48	182,476.44	38,760.00

Table 10.15 Evaluation of HVAC – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF2_BB	2,408,248.06	1,004,731.71	389.65	667.01	95.41	117.85	15,1824.80	4,000.00
MF2_HP	3,008,714.13	1,212,044.75	477.56	817.96	123.19	141.41	-7,653.45	48,400.00

Table 10.16 Evaluation of RES – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF2_SC	3,105,213.51	1,241,648.98	495.08	850.16	140.13	197.72	21,312.78	23,700.00
MF2_PV_MonoSi	2,887,162.73	1,165,226.53	452.88	780.82	138.25	180.19	26,914.97	43,301.44
MF2_PV_MultiSi	2,907,042.47	1,174,324.49	456.43	786.88	141.80	184.81	20,482.92	43,320.00

Table 10.17 Evaluation of night ventilation– MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF2_NC	3,078,972.21	1,211,170.38	485.49	836.83	125.70	148.69	7,175.46	0.00

Table 10.18 Evaluation of combined scenarios – MF2

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF2_EPS_5+W1_PVC	713,547.74	752,670.54	156.16	254.88	16.21	41.81	307,351.50	216,552.45
MF2_EPS_5+W1_PVC+BB	697,674.77	757,506.29	154.59	251.83	15.44	40.96	300,834.99	227,112.45
MF2_EPS_5+W1_PVC+BB+AC	543,880.58	723,983.95	129.81	205.54	11.11	28.41	310,303.16	275,512.45
MF2_EPS_5+W1_PVC+BB+AC+Aw_unc	518,086.05	788,538.54	123.66	198.06	10.93	26.50	242,153.06	352,312.45
MF2_EPS_5+W1_PVC+Aw_unc+NC	473,808.71	728,579.63	106.55	176.76	11.52	26.30	301,818.67	293,352.45
MF2_EPS_5+W1_PVC+BB+AC+Aw_unc+NC	497,150.72	779,921.35	119.44	191.19	10.48	25.18	248,240.05	352,312.45
MF2_EPS_5+W1_PVC+BB+AC+SC	543,409.23	743,732.13	134.16	210.30	10.83	28.41	289,394.65	299,212.45
MF2_EPS_5+W1_PVC+BB+AC+PV	327,506.28	667,928.99	92.25	141.47	5.86	28.41	337,184.94	318,813.89
MF2_EPS_5+W1_PVC+ GR_ext	689,665.41	754,372.02	150.47	246.30	16.05	40.04	302,320.79	229,592.45
MF2_EPS_5+W1_PVC+BB+AC+ GR_ext	736,876.37	813,332.02	166.89	266.91	16.05	40.04	243,360.79	288,552.45
MF2_EPS_5+W1_PVC+BB+AC+Aw_unc+NC+ GR_ext	488,982.27	788,436.47	117.12	188.01	10.58	24.47	238,396.33	365,352.45
MF2_EPS_5+W1_PVC+BB+AC+NC+ GR_ext	520,502.79	727,401.43	125.10	198.24	10.60	26.94	304,060.30	288,552.45
MF2_EPS_5+NC+ GR_ext +CM	658,901.61	692,815.48	144.50	235.10	15.28	38.17	360,279.69	180,288.55
MF2_EPS_5+W1_PVC+BB+AC+NC+ GR_ext +CM	488,982.27	722,044.57	117.12	186.12	10.58	24.47	304,788.23	298,960.55

Table 10.19 Evaluation of the thermal insulation scenarios – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_XPS_T1	518,078.18	327,989.91	112.43	176.46	39.95	103.26	58,071.67	37,115.40
MF3_XPS_T2	508,206.80	331,201.77	111.95	175.67	38.43	101.94	54,274.02	42,802.50
MF3_XPS_T3	499,237.99	336,247.10	112.58	176.36	36.72	100.49	48,771.04	50,385.30
MF3_XPS_T4	517,206.37	327,802.19	112.30	176.27	39.84	103.16	58,204.27	37,115.40
MF3_XPS_T5	502,528.36	329,902.70	111.11	174.42	37.73	101.29	55,191.65	42,802.50
MF3_XPS_T6	496,526.87	335,688.65	112.20	175.80	36.37	100.22	49,165.51	50,385.30
MF3_SW1	516,054.17	329,925.97	110.81	174.06	40.03	103.37	56,970.83	38,063.25
MF3_SW2	507,776.24	333,818.54	110.16	172.99	38.83	102.29	52,818.90	43,750.35
MF3_SW3	495,932.17	338,966.23	109.56	171.79	36.99	100.72	47,489.64	51,333.15
MF3_EPS_T1	513,648.04	326,795.33	109.37	172.74	39.84	103.16	59,152.12	36,167.55
MF3_EPS_T2	503,513.17	330,177.75	108.09	171.03	38.43	101.94	55,221.87	41,854.65
MF3_EPS_T3	492,199.51	335,191.81	106.80	169.43	36.72	100.49	49,718.89	49,437.45
MF3_EPS_T4	512,519.85	326,783.05	109.35	172.71	38.95	103.06	59,219.51	36,167.55
MF3_EPS_T5	497,834.73	328,878.69	107.25	169.78	37.73	101.29	56,139.50	41,854.65
MF3_EPS_T6	489,488.38	334,633.37	106.42	168.87	36.37	100.22	50,113.36	49,437.45

Table 10.20 Evaluation of the openings scenarios – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_W1_Aloum	999,468.87	520,550.68	185.95	288.56	97.68	161.63	-112,927.52	126,296.00
MF3_W1_PVC	989,489.60	441,615.68	183.53	283.62	97.68	161.63	-33,992.52	47,361.00
MF3_W1_Wood	977,648.87	495,922.96	180.04	280.96	97.68	161.63	-88,299.80	101,668.28
MF3_W2_Aloum	964,618.33	540,308.43	180.58	281.30	93.55	157.24	-135,227.70	154,712.60
MF3_W2_PVC	954,639.07	462,320.65	178.16	276.38	93.55	157.24	-57,239.92	76,724.82
MF3_W2_Wood	942,798.34	546,717.95	174.68	274.58	93.55	157.24	-141,637.22	161,122.12
MF3_W3_Aloum	963,586.06	566,098.24	180.42	281.80	93.43	157.11	-161,093.48	180,761.15
MF3_W3_PVC	953,606.80	491,109.99	178.00	276.97	93.43	157.11	-86,105.23	105,772.90
MF3_W3_Wood	941,766.07	607,460.18	174.52	276.08	93.43	157.11	-202,455.42	222,123.09

Table 10.21 Evaluation of the cool materials' implementation – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy	Primary Energy	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_CM	875,729.15	375,853.83	160.80	251.06	85.38	150.72	25,296.42	3,644.25

Table 10.22 Evaluation of the shading systems – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF3_Louvre_Con	1,062,204.25	465,031.94	188.61	293.76	108.25	172.31	-51,190.68	49,600.00
MF3_ Louvre _Uncon	1,102,312.56	456,444.83	194.80	302.55	112.99	177.39	-39,663.57	31,000.00
MF3_Aw_Con	**1,066,822.16**	**432,934.23**	**189.37**	**293.96**	**108.76**	**172.98**	**-18,710.58**	**16,200.00**
MF3_Aw_uncon	1,134,197.74	444,383.20	199.78	309.49	116.72	181.54	-25,212.34	10,800.00

Table 10.23 Evaluation of the green roofs – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF2_GR_ext	849,667.77	381,820.75	**155.88**	**243.63**	86.69	**145.52**	**16,514.00**	**19,200.00**
MF2_GR_semi	844,994.09	385,603.66	155.20	242.76	83.07	145.02	12,432.46	24,000.00
MF2_GR_int	878,679.15	397,873.62	160.13	250.18	82.48	148.71	2,355.84	28,800.00

Table 10.24 Evaluation of HVAC – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_BB	879,196.02	365,535.90	158.70	246.33	88.13	145.22	33,020.58	2,160.00
MF3_HP	1,035,742.35	413,038.59	185.27	286.03	104.84	165.91	-2,705.33	9,554.00

Table 10.25 Evaluation of RES – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_SolarCollector	534,641.42	263,910.46	99.26	148.32	113.94	167.99	95,898.06	32,500.20
MF3_PV_MonoSi	546,898.16	287,314.07	104.30	155.53	118.57	185.53	71,382.14	59,692.03
MF3_PV_MultiSi	575,812.98	300,457.37	109.49	164.38	121.62	190.29	62,098.00	59,692.03

Table 10.26 Evaluation of night ventilation– MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_NC	1,047,893.75	412,159.13	186.49	289.19	106.49	170.68	721.16	0.00

Table 10.27 Evaluation of combined scenarios – MF3

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m^2]	[kWh/m^2]	[€]	[€]
MF3_EPS_T4+BB	446,775.39	337,934.88	95.42	152.50	35.44	92.69	57,074.30	51,859.53
MF3_EPS_T4+BB+AC	418,352.78	332,116.95	90.92	144.00	32.52	84.25	58,378.70	61,413.53
MF3_EPS_T4+BB+AC+NC	415,731.10	331,037.84	90.39	143.14	32.32	83.66	59,140.96	61,413.53
MF3_EPS_T4+BB+AC+ GR_ext	435,047.83	354,889.49	93.32	148.08	34.65	86.00	36,655.13	80,613.53
MF3_EPS_T4+BB+AC+ GR_ext +CM+NC	431,647.19	357,415.45	92.72	147.23	34.31	85.40	33,800.82	84,257.78
MF3_EPS_T4+W1_BB+AC+ GR_ext +CM+NC	390,782.82	395,403.93	86.65	139.57	29.27	80.73	-6,939.63	131,618.78
MF3_EPS_T4+BB+AC+NC+SC	**159,275.51**	**252,535.25**	**44.45**	**65.33**	**11.32**	**83.66**	**105,080.15**	**93,813.53**
MF3_EPS_T4+BB+AC+NC+PV	130,893.34	259,295.24	41.32	59.22	7.43	83.66	92,291.99	121,103.93

Table 10.28 Evaluation of the thermal insulation scenarios – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_XPS_T1	722,116.65	492,056.20	133.48	222.17	75.86	113.54	-23,509.81	59,033.34
MF4_XPS_T2	696,916.78	512,326.37	130.90	217.59	71.95	110.12	-44,456.25	85,396.56
MF4_XPS_T3	677,762.27	519,820.79	128.92	213.88	68.95	107.55	-52,546.75	97,564.20
MF4_XPS_T4	663,154.72	532,729.19	127.56	211.40	66.61	105.59	-65,652.46	113,787.72
MF4_XPS_T5	719,095.20	491,255.60	133.13	221.51	75.34	113.19	-22,944.28	59,033.34
MF4_XPS_T6	692,291.45	510,971.12	130.29	216.49	71.24	109.52	-43,498.94	85,396.56
MF4_XPS_T7	673,364.89	518,551.85	128.34	212.84	68.26	106.99	-51,650.40	97,564.20
MF4_XPS_T8	658,945.93	531,506.68	127.01	210.40	65.96	105.05	-64,788.90	113,787.72
MF4_SW1	716,408.98	428,864.18	128.04	215.22	76.23	113.95	-26,181.75	61,061.28
MF4_SW2	691,553.36	449,121.40	124.92	210.15	72.44	110.59	-47,222.95	87,424.50
MF4_SW3	671,996.98	456,384.79	122.49	205.95	69.42	107.97	-55,236.53	99,592.14
MF4_SW4	657,158.64	469,165.87	120.70	203.04	67.09	106.01	-68,338.58	115,815.66
MF4_EPS_T1	722,100.64	489,965.14	133.38	222.01	75.86	113.54	-21,481.87	57,005.40
MF4_EPS_T2	696,869.93	510,109.45	130.64	217.27	71.95	110.12	-42,428.31	83,368.62
MF4_EPS_T3	677,693.60	517,514.93	128.54	213.44	68.95	107.55	-50,518.81	95,536.26
MF4_EPS_T4	663,064.22	530,334.39	127.07	210.84	66.61	105.59	-63,624.52	111,759.78
MF4_EPS_T5	719,079.19	489,164.54	133.03	221.35	75.34	113.19	-20,916.34	57,005.40
MF4_EPS_T6	692,244.60	508,754.21	130.03	216.16	71.24	109.52	-41,471.00	83,368.62
MF4_EPS_T7	673,296.22	516,246.00	127.97	212.40	68.26	106.99	-49,622.46	95,536.26
MF4_EPS_T8	658,855.43	529,111.88	126.52	209.84	65.96	105.05	-62,760.96	111,759.78

Table 10.29 Evaluation of the openings scenarios – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_W1_Aloum	896,628.95	665,129.08	168.45	278.66	95.78	132.03	-184,307.02	190,640.00
MF4_W1_PVC	881,565.55	545,979.08	164.80	271.19	95.78	132.03	-65,157.02	71,490.00
MF4_W1_Wood	863,692.33	627,954.28	159.54	267.17	95.78	132.03	-147,132.22	153,465.20
MF4_W2_Aloum	830,820.45	686,333.33	158.33	262.31	87.47	122.17	-211,879.85	233,534.00
MF4_W2_PVC	815,757.05	568,613.13	154.67	254.88	87.47	122.17	-94,159.65	115,813.80
MF4_W2_Wood	797,883.83	696,008.31	149.41	252.16	87.47	122.17	-221,554.83	243,208.98
MF4_W3_Aloum	808,610.12	719,122.65	155.37	258.09	84.09	119.26	-246,586.57	272,853.50
MF4_W3_PVC	793,546.72	605,930.15	151.72	250.79	84.09	119.26	-133,394.07	159,661.00
MF4_W3_Wood	775,673.50	781,557.25	146.46	249.45	84.09	119.26	-309,021.17	335,288.10

Table 10.30 Evaluation of the cool materials' implementation – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_CM	860,711.34	477,156.88	152.96	255.17	95.64	132.61	4,112.56	1,395.20

Table 10.31 Evaluation of the shading systems – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_ Louvre _Con	856,194.81	706,244.47	150.20	258.01	97.63	130.04	-226,551.27	235,600.00
MF4_ Louvre _Uncon	887,743.75	627,477.68	154.58	263.31	102.20	134.33	-144,970.64	147,250.00
MF4_Aw_Con	857,046.45	531,089.82	150.03	252.86	98.12	129.88	-51,368.32	60,600.00
MF4_Aw_uncon	907,434.86	525,463.25	156.64	264.28	105.88	136.40	-41,536.39	40,400.00

Table 10.32 Evaluation of the green roofs – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF2_GR_ext	856,538.97	496,338.07	152.15	254.44	95.31	131.84	-15,655.25	22,323.20
MF2_GR_semi	855,798.09	501,745.27	152.07	254.45	95.17	131.76	-21,113.42	27,904.00
MF2_GR_int	853,554.36	506,432.97	151.64	253.90	94.99	131.34	-26,063.36	33,484.80

Table 10.33 Evaluation of HVAC – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_BB	727,573.09	435,318.11	133.12	220.42	78.23	112.96	33,230.59	2,880.00
MF4_HP	852,064.28	479,030.20	151.26	251.01	96.68	125.83	-1,832.71	17,136.54

Table 10.34 Evaluation of RES – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_SolarCollector	692,498.83	435,524.12	131.21	214.94	116.41	180.88	29,167.55	16,222.08
MF4_PV_MonoSi	755,390.29	451,401.66	133.73	222.57	126.07	197.97	13,966.46	29,795.80
MF4_PV_MultiSi	768,910.24	457,492.60	136.12	226.68	129.31	203.05	9,590.24	29,795.80

Table 10.35 Evaluation of night ventilation– MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_NC	878,856.80	479,509.63	154.45	258.32	99.54	134.13	2,860.28	0.00

Table 10.36 Evaluation of combined scenarios – MF4

Scenario	CO_2eq	LCC	Env. Score	Score	Final Energy Consumption	Primary Energy Consumption	NPV	Investment cost
	[kg]	[€]	[pt]	[pt]	[kWh/m²]	[kWh/m²]	[€]	[€]
MF4_EPS_T4+BB	570,574.53	446,735.62	112.54	184.64	54.16	92.52	8,712.80	59,885.40
MF4_EPS_T4+BB+AC	520,711.91	436,760.31	104.69	169.76	49.76	79.75	10,727.49	77,021.94
MF4_EPS_T4+BB+AC+NC	512,504.77	433,382.17	103.04	167.06	49.21	78.16	13,113.73	77,021.94
MF4_EPS_T4+BB+AC+NC+CM	509,666.59	442,102.06	102.62	166.61	48.82	77.76	4,129.99	86,640.44
MF4_BB+AC+NC+CM	705,453.92	446,733.62	131.07	215.18	75.42	105.76	17,311.07	29,635.04
MF4_BB+AC+NC+CM+SC	512,015.76	406,176.80	107.65	170.87	47.80	105.76	39,000.69	53,335.04
MF4_BB+AC+NC+CM+PV	572,149.88	414,576.42	108.36	176.21	65.36	105.76	31,277.53	59,430.84

11 Nomenclature

CDH	Cooling Degree Hours
DHW	Domestic Hot Water
E.E.A.	European Environmental Agency
El.Stat.	Hellenic Statistical Authority
EnEV	Energie-Einspar-Verordnung
EPBD	Energy Performance of Buildings Directive
ETICS	External Thermal Insulation Composite System
G.C.R.	General Construction Regulation
H.V.A.C. systems	Heating, Ventilation and Air-Conditioning systems
HDD	Heating Degree Days
KENAK	Energy Performance of Buildings Regulation
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
MF – building	Multifamily buildings
NPV	Net Present Value
Polykatoikia	Greece's typical multifamily buildings
PV	Photovoltaic
RES	Renewable Energy Systems
SWH	Solar Water Heater
T.I.R.	Thermal Insulation Regulation (1979)
T.O.T.E.E.	Technical Directives of the Technical Chamber of Greece
U-value	Heat transfer coefficient [W/m^2K]
λ	Thermal conductivity [W/mK]