POLITECNICO DI MILANO

School of Industrial and Information Engineering
Master of Science in Management Engineering

Internet of Things & Energy Management: a model to assess costs and benefits of a smart building retrofitting intervention

Supervisors: Prof. Angela TUMINO
Co-supervisor: Dr. Roberta VADRUCCIO

Master Thesis by:

Andrea BARBIERI ID number: 945057
Alessandro BOSI ID number: 953086

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ABSTRACT ENGLISH

Buildings are responsible for 40% of energy consumption and in the EU 75% of the housing stock is considered to be energy-inefficient with low annual renovation rates.
In this context the opportunities enabled by better management and conservation of energy in buildings are huge. There is a clear need to accelerate and finance building renovation investments and leverage smart, energy-efficient technologies if the EU wants to reach climate neutrality by 2050. IoT components have enabled new possibilities for improving efficiency in Smart Buildings, both in Commercial and Residential.
The goal of this master thesis is to understand the current smart building state of the art, what startups are doing, the main existing projects, and then build a quantitative model to help potential investors evaluate the sustainability of an investment in the field.
The model is represented by a quantitative assessment of a retrofitting intervention for an Italian city building composed of both offices and apartments. The model is elaborated in general terms considering costs of real reference IoT components and benefits obtained from average consumption values.
The objective of the model is to estimate the investment of an IoT energy-efficiency installation and the associated energy savings. A sensitivity analysis is performed to make clearer how costs and benefits vary considering the building scenario. How the payback time is impacted by the different characteristics is investigated according to the variation of building dimension, climatic region, energetic class, and building type.

ABSTRACT ITALIAN

Gli edifici sono responsabili del 40% del consumo energetico e nell'UE il 75% del patrimonio abitativo è considerato inefficiente dal punto di vista energetico con bassi tassi di ristrutturazione annuale.
In questo contesto le opportunità offerte da una migliore gestione dell'energia negli edifici sono enormi. Se l'UE vuole raggiungere la climate-neutrality entro il 2050, è evidente la necessità di accelerare e finanziare investimenti per la ristrutturazione degli edifici e di sfruttare tecnologie intelligenti ed efficienti.
I componenti IoT hanno aperto nuove possibilità per migliorare l'efficienza negli Smart Building, sia in ambito commerciale che residenziale.
L'obiettivo di questa tesi di laurea magistrale è comprendere l'attuale stato dell'arte degli Smart Building, cosa stanno facendo le startup, i principali progetti esistenti e la costruzione di un modello per aiutare gli investitori a valutare la sostenibilità di un investimento nel settore.
Il modello è rappresentato da una valutazione quantitativa di un intervento di retrofit in un edificio cittadino italiano composto sia da uffici che da appartamenti. Il modello è elaborato in termini generali considerando i costi dei componenti IoT reali e i benefici ottenuti dai valori medi di consumo.
L'obiettivo del modello è stimare l’investimento di un'installazione IoT per l'efficienza energetica e dei relativi risparmi. Viene eseguita un'analisi di sensitività per capire come variano costi e benefici considerando le peculiarità dell'edificio. Viene studiato il modo in cui il payback-time dell'investimento è influenzato dalle diverse caratteristiche considerate: variazione della dimensione dell'edificio, della regione climatica, della classe energetica e del tipo di edificio.

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EXECUTIVE SUMMARY

Context

Energy efficiency is probably one of the top trends worldwide: companies, institutions, and international governments are struggling with it in every sector. This is related to the viability of our lifestyles with consequences on environmental sustainability. To avoid the global warming catastrophe EU has committed to reach carbon neutrality by 2050 involving two main strategies: on one hand the exploitation of renewable energy sources, the so-called "Green Revolution"; on the other hand, consumption reduction is fundamental as well as energy usage optimization, improved control strategies and energy conservation.
In this context, it was born the concept of Smart Energy which is defined as the intelligent and on-demand provision of energy to applications and devices, with unconsumed energy being saved for later use or offered for other scopes. Smart energy management is not possible without IoT devices. Sensors record interactions with the outside world and exchange this data with other devices or end-users thanks to the connection through the IoT network.
The application of IoT in the energy field can be sub-categorized under different levels, including Smart Building. The concept of Smart Building is strictly tied to IoT and usually cannot be divided.
It is evident by analysing the size of the two sectors. The Smart Buildings' market is projected to grow from 66.3 billion USD in 2020 to 108.9 billion USD by 2025, at a CAGR (Compound Annual Growth Rate) of 10.5% during the forecast period (marketsandmarkets, 2021). While in a similar time horizon spending on software and hardware related to the overall IoT is projected to grow rapidly, from 726 billion USD in 2019 to 1.1 trillion USD in 2023, according to a market research report. (Deloitte, 2020). The CAGR over the projection period is predicted to grow even faster at 14.4%. The two growth rates values have a similar increasing trend, demonstrating the interest in the IoT components and its application area.
It is not hard to see why these numbers exploded in the last few years. The quantity of data Smart Objects are able to generate is a constant flux of possible insights that eventually will translate into increased value for the company or the people using them. The IoT data valorization is where the real interest in the wide world of Smart Objects resides. How to capture value is the challenge nowadays, companies and startups are dealing with it in a continuously evolving ecosystem. Energy management using IoT objects can be considered as one of the main strategies to exploit the data flux.
Given the above, this work focuses on Smart Building and energy efficiency. Within the Smart Energy topic, Smart buildings are responsible for 40% of energy consumption worldwide (Majumdar et al., 2016), and in a world that tries to give us hints about the non-sustainability of our behaviour, it is something to take care of. Actually, the systemic approach adopted by all the countries in the Paris Agreement (2015) is the direction to follow, but the goal of remaining under 1.5°C of temperature rise cannot be done without touching the building stock. In Europe 75% of buildings are considered inefficient with low renovation rates of 0,4-1,2% (European Commission, 2019).
Renovation interventions seem the only way to deal with the problem. All the countries have developed plans to foster this type of investments and in Italy we have seen, among other, the introduction of Ecobonus and then after the Covid-19 pandemic also the Superbonus. This incentive is particularly favourable for those who have buildings with low energetic performances, and it guarantees reimbursement till 110% for energy efficiency interventions. The type of interventions defines the percentage incentives, even for domotics it is 65%.

The interest and curiosity towards many of the services mapped through literature analysis and startup investigation are relevant, but the operators in the sector are unable to transform them into a real market demand. This is mainly due to a limited level of awareness in terms of the real benefits provided by these services associated with smart building. In this regard, it will be necessary to be able to measure and quantify the benefits guaranteed by the presence of these services in a building, so that they can spread on the market.

Objectives and Methodologies

The objective of this thesis is to fill the gaps seen in the literature about Smart Buildings, estimating the economic impacts deriving from the implementation of innovative solutions for energy efficiency. The gaps identified are basically two, summarized in the following lines.
Many papers deal with energy efficiency solutions in the residential sector and as many in the commercial one, but few do so jointly (16% of the papers analysed). During the entire literature review process, no model was ever found that calculated the benefits of the IoT in a "Smart Mixed Building" with a dual purpose: both residential and commercial.
Moreover, the majority of the papers are focused on a limited number of technologies, and those that deal with multiple of them simultaneously are related to literature reviews or general market analysis (only 13% of the papers are investigating more than 5 technologies at the same time). The application of a quantitative method, like a mathematical model or simulation, that considers in an extensive way multiple technologies in a single building has been found only in very few cases.
Starting from that, the ultimate objective is to answer the following research questions:

RQ1. What is the current Smart Building state of the art?
This first question has been developed to understand what the main trends in the market are, what startups are doing and the main existing successful projects.

This first question has been split in the following sub-questions:

> ***RQ1.1 What is the application scenario and the technological frontier?***
> What are the peculiarities of the offer and the current state of the market is investigated considering what is going to be implemented right now and what in the future.
> ***RQ1.2 What are the current data valorisation strategies implemented in Smart Building?***
> Looking at the initial focus of extracting valuable information from IoT data, the goal is to understand how Smart Building players intend to use the enormous quantity of information gathered to produce value.

RQ2. Which are the IoT-enabled benefits and costs of the IoT solutions for energy management in Smart Buildings?
The objective is to dig deeper into an analysis of what could be the costs and benefits of introducing IoT solutions in a building retrofitting intervention.

To adopt the right approach and obtain realistic results complementary methodologies were exploited. Both qualitative and quantitative tools have been included in the work.

Literature Review: 97 articles related to Smart Building, IoT and Energy Management were analysed in order to identify the state of art of scientific research. Several research papers coming from scientific Journal and Conferences, combined with whitepapers from leading components companies (i.e.

Schneider Electric, ABB, BTicino), were useful to deepen the understanding on such topics. Relating to Smart Building, the Literature Review helped in understanding the main gaps and creating the first track for the work, the range of dates for the research papers analysed is 2015-2021. The starting point considered coincide with the date of one of the most important accord related to energy management: the "Paris Agreement", an international alliance to fight climate change.

Analysis of secondary sources: 307 startups were analysed in order to get useful information about how new technologies in Smart Building are deployed to challenge the status quo. Further review of 11 Smart Building examples was also useful to get insights about the latest smart constructions. The main source of information was the well-known startup web database “CrunchBase”. Main parameters analysed were in terms of startup demography, finance and application field, to have a 360° general comprehension at a worldwide level about this evolving ecosystem. The most important startups were further analysed.

Quantitative Cost and Benefit model: an analytical model was deployed for computing the main costs and benefits of a Smart Mixed Building. This methodology is important because enable a quantitative assessment of a retrofitting intervention for a city building composed of both offices and homes. Heating, lighting and energy management systems were considered. After assessing the base case considering average values of dimension, consumption and energetic performances, a sensitive analysis was performed by varying the most peculiar characteristics of the building. The aim of the cost-benefit model is to act as a support tool for the strategic decision-making process, to know whether the investment is convenient or not before taking part in the project.

The Model

The core part of this work is the formulation of a model that considers a retrofitting intervention for a building with the application of IoT-based technologies aimed at obtaining energy savings, optimization and consumption reduction. The model will be useful for understanding the main costs and benefits of the intervention for whoever wants to enter into such an investment. Four recipients were identified:

- Private Building owners and Public Administrations;
- Regulators that should understand the size of the investment. They have to decide how to encourage these initiatives with actions aimed at overcoming barriers that prevent people from investing money;
- Companies that own an office, or even the whole building;
- Homeowners that are interested in building automation and want to understand the economic feasibility of a plug and play solution.

Model Formulation

The peculiarity of the model is that it considers three different space typologies: open space offices, offices of professionals and apartments for the same building, with the application of different technologies according to the specific needs, even if with the common objective of energy saving.
Only those components needed to increase the level of smartness of the system (HVAC and Lighting) were considered, meaning actuators, sensors, controllers and the related software. The goal of the model is to understand the impact of an IoT-focused intervention. For instance, Solar Panels would have had a great impact on energy savings, but they would have made lose the IoT focus.

The approach adopted, puts at the centre the building and the owner of the building was considered as the one who should make the investment. However, the estimation of all the benefits of these interventions is related to the occupants, being companies or families. The capital expenditure of this type of project depends on the technology and the building dimension.
In the offices, the energy savings due to lighting systems are driven by new LEDs with dimmable function, equipped with lighting sensors and actuators and also the shading system with venetian actuators. The HVAC system in offices is composed of indoor units powered by heat pumps. The intervention is about the technologies to make it “Smart” in order to obtain benefits related to the control strategies. Sensors with multiple functions, new types of thermostats, and HVAC actuators were included.
The architecture of the control system is based on products that are all KNX or DALI compatible according to the system to be managed: DALI protocol for the luminaires, KNX protocol for commands, sensors, and actuators. Those common standards were taken as the reference for defining the components needed. The DALI standard was considered because it can enable daylight-linked lighting control. This technique is of particular interest as most commercial and office spaces have sufficient daylight from windows to strongly reduce the need for electric lighting.
These energy-saving smart lighting systems are generally installed in office buildings as they have the highest potential for power consumption reduction and are relatively straightforward to retrofit.
In the smart homes, the lighting and heating systems have been considered like in the offices even if the components are not exactly the same. The first difference is about the communication protocol, which in the case of the residential floors is ZigBee.
The homes in the model are equipped with smart sockets, smart switches, a gateway and windows/doors sensors for the lighting system. Contrary to the offices, the residential part of the building is heated by radiators. Therefore, automated thermostatic valves have been considered to automate the system in strict correlation with sensors and smart thermostats.
Components were dimensioned starting from the real need of a hypothetical building, heating and cooling requirement per square meter and the lumens required by law. The components are taken from real catalogues on the market and have been dimensioned according to their specifics.
The calculation of savings takes into account two main things:

- The percentage savings on the total initial energy consumption, that can be obtained from the technologies and control strategies (reference values are obtained from the literature);
- Average consumption of residential and commercial buildings, that could vary according to the scenario.

Initial investment is calculated as a sum of acquisition costs of single pieces and the installation costs. Acquisition costs are taken from real market products but are influenced by economies of scale, introduced according to the number of pieces needed and, therefore, the building dimension.
The results in terms of Payback Time are obtained by actualizing the value of savings and costs during the years by adjusting them with the cost of capital.

Model Application

The base case is composed of an 8-stories building, each of 500 m^2 of surface area, for a total area of 4000 m^2. The model is focused on city buildings, in particular a construction where IoT technologies have not been installed yet. The floors have different usage destinations:

- Ground and First floor: Open Space Offices
- Second and Third floor: Professional Offices
- Fourth, Fifth, Sixth and Seventh floor: Residential

Professional Offices floors are divided in multiple offices of different dimensions, in particular three different sizes according to the usage destination. There are 8 offices of 15 m^2, 4 bigger offices of 40 m^2, and a greater open office of 100 m^2 where all the desks for the employees are. Bath area extension is about 60 m^2 and it is composed of a 30 m^2 male bathroom and a female one of 30 m^2. To complete the floor, there is also a 60 m^2 common area for relaxing, eating or taking a break.
For what concerns the Open Space Offices, they are composed of a large environment with no boundaries to divide the zones, which could also have separations, but the system is managed like one single zone. An example of that could be the common working areas popular in tech companies. The environment is considered as one single area of 440 m^2 with only the bath areas (equal to the one of professional offices floors) as separate zones.
The residential floor is also composed of different spaces, which in this case are different sized apartments. In each floor there are two small apartments (85 m^2), one medium apartment (120 m^2) and a bigger one (180 m^2).

The main outcome of the application of the model is the Payback Time which is the main driver to be analysed in order to understand the sustainability of the investment. In the base case the value of Payback Time is about 6,2 years and an initial investment of € 84.734 is required. The period costs are much lower with respect to the annual benefits obtainable by summing up HVAC savings and Lighting savings, resulting in a positive Net Annual Benefits.

Surface	Initial Investment	Period costs	Annual Benefits	Net Annual Benefits	PBT (years)
4000 m^2	€ 84.734	€3.193	€17.866	€14.673	6,20

Table E.S.1: Base case scenario model application

Sensitivity Analysis

The baseline case already described constitutes the starting point, but then a more detailed analysis was needed to account for the different requirements of the buildings. Distinct scenarios were considered according to the variation of building macro-variables:

Scenario 1: Variation of the building dimension together with the climatic region

The analysis considered a smaller building of 2000 m^2 and a bigger building of 8000 m^2, with the ratio between floor typologies kept constant. It is important to underline that for the sake of simplicity the floor dimension remains the same (500 m^2).
The variation of the climatic region is important because the area where the building is built can have a significant impact in terms of heating/cooling requirements. Consumption levels are taken from average values identified by ENEA (2019) about offices in NORTH, CENTRE and SOUTH Italy, considering

the same geographical division for apartments. While the building dimension will vary both the costs and the savings, the belonging climatic region will act only on the benefits achievable.
The investment is more convenient for bigger buildings placed in colder climates. For the higher heating consumption in Northern Italy, it is possible to reach higher savings, which translate into 5,06 years of PBT (case 4000 m^2). In Centre and South Italy values of PBT are similar because the starting consumption levels are similar. Considering the dimension variation, bigger buildings enable higher economies of scale and higher savings, obtaining lower PBT. Even in the worst case of 2000 m2 in South and Centre Italy the investment is sustainable.

Surface	Climatic Zone	Initial Investment	Period costs	Annual Benefits	Net Annual Benefits	PBT (years)
2000 m^2	North Italy	€ 44.412	€1.614	€10.486	€8.872	5,33
2000 m^2	Centre Italy	€ 44.412	€1.614	€8.170	€6.556	7,35
2000 m^2	South Italy	€ 44.412	€1.614	€8.219	€6.605	7,30
4000 m^2	North Italy	€ 84.734	€3.193	€20.972	€17.779	5,06
4000 m^2	Centre Italy	€ 84.734	€3.193	€16.341	€13.148	6,97
4000 m^2	South Italy	€ 84.734	€3.193	€16.438	€13.245	6,91
8000 m^2	North Italy	€ 161.289	€6.315	€41.945	€35.630	4,79
8000 m^2	Centre Italy	€ 161.289	€6.315	€32.681	€26.366	6,59
8000 m^2	South Italy	€ 161.289	€6.315	€32.876	€26.561	6,54

Table E.S.2: Model application results (variation of building dimension and climatic region)

Scenario 2: Variation of the energetic class

The sensitivity analysis for the energetic class started from the building's classification based on its energetic status, certified by the APE (Attestato di Prestazione Energetica). This ranking presents seven main classes from A to G, corresponding to seven different energy consumptions. To estimate the energy class of a building the technicians take into consideration a plurality of factors. The primary energy requirement for winter heating is the data that can help even a non-professional to get an idea of the energy class of the building. The consumption of buildings was calculated for each class. Class F is considered the starting point in which the base case is placed.
In the end, it results that in A, B, and C classes the PBT increases a lot, due to the starting level of energy conservation standards. Class G is the best one in terms of repayment with 5,37 years PBT. The difference between A and G is about 125% (6,71 years).

Energetic Class	Initial Investment	Period costs	Annual Benefits	Net Annual Benefits	PBT (years)
A	€ 84.734	€3.193	€11.159	€7.966	12,08
B	€ 84.734	€3.193	€12.501	€9.308	10,15
C	€ 84.734	€3.193	€13.574	€10.381	9,00
D	€ 84.734	€3.193	€14.647	€11.454	8,09

E	€ 84.734	€3.193	€15.988	€12.795	7,18
F	€ 84.734	€3.193	€17.866	€14.673	6,20
G	€ 84.734	€3.193	€20.012	€16.819	5,37

Table E.S.3: Model application results (variation of the energetic class)

Scenario 3: Variation of the building type

The last variable analysed is the building type. The variation of it was proposed trying to understand what differences could arise from having a building dedicated to "Only Offices", "Only Residential" or the base case which is a "Mixed" Building.

The higher savings can be achieved in an office setup with a PBT of 5,48 years, it is even better than the Mixed configuration because higher synergies can be achieved. It should be noticed that the residential's floors of the model achieves lower savings having lower starting consumption values with respect to offices. The "Only Residential" building repays the investment in 10,37 years.

Type of Building	Initial Investment	Period costs	Annual Benefits	Net Annual Benefits	PBT (years)
Mixed	€ 84.734	€3.193	€17.866	€14.673	6,20
Offices	€ 141.895	€5.992	€33.602	€27.610	5,48
Apartments	€ 50.692	€1.214	€6.678	€5.464	10,37

Table E.S.4: Model application results (type of building variation)

Comprehensive Analysis

In the end, it is also provided a comprehensive sensitivity analysis that considers the variation of the variables together. The results are in the form of specific Payback Time values drafted according to the characteristics of the single situation.

The following tables are aimed at giving a visual expression of the results to have an immediate way to understand the feasibility of the investment. The tables down below include in each cell a value of PBT calculated considering the intersection of the variables, NORTH A for instance means that the payback time is referred to the average North Italy value of PBT for Energy Class A buildings.
The greener the cell the better the values, red numbers are associated with a longer repayment time.
The values of "Mixed" and "Offices" are very similar even if a difference of 1 or 2 years can always be registered. Considering only offices, the costs associated with the investment will be much higher but at the same time, it is the place where bigger savings can be made. For both the cases bigger surfaces are better, but good results can be achieved also in smaller buildings. The real and important difference arises when comparing "Mixed" and "Offices" with the residential type, here only in low energy performance building the investment is profitable. One thing to remark is that only if the PBT is lower than 20 years the investment can be made because after that some components started to be substituted. For "Only Residential" buildings from class G to class E there is a positive payback time, while from class C there are high PBTs. Class D is at the boundary suggesting that maybe other most profitable investments can be found, an investor can enter into such a project if he considers as a priority not only economic savings but also the related environmental savings (e.g. emission reduction).

Mixed Building											
	2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²
NORTH A	**10,23**	**9,68**	**9,13**	CENTRE A	**14,65**	**13,79**	**12,96**	SOUTH A	**14,08**	**13,26**	**12,47**
NORTH B	**8,64**	**8,18**	**7,73**	CENTRE B	**12,22**	**11,53**	**10,86**	SOUTH B	**11,86**	**11,20**	**10,55**
NORTH C	**7,69**	**7,28**	**6,88**	CENTRE C	**10,79**	**10,19**	**9,61**	SOUTH C	**10,54**	**9,96**	**9,40**
NORTH D	**6,92**	**6,56**	**6,21**	CENTRE D	**9,66**	**9,14**	**8,62**	SOUTH D	**9,49**	**8,97**	**8,47**
NORTH E	**6,15**	**5,84**	**5,53**	CENTRE E	**8,54**	**8,09**	**7,64**	SOUTH E	**8,43**	**7,98**	**7,54**
NORTH F	**5,33**	**5,06**	**4,79**	CENTRE F	**7,35**	**6,97**	**6,59**	SOUTH F	**7,30**	**6,91**	**6,54**
NORTH G	**4,62**	**4,39**	**4,16**	CENTRE G	**6,35**	**6,02**	**5,70**	SOUTH G	**6,32**	**6,00**	**5,68**
Only Offices											
	2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²
NORTH A	**8,69**	**8,27**	**7,86**	CENTRE A	**12,28**	**11,68**	**11,07**	SOUTH A	**11,82**	**11,23**	**10,66**
NORTH B	**7,42**	**7,07**	**6,72**	CENTRE B	**10,40**	**9,89**	**9,39**	SOUTH B	**10,10**	**9,61**	**9,13**
NORTH C	**6,65**	**6,34**	**6,03**	CENTRE C	**9,27**	**8,82**	**8,38**	SOUTH C	**9,05**	**8,62**	**8,19**
NORTH D	**6,02**	**5,74**	**5,46**	CENTRE D	**8,36**	**7,96**	**7,56**	SOUTH D	**8,20**	**7,81**	**7,42**
NORTH E	**5,39**	**5,14**	**4,89**	CENTRE E	**7,44**	**7,09**	**6,74**	SOUTH E	**7,34**	**6,99**	**6,65**
NORTH F	**4,70**	**4,48**	**4,27**	CENTRE F	**6,45**	**6,15**	**5,85**	SOUTH F	**6,40**	**6,10**	**5,80**
NORTH G	**4,10**	**3,91**	**3,72**	CENTRE G	**5,60**	**5,34**	**5,08**	SOUTH G	**5,58**	**5,32**	**5,06**
Only Residential											
	2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²
NORTH A	**> 30**	**> 30**	**> 30**	CENTRE A	**> 30**	**> 30**	**> 30**	SOUTH A	**> 30**	**> 30**	**> 30**
NORTH B	**> 30**	**> 30**	**> 30**	CENTRE B	**> 30**	**> 30**	**> 30**	SOUTH B	**> 30**	**> 30**	**> 30**
NORTH C	**26,24**	**23,72**	**21,44**	CENTRE C	**> 30**	**> 30**	**> 30**	SOUTH C	**> 30**	**> 30**	**> 30**
NORTH D	**17,47**	**16,06**	**14,75**	CENTRE D	**28,63**	**25,76**	**23,19**	SOUTH D	**29,55**	**26,53**	**23,84**
NORTH E	**12,34**	**11,46**	**10,62**	CENTRE E	**18,88**	**17,31**	**15,86**	SOUTH E	**19,43**	**17,80**	**16,29**
NORTH F	**8,76**	**8,19**	**7,64**	CENTRE F	**12,82**	**11,90**	**11,01**	SOUTH F	**13,18**	**12,22**	**11,31**
NORTH G	**6,58**	**6,18**	**5,78**	CENTRE G	**9,39**	**8,77**	**8,17**	SOUTH G	**9,65**	**9,00**	**8,38**

Table E.S.5: Payback time results (Mixed Building, Only Offices, Only Residential)

Investment Analysis

The model concludes with the analysis of the investment and its modularization to help decision-makers in taking better choices. The amount of the initial investment could represent a problem and its distribution in a longer time horizon would be an interesting possibility. Therefore, it should be investigated deeper what are the parts to prioritize. The floors of the building are equipped with components that could be reconciled to the lighting system and HVAC system which is why these investments are considered separated to better understand the numbers.

Looking at the values of Payback time for professional offices for each separated system, the values of Lighting and HVAC investments are almost equal, meaning that it is hard to say which one is the best. The two systems are equally impacting on the single floor, but the differences start arising if the two are implemented together and for an entire building. This would cause a reduction in PBT of about 20% from almost 6,9 years to 5,48 years, meaning that applying them together has a certain impact.
Considering instead the Open Space Office floor we can say that the lighting system is the one to prioritize with PBT of 5,31 years with respect to 15,74 years of the HVAC.
Performing the HVAC intervention after having repaid the first one has a positive impact resulting in a payback time for the single system of 4,7 years. Having already sustained costs related to the shared components (e.g. Multisensor), the system is now more affordable if compared to the case in which this investment was prioritized.
Also, in this case, splitting the investment into two according to the system will distribute the total amount on a larger time horizon and will require lower economic outlays. Once the investor repays the investment it enters in the second.
For what concerns the Smart Home, the investment for heating should be the one to prioritize because savings are much higher than in the lighting. Apartments' interventions will be also analysed according to the perspective of the single homeowner who wants to undergo a similar investment. An intervention in a 120 m^2 apartment can reach 11,16 years of PBT with an investment of € 1.935. This last analysis suggests that also this type of investor could have positive returns to introduce this IoT configuration.

Type of Apartment	Surface (m^2)	Initial Investment	PBT (years)
Small	85	€ 1.532,30	12,93
Medium	120	€ 1.934,90	11,16
Big	180	€ 2.337,50	8,57

Table E.S.6: Investment for single apartments summary (dimension variation)

Conclusions

The major goal of this work is to develop an analysis of the Smart Building environment, focusing the attention on the application of IoT components to energy efficiency purposes. Thanks to the analysis performed, it is possible to answer the Research Questions previously formulated:

RQ1. What is the current Smart Building state of the art?
Answered through the following split:

RQ1.1 What is the application scenario and the technological frontier?
From the literature review emerged that topics related to Building Management System and HVAC system are the most discussed, meaning that the sector is concentrating mainly on them. Energy optimization of building systems remains the most tackled topic that arose in the Startup analysis, with almost 40% of players in the field dealing with the problem.
Comprehensive solutions are not widespread but usually, buildings have installed measures for one or two functionalities (e.g. security, HVAC, lighting).
Single successful examples were also analysed to understand the main direction of the market.

RQ1.2 What are the current data valorisation strategies implemented in Smart Building?

The startup analysis is useful to investigate what strategies do the most important newcomers implement to extract value from IoT. The approaches found were mainly about “Process Optimization” according to the classification of Tumino et al. (2012). The main strategies were about the optimization of energy usage inside the building systems declined in different solutions according to the company. Predictive maintenance is also a popular data valorisation strategy in the process optimization category. Approaches related to the “Customisation of product/service” were also found. Startups like WeMaintain use data obtained from IoT to provide a customised service in the field of lift predictive maintenance. Most of the startups will exploit a software business model meaning they provide services based on software functionalities.

RQ2. Which are the IoT-enabled benefits and costs of the IoT solutions for energy management in Smart Buildings?

This question is answered by looking at the model application part, the sensitivity analysis and the investment analysis.

The usefulness of the model is to provide insights and suggestions as well as a first estimation of an IoT energy efficient retrofit intervention on an existing building.

The information gathered about benefits is taken from the literature, therefore a certain margin of error should be considered, given that the application in the single case could have a range of savings that vary a lot. These considerations are not as strong as the background of technicians, who can choose the most appropriate technologies and better scale the systems according to the unique building.

Results are in line with the expectation with PBT generally positive. The benefits achieved are not high in absolute terms because there are not strong masonry works, but only installations of sensors and actuators. The approximation in costs and benefits with respect to the values of an actual Smart Building implementation project is, of course, one limit.

Further development of the research could include not only energy efficiency but also estimation of comfort and wealth that these types of installations provide. A more comprehensive study can be done in this way or considering technologies not only related to energy efficiency but other functionalities of the Smart Building, like security and safety.

Given the rate of adoption of IoT, the development of the market and the size of investments startups are receiving, it won’t be surprising if those technologies will evolve fast. Thus, an update of the model will be needed to adjust it for new technologies and the evolution of existing ones.

Chapter 1:
INTRODUCTION

This is the introduction chapter in which we want to tackle the main themes of our thesis. Starting from an overview on the IoT technology, numbers and potentialities we reach the Smart Energy field which is useful to understand its implication and introduce our central topic: the Smart Building. Right after the IoT overview, we tried to put on the table the main strategies to extract value from IoT data. Those strategies will be recurrent in our thesis, a research question will be related to them.
We can start directly from understanding the concept of IoT.

1.1 IoT Overview

The fundamental elements for the IoT paradigm are the Smart Object and a Network enabling the connection among these devices.
Smart Objects are smart because of all the components included: sensors, actuators, microprocessors, data storage systems, etc… which can collect, analyse and exchange data and information.
Smart components greatly increase the potential and the capabilities of the physical ones, enlarging their value. IoT cannot be considered as a single technology, but rather it is a combination of different technologies that work together.
According to the Tumino et al. (2012) to make an object smart are needed three main characteristics, not necessarily present all together:

- **Self-awareness**:
  Self-awareness is related to three different features: Identification, Localization and Asset Management. Identification means that the object can be recognized, transported and identified in the digital world through a unique digital identifier. The Localization feature is the objects' ability to detect their position. This may happen in real-time or elaborating tracing information. This feature is useful to know the origin and the history of the item. A Smart Object is an everyday object that has to guarantee both the Identification functionality and the Connectivity one, which we will explain later.
  Asset management relates to the diagnostic feature of the smart object. It is the capability to monitor internal parameters, analyse how it is working and eventually require maintenance activities.

- **Interaction with the environment**:
  Smart objects are everyday objects that usually have the capability to interact with the external environment. This could happen in various forms:
    - **Data Acquisition**: usually this feature could be performed through Sensing or Metering. The first one is the ability to measure state variables needed (such as temperature, pressure, or noise) in a non-continuous flow in time. Metering, instead, is the capability of being able to measure flow variables, for instance, energy consumption or miles covered;
    - **Actions Execution**: it refers to the capability to perform actions commands through remote actuators or after the elaboration of data in loco if the conditions require it;

- **Data processing**:
  It consists in the processing of information obtained from the external environment through algorithms that can be implemented later after the data acquisition.
  Data Elaboration can be basic (for example filtering, averaging) or advanced (for example statistical analysis or forecasts).
  This feature is needed when the time of reaction is low or we should have a response even without an internet connection (like emergency low distance brake by cars).

In this brief description of the characteristics it hasn't been mentioned the term IoT yet. Smart Objects are a part of the paradigm, and it is useful to understand why they are not called Smart Things but Internet of Things. The usage of the word Internet is related to properties in common with the Internet. These properties are:

- **Open Technological Standards**: Communicate in a standard way so that objects can connect one another. Like what the Internet does with open technological standards. It is not required to have a single common standard, what is necessary is interoperability.

- **Accessibility of Single objects**: We can get from the object the information we need.
  For instance, it can be asked to an object, that is measuring the temperature, to define the frequency at which we receive information to develop the application we are thinking about. There is a dynamic interaction.

- **Multifunctionality**: Develop multiple applications based on the same objects.
  One example here is about the usage of connected appliances. They can be used on one side to monitor energy consumption and on the other to monitor the behaviour of people in the house. Consider a case in which some elderly people could have problems. If the person does not cook for himself, this could be a soft signal that something is not going well for him.

1.1.1 Communication Technology and Protocols

In this paragraph it has been tackled the communication property of smart objects, considering the types of connectivity with the classification provided by Porter et al. (2014) and the communication technology useful for the IoT network.

Connectivity

The fourth feature that objects should have in order to be smart is not related to the components themselves but rather to its capability of communicating (through a wired or wireless connection) and transporting information gathered locally (outside the physical device) towards remote applications in the so-called "Product Cloud". Connectivity is the main characteristic of smart objects and is carried out using ports, antennae and protocols.

The IoT paradigm is not limited to only Smart Objects but to the overall network that they create through their interactions.
According to Porter et al. (2014), there are different forms of connectivity:

- **One to one**: a single device connected with another item.
- **One to many**: center-star configuration; a central item connected using a star configuration, it communicates at the same time with more than one device. In this case, an example is the one

of a smart home that usually is equipped with a central gateway able to manage the interactions with the other Smart Objects of the house.

- **Many to many**: several products are related to many other types of items and eventually to external devices. Multiple products are connected at the same time. To generate a network of Smart Objects that exchange information between them is the necessary form of connectivity. With this feature, the full IoT potential can be exploited.

Connectivity is fundamental to completing the IoT paradigm and serves two different scopes. The first one is the simplest, meaning the exchange of data and information between the user, maker, its operating environment, and other products or systems. The second one is related to the possibility of making the object exist in the product cloud, enabling functions that can exist outside the physical device.

Communication Protocols

Considering the IoT architecture to create a "Network of things", Smart Objects must have the communication capability to make edge units interact with remote applications and enable all the functions. According to Tumino et al. (2012), a lot of technologies exist each with its own characteristics, the following table is developed to propose a general overview. A full description of the single communication mean is provided in the Appendix A.

There are a plethora of different ways to communicate between Smart Objects, from wired to wireless, from short-range to longer range. What is important to underline is that according to the single requirement of the application the best solution is adopted. For instance, in Smart Homes and industrial and agriculture the requirements are related to two main things:

- Low power devices: when devices are equipped with batteries, they cannot pretend to use Wi-Fi because requires too much energy to work.
- Low data rate: only packets of data need to be transmitted.

For those IoT requirements standards were specifically developed:

- Mesh Low Power Network: for short-range communication.
- Low Power Wide Area Network: Cellular-like networks develop to cover a gap for long-range communication.

Network	Type of Communication	Popular Use Cases
Ethernet	Wired, short-range	(Stationary IoT) Video Cameras, Game Consoles, Fixed Equipment
Wi-Fi	Wireless, short-range	Smart Home, devices that can be easily recharged
NFC	Wireless, ultra-short-range	Payment Systems, Smart Home
Bluetooth Low-Energy	Wireless, short-range	Wearables, Beacons
LPWAN	Wireless, long-range	Smart Home, Smart City, Smart Agriculture (field monitoring)
LPMN (Zigbee)	Wireless, short-range	Home Automation, Healthcare and Industrial sites

Wireless Bus	Wireless, short-range	Industrial, Water & Gas Metering
Cellular Network	Wireless, long-range	Drones sending video and images

Table 1.1: Communication Network typologies and use cases

The heterogeneity of the protocols proposed depends on the solution adopted for solving contingent problems and the single smart object use case. Today companies are working to overcome these limitations, creating interoperability among different devices.

1.1.2 IoT Architecture

To present the overall architecture that stands behind the IoT supply chain, the authors of Sethi et al. (2017) developed a framework that identifies a three-layer structure.
In order to explain what those three layers are, we want to tackle the topic with two examples:
The first one is about healthcare and in particular remote monitoring systems for elderly patients.
The system should include body sensors to collect patient data, gateways to filter and forward the data, processors for real time-analysis as well as a communication tool and network connectivity to transfer the data to healthcare providers for monitoring purposes or directly to emergency services.
Considering this scenario, the IoT architecture for the system consists of three stages: perception, network, and application.

- The first layer is constituted of sensors that track and evaluate a patient's vital signs such as nutrition or physical activities. The perception layer could also include all the smart home sensors that collect information from the external environment to check if there are adverse conditions for the patients in terms of temperature, air quality, etc. What cannot be missing are actuators that help to maintain optimal parameters in the house. The level described is the “Perception layer”, responsible for collecting data from “things” or the environment around them and sometimes started processing them.
- The “Network layer” transfers data collected into meaningful information and data streams directed towards the third layer (the control centre). Its features are used for transmitting and processing sensor data.
- The third layer receives data, stores them and processes them using cloud-based data analysis engines and machine learning. From all the algorithms and analysis performed the system is able to obtain insights that can be used to recommend the proper healthcare service for each specific situation. The “Application Layer” is represented by the units that receive information from the other layers, elaborate and store data.

The second example is about a smart building, even if the possible applications are very different the underlying structure is always the same:

- The “Perception layer” contains all the tools that directly interact with the environment or the system inside the building. It is the so-called field level in which sensors and actuators are the main components.
- In the “Network layer” what is central are the controllers that act as an intermediate element between actuators, sensors and the other parts of the system. They receive input commands and transmit output ones in order to enable building automation.
- Data management solutions, platforms, information systems are the main elements included in the “Application layer”. In this case, it refers to the software components whose goal is to manage, supervise and control the system. Here data elaboration activities take place.

1.1.3 Historical Evolution

Having understood IoT functionalities, protocols and architecture, we want to dig deep into the history that brings us to the evolution step we are facing now, from the first connected machine to billions of devices communicating real-time with each other.
The concept of IoT has its origin since the beginning of the computer era, in the early ‘60 researchers were already thinking about the pervasivity that the functionalities of a computer could have in all the sectors. Karl Steinbuch, a German computer scientist, made a very accurate prediction in 1964 saying: “in a few decades of time computers will be interwoven into almost every industrial product”. In those years the idea of the IoT ecosystem was ready just on paper and in the tech-savvy minds of computer scientists, but the real issue was in the implementation. The lack of hardware components was a problem: too big, too slow and without a comprehensive network, such as the internet is today.

During ‘80 investment from private and public companies started blowing but the first-ever “connected machine” came as usual almost as a joke.
One day in 1982, David Nichols, a graduate student in Carnegie Mellon University’s computer science department thought about the necessity to know in real-time the status of the Coke machine, if there were any Cokes in the machine or if newly loaded drinks were cold or not. Necessity is the mother of most inventions.
Together with the other two students, Mike Kazar and Ivor Durham began working on this idea to track the machine’s contents remotely by keeping close tabs on its lights. In order to collect data from the machine, a board was installed that sensed the status of each of the indicator lights. A line from the board ran to a gateway for the department’s main computer that was connected to the ARPANET, the internet precursor.
The designed system allowed anyone on a computer connected to the ARPANET to access information about the machine: when the vendor machine needed a refill, when cokes were ready to drink or when they were still too warm, everything always live-monitored.

In 1982 nobody imagined that the Coke machine would be just the first of billions of everyday devices connected to the Internet. It was developed like a joke and a world with IoT seemed very far-off.
From there the potential of this technology was perceived and the diffusion started all over the country.

The technology was present, but the nowadays well-known term “Internet of Things - IoT” was still absent. Its inventor was Kevin Ashton, co-founder of the Auto-ID Laboratory at MIT. In 1999 during a presentation about the benefits of a connected supply chain, he coined the term “Internet Of Things” referring to RFID sensors for warehouse items connected to the internet.
The IoT was then developed and diffused and in 2009 a symbolic threshold was passed: we were living on a planet with more connected objects than people.
Defining the Internet of things as "simply the point in time when more 'things or objects' were connected to the Internet than people", Cisco Systems estimated that the IoT was "born" between 2008 and 2009, with the things/people ratio growing from 0.08 in 2003 to 1.84 in 2010 (Evans 2011).

As even newer technologies and connectivity strategies entered the market, IoT innovation continued to evolve, furthering the transformation of unconnected objects into smart connected devices. This trend impacted industries of all kinds including people's personal lives.
The growth of this technology was real. The pace at which the number of IoT devices was growing, fast and exponential, forced computer scientists to change the connection protocol IPv4 into the new version IPv6.

The new protocol address made a change from the old 32bit (2^32, around 4.3 billion, max objects connected) not anymore sufficient, to 128 bits (2^128 maximum number of addresses).

In 2014 the potential of IoT was fully understood and all the biggest firms around the globe were making investments in that field, to optimize production, gain more control over physical assets and better exploit all their resources. In the same year John Chambers, CEO of CISCO said: "IoT will be the biggest revolution ever".

Nowadays around 50 billion devices are "smart" and so connected. This number is incredible, but it's even more astonishing to think that this technology is becoming pervasive in every sector and the growth parameters are not slowing down yet.

The initial rising trend of the IoT was not as great as expected over the further years mainly due to the lack of mature IoT technologies and business processes, considering the limited guidelines for maintenance and lifecycle management of IoT devices, as well as the limited best practices available to IoT developers. Today, instead, IoT is a growing market as many companies continue to prioritize acceleration through digital transformation and drive IoT business initiatives that embrace new markets and create profitability. Thanks to the development of wireless networking technologies, the emergence of advanced data analytics, the cost reduction of connected devices and the greater use of cloud platforms, the market is expected to continue to grow at a positive rate.

1.1.4 IoT Current Status and Future Evolution

In the previous paragraph, the history of IoT was briefly covered, but to really grasp the impact of this technology we should investigate the current status of the market. The bridging that IoT is going to make between the physical and the data-digital world is a key asset in the new digital economy.
One of the core parameters to evaluate the pervasiveness of IoT in today's economy is the number of connected devices.
According to Juniper Research (2021), the number of devices, sensors and actuators connected to the Internet in 2021 is around 46 billion. This number is the result of a 200% growth over 2016, driven mainly by a "magic key" factor: cost reduction in hardware parts.
The same research, looking at the Consumer Internet of Things (CIoT), industrial IoT (IIoT) and the usage of IoT in public services, found that the latter two will perform the highest growth over the forecast period, with an annual average of over 24 percent growth.
Focusing only on the automotive industry, Gartner (2021) estimates that the automotive Internet of Things (IoT) market grew to 5.8 billion endpoints in 2020, a 21% increase from 2019. By the end of 2019, 4.8 billion endpoints were in use, up 21.5% from 2018.
Another interesting sector where IoT is having a huge impact is utilities. IoT endpoints were 1.17 billion endpoints in 2019 and increasing 17% in 2020 to reach 1.37 billion endpoints. Electricity smart metering, both residential and commercial, will again boost the adoption of IoT among utilities in the following years.
For Smart Buildings not only energy will be the main IoT character. Physical security, where building intruder detection and indoor surveillance use cases will drive volume increase, being the second-largest user of IoT endpoints in next few years according to Gartner.
Other estimates that project IoT forecasts further into the future are even more optimistic.
Cisco's expectation is of over 75 billion connected devices by 2025 and 125 billion IoT by 2030, which equates to about 15 linked devices per person. Global data transmissions are predicted to expand from

20 to 25 percent per year to 50 percent per year on average in the next 15 years, again according to Cisco (2018).

Those numbers are not converging on a single value, but still forecast an IoT market explosion both in more conservative estimates, both on more optimistic ones. A minimum of 20 % increase per year is registered by the different sources we analyse, making it one of the most improving sectors. Another consideration that should be made is that the technology that stands behind all of this application is rather simple, so why hasn't it developed before? The answer starts from considering all the technologies that have enabled IoT. Improvements in communication means like the 5G network, massive exploitation of cloud infrastructure are only two of the main aspects pushing IoT technologies. 5G is essential to the Internet of Things because of the need for a faster network with higher capacity that can serve connectivity needs. The 5G spectrum increases the frequencies on which cellular technologies will transfer data. This broader spectrum available for use increases the overall bandwidth of mobile networks, allowing for additional devices to connect.
Looking at the number in this field we can understand how the sectors follow similar increasing trends. For instance, the market of 5G IoT was valued at USD 1.50 billion in 2020 by "Research And Markets", and it is expected to reach USD 40 billion by 2026, at a CAGR of 72.9%, over the forecast period 2021-2026 (ResearchAndMarkets.com, 2021).

Talking about financial and monetary measures of the market we can see how IoT is impacting the world economy strongly. Different sources are investigated.
As a first insight we can see how IoT Analytics shows in its latest research the situation up to June 2021, reporting the global spending estimation for IoT at $159.8 billion for 2021, 24% up in respect of 2020. In that year the estimated expense was at $128.9 billion divided between IoT Security (3%), IoT Hardware (32%), IoT Services (38%) and IoT Software (26%).
Talking about security, it's forecasted a spending increase by companies on cyber and IoT security as a result of a surge in high-profile security attacks. IoT cybersecurity incidents that made the news, such as the hacking of Amazon's Ring cameras in late 2019, raised awareness of the need for stronger IoT device safety.
Furthermore, Cloud infrastructure for IoT deployments and IoT software applications will be two more areas where spending will gain momentum significantly. In the next few years, IoT software applications are likely to grow at a faster rate.
McKinsey's Global Institute predicts IoT will have an economic impact of between $4 trillion and $11 trillion by 2025. Companies can capture value by creating new revenue streams from providing connected solutions and services to consumers and enterprises and by reducing costs in operations. Much of the IoT data currently captured, however, is under-leveraged.
Deloitte's latest report on the IoT subject reveals the opportunity to take for companies all across the globe. Spending on software and hardware related to IoT is projected to grow rapidly, from US$726 billion in 2019 to US$1.1 trillion in 2023, according to a market research report (Deloitte, 2019).
Over the five-year projection period (2018-23), the IoT market is predicted to grow fast at a CAGR of 14.4%. This surge is fueled by falling computer power costs, advancements in efficient algorithm designs, advances in machine learning, and, most importantly, the emergence of low latency, high-range networks. Following the widespread implementation of 5G networks in many parts of the world, these networks will become even more prevalent (ResearchAndMarkets.com, 2021).

Values already described denote a high attractiveness for the sector and highlight the opportunities to gain from investments. It is clear that all the reports and authoritative estimates, even though they are not converging on the same values, are converging on the increasing worldwide spending and on the increasing adoption rate of this type of technology. The opportunities are even more clear after the pandemic, and we are going to describe it in the next paragraph.

1.1.5 How Covid Pandemic affects IoT project development

The recent Covid-19 epidemic has initially caused a certain slowdown in the IoT investments and their deployments.
Nevertheless, all the sectors went under major disruptions: healthcare, supply chains, governments, hospitals, insurers, logistics providers and many others have been forced to react quickly to face the current crisis and to be ready for possible future ones. As a result of this, the vendors are taking the opportunity in the Covid-19 pandemic situation by offering emerging technology-enabled solutions to overcome the crisis situation, while improving world connections.
For example, at the end of January, the Shanghai Public Health Clinical Center (SPHCC) has used the California-based connected health startup VivaLNK’s continuous temperature measuring device to monitor COVID-19 patients, which therefore reduces the risks of caregivers being exposed to the virus.
The Covid19 Pandemic was as unexpected as it was impacting. Starting from China in late 2019, the World entered an almost complete paralysis, with all the supply chains totally shattered, affecting the economic stability of all sectors globally.
The pandemic crisis has been a tragedy under humanitarian and economic terms, but also an accelerator of almost any technological trend.
Whiting those, IoT took a big step in helping, in particular, Healthcare and Industrial sectors.

The Healthcare sector was one of the most impacted and multiple IoT devices are diffusing at a fast pace to fight Covid19 and the main categories are down presented, with related explanatory examples about companies exploring those fields:

- Remote Patient Monitoring: CMED Health (Bangladesh) provides an IoT-enabled health monitoring solution via a mobile app. Users can monitor their primary health vitals remotely by integrating IoT-enabled smart medical devices with the app. During COVID-19, this allowed CMED’s team to identify and escalate emergency situations. 1.5 million people in Bangladesh have benefited from CMED Health’s platform during the pandemic.
- Healthcare Management: South Africa-based Gauteng health services introduced an electronic Bed Management System to identify the availability of beds across multiple sites. The IoT sensors placed on the beds enable hospital staff to seamlessly identify the beds’ availability. The results are important reductions in the wait time for a bed, providing patients in emergency departments with timely access to the care.
- Vaccine Cold Chain Monitoring: SmartSense cold chain monitoring system helps retail pharmacy chains and hospital pharmacies to continuously monitor the temperature of vaccines from one cloud dashboard. Already, SmartSense technologies collect more than 10 million sensor readings per day in 28,000 retail pharmacy locations and their supporting distribution centers.
- Healthcare Delivery Drones: Zipline enabled drones to deliver vital medical supplies to rural health centers in Rwanda and Ghana. The drone company delivers about 160 different medical products, serving close to 2,500 hospitals and health facilities across Rwanda and Ghana during the pandemic (Ndiaye et. al 2020)

According to Dimiter (2016) the mIoT (medical Internet of Thing) is revamping healthcare services, as people have started using IoT to manage their health requirements. The primary duty of the clinicians will be to work collaboratively when the organization is shifting towards IoT-enabled infrastructure.

With information recorded electronically, health data information will be available in just a tap thanks to on-field mobile technology.

Switching from Health to the Industrial sector, according to McKinsey Institute, companies can overcome the current crisis by thinking about 3 main horizons:

1) Resolve. *How can we ensure business continuity now?*
   Firstly, ensuring employees' safety and security. Companies have modified their workforce organization as a result of having to deal with remote labour on a wide scale, as well as new worries about protecting their remaining on-site personnel. To solve related issues, IoT became fundamental in: improving remote employee collaboration, workforce tracking, vision-based control system and remote asset control.
   Secondly by improving liquidity. With COVID-19 impacting both supply chains and customer demand, industrial enterprises must better manage the shrinking liquidity. The Internet of Things can provide benefits thanks to: IoT-enabled inventory management, waste reduction thanks to sensor indicators, longer maintenance cycles thanks to real machine status monitoring.
   Thirdly, short-term cost reductions are a crucial aspect of the Covid19 resilience, and several IIoT-enabled tools can help in this respect in two main ways. IoT-based software solutions can give a real-time dashboard of key performance indicators to assist shop-floor performance dialogs, with performance improvements up to 40%. Instead, remote support and maintenance solutions have been shown to save 10 to 40% on field-service costs.
2) Return and resilience. *How can we return to business and increase our flexibility to thrive in the "new normal"?*
   Better visibility across the supply chain is enabled by strong connectivity and cybersecurity, allowing industrials to respond more quickly to disturbances. They are the enabler to obtaining large-scale connectivity rollouts, with better performance in terms of cost and time for maintenance operations. Meanwhile, simple cybersecurity measures can prevent large system damage.
   Mid-term cost improvement and flexibility can be achieved thanks to IIoT-enabled asset optimization and real-time procurement transparency with the implementation of analytical platforms based on data coming from supply chain sensors.
   Last but not least, companies can obtain revenue stability by having big data about their customers. coming from smart objects. They can so take better decisions about new products and services while implementing dynamic pricing actions.
3) Reimagination and reform. *How can we improve our business over the long term, in a world changed by the pandemic, and emerge even stronger?*
   Even after the outbreak has passed, the pandemic will have a long-term impact on businesses. Industrials may experience a permanent move toward contactless delivery or more end-user configuration. They might also opt to apply new techniques throughout the supply chain to minimize disruptions like the ones they experienced in early 2020.
   Supply-chain integration enables real-time data sharing between all supply-chain actors, resulting in an integrated picture of production programs, scheduling, stocks, quality, and expected delivery timeframes. With IoT in-line process optimization, companies can adjust machine settings depending on prior and subsequent production stages by combining data from individual machines.

1.2 IoT & Data

In the previous paragraph we have already introduced some techniques to use IoT at is maximum in a continuously changing environment. It is the power of data that, if correctly analysed can produce insights useful to deal with a lot of different scenarios. Information obtained from IoT is usually data that monitors the situation to enable system actions or produce suggestions for the decision maker.
In this paragraph we want to cover the main aspects related to data extracted from IoT, in particular our focus is on the ways companies have adopted these strategies to extract value from data. Moreover, some characteristics of the sector are investigated looking at relevant contributions in the literature.

1.2.1 IoT Data Valorization Scenario

According to hundreds of experts, data is the new oil and what comes directly from the Internet of Things is a constant increasing flux of enormous quantities of them, directly from sensing or metering activities. Not so immediate is the exploitation of these data and their transformation into a money flow. Companies looking to capture that value are adapting their Business Model to be able to take this huge opportunity, even if the full value would come by taking an holistic approach, trying to identify opportunities across digital and analytics. This statement is what emerges in synthesis from McKinsey (2018) in which they investigate how to unlock the full value of IoT. The paper started with the suggestion, for companies, to develop an operating model around three IoT elements:

- Enabling Hardware: the ability to generate data and transmit them to a “brain” which could be local or remote.
- Harnessing Data: even if the phase of processing data is fundamental, what cannot be missing is the management phase of data. Data cleaning activities, standardization ones and also their combination and integration with other data sources like CRM data. Once the processing activities are carried out it is also important the generation of insights from this analysis, which could be simple (e.g. regression) or more advanced (e.g. machine learning).
- Delivering value through existing processes: Once insights are generated and the system is able to guarantee a certain level of quality for them, it is important to integrate them into existing processes and workflows. The paper here makes the example of predictive maintenance insights integrated into the existing manufacturing system.

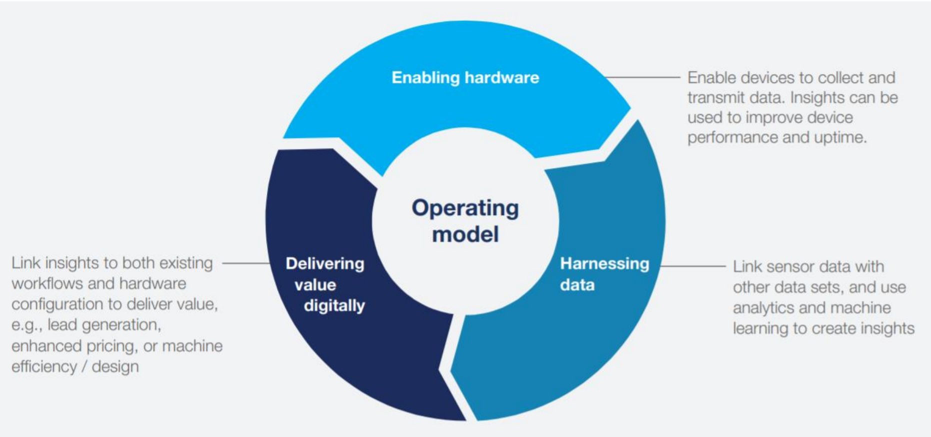


Figure 1.1: Operating model to maximize impact of tech-enabled transformation

Moreover, this IoT operating model requires leveraging other enabling technologies such as cloud-based data platforms and digital workflows to manage the value creation, delivery and capture.

Value Chain

Operating models, strategies and approaches need to be shared across the value chain and its operators. In order to clarify the value chain configuration and what the main stakeholders are, some papers were investigated. We decided to report here the one from Artemis.AI (2020), because it shares some good points. According to the research some actors were identified along the chain, in the large majority they belong to these categories:

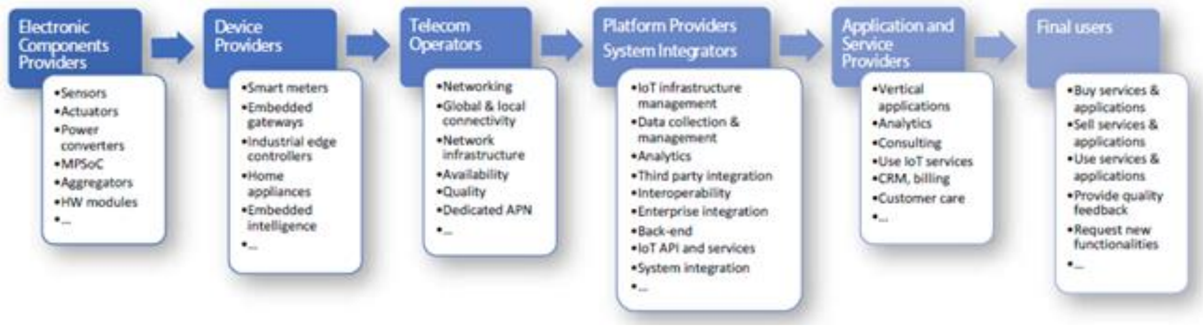


Figure 1.2: Example of the IoT value chain

- Semiconductor companies represent the basement of the value chain, since every electronic device around us depends on semiconductors, including the IoT with its sensors, actuators, and devices.
- Device providers could capture only a limited part of the market (around 10%) but they have an important role for what concerns edge computing.
- Telecom Operators are the third important role of the value chain. They provide internet connectivity but, in a business driven by data usage, they could be relegated to the role of communication channel providers if the connectivity would become the non-value-added part of the value chain.
- IoT platform providers assumed the central position of the chain. The platform is the core infrastructure with a role of orchestrator between the different parts.
  Platforms provide a wide range of features and functionalities:
  - Device and endpoint management
  - Data acquisition and storage
  - Processing and analytics
  - Data visualization
  - Subsystem interfacing and integration (e.g. API, SDK)

  According to the Artemis-IA (2020), more than 600 platforms have emerged already in 2019 with fragmentation as the main characteristic of the market, due to the presence of many niches.
- System Integrators players are crucial for the IoT value chain in order to ensure the seamless integration of components and systems, they contribute to manage the intrinsic heterogeneity of IoT.
- Application or service providers are almost at the end of the value chain, where the large part of the added value offered by IoT lays. They should operate in a strong partnership with other stakeholders of the value chain.

In a traditional model, like the one already described, roles can change according to the circumstances and the vertical domains, some players could act as multiple actors in the chain and try to vertically integrate. There could be the possibility of having holes or overlaps and the responsibilities can shift.

The most important advantage of the value network for a company participating in it is the possibility to extend its business model to the entire ecosystem generating additional value.

Monetization Models

Having clearer how data coming from IoT should be managed and how is the architecture of the value chain in the sector, the real focus of this paragraph is to understand the main methods to monetize the new oil extract from IoT devices.
Monetization models for IoT have been discussed in Capgemini (2014), which identifies four distinct models. Starting from the simplest "Hardware Premium" model directly toward "Ecosystem Building", in the figure 1.3, these models are placed in a matrix according to their complexity and the type of relationship with customers.
In the "Hardware Premium" a price premium is charged for having connected features of the product. Even if the strategy is very simple it leads to immediate results but it can be considered only for a transactional phase, waiting for more advanced models. The natural shift for the companies is the identification of opportunities in the servitization approach. The "Service Revenue" model tries to convert what has been a traditional product into a service, introducing specific pricing models. The "Data Revenues" model tries to sell data gathered from the IoT sensors in a package towards interested stakeholders.
At the end the more advanced one is the "Ecosystem Building" that allows to obtain money from a dual-sided market. The central concept here is the platform that is shared for some players in the ecosystem. The value generated does not lie anymore in the product or services but in providing a bigger ecosystem which is translated into a greater value for all stakeholders (e.g. customer, software developers, hardware manufacturers)

Figure 1.3: Monetization Models for the IoT

Other papers tackle the topic from a more strategic perspective, trying to investigate it from a business logic point of view. It is the case of Gebauer et al. (2020), whose aim is to picture business model changes following an IoT based approach to enhance revenues. In the paper it is described how usually companies start from an immediate and simple approach, which then evolves into a more valuable one, like the "Ecosystem Building" described before. Extracting value from forefront technologies is always a challenge and in the paper are described some cases according to the framework developed:

- **Augmenting products through a “hardware-plus” logic**
  Let’s think about a company initially product oriented. The company recognizes in IoT an enablement towards digital offerings to create new customer experiences. For instance, it could duplicate the user interface of a certain machinery on a pc. Digital offering can help to improve the existing equipment and justify the price premium.
- **Converting services into an outcome-based Business Model**
  When those digital offerings become more mature, new differentiation advantages are triggered by customers demanding outcomes rather than equipment together with services. They demand improvements and guarantees on equipment availability, uptime, usage, and performance. Accordingly, the company evolves its value propositions guaranteeing adequate equipment usage levels and levels of performance. When talking of machinery this strategy could be translated into a better usage of data from sensors to minimize breakdowns and maximize availability (example of that could be predictive maintenance).
- **Exploring a Software Business Model**
  The third situation explained in the paper is that of a company that tries to modify its business model and its value proposition from a hardware and service focus towards software, meaning in this case data about condition and usage. The company value proposition was related to obtaining and analysing data about customer processes and not in terms of guaranteeing a certain performance outcome as the previous case.
- **Exploring a platform Business Models**
  Think of a company that tries to implement all the changes in the Business model described in this paragraph. The customer value is created by a combination of different offerings starting from hardware-plus to software applications. In order to do so, the company needs to integrate these strategies by introducing a platform logic. A platform introduced to integrate the BMs internally and to open them up for external collaboration partners, needs to be equipped with its fundamental building blocks like digital twins (in the case of machinery etc.) and data analytics features.

1.2.2 The 5 IoT Data Valorisation Strategies

In this paragraph we analyse the main 5 IoT data valorization strategies categorized by Tumino et al. (2017).
They identified three reasons why data valorisation is fundamental in a business. It all started from data analytics of large quantities of data collected through IoT objects, which represents a simple way to:

1) Provide value added services; personalization and servitization are good examples of what can be done.
2) Open the path for new business strategies for established companies.
3) Innovate and exploit new business opportunities for startups and investors

The size of the available data sets has grown rapidly as data is collected by every kind of device that has capacity to sense information from the environment. IoT is characterized by cheap information-sensing devices that are diffusing in every context. Therefore, finding ways or strategies regarding data valorisation is needed and it represents the actual trend between telcos, OTT and smaller startups.
In an attempt to illustrate how companies are already enhancing Big Data IoT, the “Osservatorio Internet of Things” has identified 5 ways.
The schemes can also be adopted jointly, with more than one strategy per time, to fully grasp the possible benefits.

Process Optimization

The most simple and established way to exploit data obtained from Smart Objects is to improve internal processes of the firms with the objective of increasing efficiency (time or cost reduction) or effectiveness (client service).
Thanks to IoT it is possible to monitor in real time a productive plant, collecting data that would be useful for introducing predictive maintenance and avoiding production stops. In case of malfunctioning it would be guaranteed rapid intervention thanks to the improved diagnosis feature obtained through IoT and data gathered.

New generation of Product/Service

Data on the use of connected objects by customers can be exploited in the process of developing improved versions, to reduce the most recurring defects, improve usability and understand what features are the most appreciated and the less used.
For example, a clothing retailer can implement IoT solutions within their stores using RFID labels and gates to monitor the passage of garments inside the dressing rooms. By jointly analysing the data collected in the test spaces and those referring to sales, the company can better understand which garments have wearability problems (e.g.: because they are often worn in the dressing room, but they're rarely purchased). This type of analysis can help designers obtain feedback to support the development of next collections.

Customised product / Service

Firms could exploit data collected from IoT devices to personalize their offer. In this way they are able to better satisfy customers' needs.
The strategy tries to grasp the needs of a single individual thanks to a better user profiling on the basis of his habits (the focus is on the single individual). In the case of a Utility on the basis of the energy consumption of the home, you can give advice to users to reduce waste or define custom contracts. Thanks to IoT data collected it is possible to obtain user profiling similar to the one of the digital world (through cookies), and it is obtained through analysis of the data collected regarding the use and habits of the customer.
This strategy can be adopted in the healthcare sector with personal ad-hoc assistance to the patients through monitoring devices equipped with sensors but also mobile apps and other user-friendly tools for the person's well-being.
For other sectors like the insurance one, Smart Object's data could become useful for personalizing offers and tariffs.

Data reselling

New opportunities arise when talking of selling collected data to third parties interested in the information that these data can bring. The strategy can represent an additional source of revenues.

Advertising & Commerce

Like what happens with Google and Facebook talking of user profiling for targeted advertising, something similar can be done in the physical world when a person interacts with smart connected objects.
Amazon has also launched several innovative projects that exploit the data collected from connected devices: for the company, in fact, it is important that the Smart Home is synergistic with eCommerce.

The goal is to maintain a very high interaction with the user, assisting him in the most recurring daily activities, with particular attention to home shopping. An emblematic example in this direction is the integration of the Dash Button with connected dishwashers that monitor the residual stocks of the detergent tablets needed for washing and carry out the repurchase order automatically.

Data valorization schemes diffusion is not uniform, it depends on the level of maturity of the scheme but also on the transformation implemented in the company. The whitepaper Capgemini (2014) deals with the topic and what emerges is that successful data monetization demands significant investment. Acquiring new functional capabilities is not cheap and introducing them in an established way of working is not simple. For instance, organizations need to increase their product management capabilities with additional skills, it could be needed the introduction of specialized customer support teams to respond rapidly to customer queries in real-time and so on.

Following the line of research of the "Osservatorio Internet of Things" we can understand the diffusion of the previously defined strategies in 2017 was primarily related to the process optimization being the simplest to apply in a pre-existing business model. The Advertising & Commerce and Data Reselling were the less diffused.
Talking about direct monetization of data it must be said that its diffusion is strictly related to the presence of data sharing platforms. Tools like IOTA or Xignite (that sell data coming from the financial industry) are born with the aim of facilitating the online trading of various data.

1.3 IoT & Smart Energy

We already deal with the IoT concept, its history, technologies and data exploitation.
Moving from the IoT discussion towards energy management the first topic to be undertaken is Smart Energy. IoT and energy management are the two central foundation of this thesis, which can be intersected into Smart Energy and in the following chapters are also investigated in the concept of Smart Building.

1.3.1 What is Smart Energy

According to Ritchie et al. (2020) in 2019, almost 16% of global primary energy came from low-carbon sources. Low-carbon sources are composed of both nuclear energy and renewables (hydropower, wind, solar, bioenergy, geothermal) (Schlömer et al., 2014).

World's energy needs are covered for about 84% by fossil fuels and their combustion causes a huge impact on the environment, health, and economy due to air pollution and climate change. Climate change and global warming require a paradigm shift in the exploitation of resources and more efficient management of energy.
To avoid the global warming catastrophe EU has committed to reach carbon neutrality by 2050 involving two main strategies: on one hand is the exploitation of renewable energy sources, the so called "Green Revolution"; on the other hand consumption reduction is fundamental as well as energy usage optimization, improved control strategies and energy conservation.

The combination of both renewable sources adoption and better energy management strategies results in the birth of the paradigm.

Smart energy is defined as the intelligent and on-demand provision of energy to applications and devices, with unconsumed energy being saved for later use or offered for other uses. The overall goals of smart energy are to enhance energy supply efficiency, dependability, and sustainability while lowering prices (Loske, 2017).
Smart energy management is not possible without IoT devices, equipped with sensors that record interactions with the outside world and exchange this data with other devices or end users thanks to the connection through embedded systems.
All intelligent technologies of energy generation, storage, transmission, distribution, consumption, and control are referred to as "Smart Energy." As a result, the whole value chain is addressed, from energy generation to energy consumption.

To provide the actual reasons why the concept is expanding we start from analysing the term. The Treccani definition of smart stresses the concept of flexibility: “Smart means the capacity to adapt to new situations and to react by changing the situation itself in presence of obstacles for adaptation”, and fits very well with the smart concept for energy.

The “adapt and react” capability of Smart Energy embeds the use of the Internet of Things (IoT). This technology enables many sustainability practices, such as convenient access to real-time machines and consumer usage information. These practices help providers make smarter decisions about energy distribution while helping their customers conserve energy and save money.
About the economic sustainability of this market, according to the estimation of Technavio, the global market of Smart Energy will increase with a CAGR of nearly 15% in 2016-2020 (Technavio, 2021).
The application of IoT in the energy supply chain can be sub-categorized under different levels, including smart cities, smart grids, smart homes, smart buildings, smart factories, intelligent transportation and smart agriculture, which are treated extensively in the following paragraphs (Naser H. et al., 2020).

1.3.2 Application Areas

Smart Energy is a wide topic in which some main recurrent topics can be identified. Here below is a categorization of the most important branches of Smart Energy and their respective deep dives.

Smart cities

The IoT technology plays a relevant role in solving the problems of a smart city such as energy access, water and air pollution that create environmental worries.
With IoT solutions, it is possible to monitor and control every aspect of the city, from pollution to buildings and transport, up to energy networks and urban infrastructures.
Information about the consumption of energy during the different hours of the day can be collected ensuring an efficient energy system management of the smart city.
For instance, the monitoring of vehicles with IoT allows the modulation of the lights in the streets according to the traffic intensity as well as the authorities to make decisions on transportation on the basis of the collected information.
Concerning the monitoring of air quality, governments, industries and communities could view, correlate, analyse data collected from multiple devices located in the space, set threshold limits and make real-time decisions on air quality.
Talking about energy management, smart energy systems will be a structural part of the development of smart cities. Let’s think about the creation of a digital twin of the city where information from

multiple infrastructures, including energy ones, is brought together, and then used to balance needs and consumption.
According to O'Dwyer (2019) the vision for a future Smart Energy system in a Smart City is to have algorithms which are able to learn demand and usage profiles of single users from historical data, leverage on that information to optimise and coordinate the distribution of energy coming from different energy vectors, while simultaneously taking into account the system constraints and the policy objectives.

Smart grids

Smart grids are "intelligent power grids" applying information and communication technologies (ICT) to control and optimize energy generation, T&D grids, and energy final use.
Here below two definitions of smart grids as extracted from the following paper:

1) "A smart grid is an electricity network enabling a two-way flow of electricity and data with digital communications technology enabling it to detect, react and pro-act to changes in usage and multiple issues. Smart grids have self-healing capabilities and enable electricity customers to become active participants"
2) "A smart grid is an intelligent digitized energy network delivering energy in an optimal way from source to consumption".

Smart grids are able to collect and process information concerning the change in operations and parameters such as voltage and consumption related to the various nodes connected to the network. These characteristics allow proper management of the system with efficient energy distribution. The electricity demand is maintained in line with the supply during the peak time of usage; this is namely Demand Side Management (DSM) which reduces the electricity cost by modifying the system load.
One of the most relevant characteristics of the smart grid is its increasing social impact: the consumer becomes also a producer by participating in the energy system as a prosumer. In this context, the role of smart metering is uppermost giving in real-time information on consumption to the consumers and providers. (Manuel de V. et al., 2021)

Smart home

A smart home, or smart house, is set up with appliances and devices that can be automatically controlled remotely from anywhere with an internet connection using a mobile or other networked device.
According to Rehm (2018) Smart Home describes the networking of household's appliances with the aim of increasing comfort, living quality, safety and energy efficiency. Households get smart only if the devices are able to communicate with each other. Through these Smart Home automations residents are supported in their everyday life.
Security access to the home, lighting and Heating, Ventilation, and Air Conditioning (HVAC) are some of the functions that can be controlled besides systems used for the control of multimedia audio and video devices.
The implementation of the new technologies to the traditional functions in the living environment improve both people's well-being for their comfort, security and entertainment while increasing the energy-saving with reduction of the environmental impact and the economic cost.

Smart buildings

Smart buildings use ICT to connect building systems together to enable automatically building operations and controls. The use of advanced sensors and automated controls in HVAC, lighting, plug loads, window shadings besides automated data analysis allows to save energy and improve occupants' accommodation.

According to King et al. (2017), it is estimated that a smart building with integrated systems accounts for around 30-50% savings in respect to traditional buildings.

One of the most impacting system is HVAC and for this reason its optimisation if fundamental. Therefore, the IoT devices to manage HVAC systems have a crucial role in reducing electricity consumption.

For example, through dedicated sensors, it is possible to identify unoccupied places and consequently the HVAC systems react to reduce the energy consumption in that area.

The energy losses of lighting systems can also be managed with IoT; the users receive a warning when the energy consumption reaches an unexpected value. The real-time analysis of the energy consumption allows optimizing the use of electrical energy with cost-effective and reduction of greenhouse gas emissions.

According to the EPBD (EU Energy Performance of Buildings Directive) all new buildings have to be nearly zero-energy buildings (NZEB) from 2021 (public buildings from 2019). This means that a building needs to have a very high energy performance and the low energy required should be derived from renewable sources, including sources produced on-site.

This is the main prerequisite for the creation of a smart building in compliance with energy and environmental sustainability.

Smart factories

Factories are in the middle of a great transformation becoming smarter, more flexible and sustainable with the modernization of their software infrastructures and application of IoT. The final result is the digitization of manufacturing to create the new factories generation

This transformation process is called Industry 4.0 or the Industrial Internet of Things (IIoT).

IoT and its enabling technology have a relevant role in the industry to reduce energy consumption while optimizing production (Nader et al., 2019).

The traditional factories spent a lot of energy in manufacturing the finished product and for its final quality control. With the use of IoT, allowing implementation of flexible and agile systems, the smart factories can point out any issue in real-time during the manufacturing process and take the proper actions to avoid wasting product and related energy.

The energy losses in smart factories can be reduced by monitoring every single component of the industrial site; if the component consumes more energy than expected, the failure can be solved within minutes.

In a smart factory, the core of the whole system is data processing, through which data in the cloud platform are analysed to support managers in making decisions in a timely manner.

An appropriate IoT platform and tools can contribute to reducing mechanical devices' wear and tear with less maintenance cost. Through IoT monitoring, the mechanical device never reaches its threshold limit resulting in a long last.

Thanks to IoT- base agile systems, a strict collaboration between customers and manufacturers can be also implemented. A specific product is manufactured on the basis of the customer's order. Therefore, for example in the case of spare parts, there is a significant decrease in the energy losses both concerning the energy used during the production process and the energy wasted in warehouses to keep the spare parts. This enhances the management of energy consumption and production efficiency.

Transportation

The traditional transportation systems are facing a huge transformation thanks to the innovative technologies and the global connectivity available with the Internet.
The application of IoT technologies in transportation offers a global management system on the contrary of the traditional transportation system where each system is stand-alone. The components of the transportation system can be connected together, and their data can be processed together in real-time.
Smarter, safer and more autonomous vehicles that will communicate with other vehicles and with traffic lights as well as with the city building will be the standard of the art.
This new approach to transportation is called Intelligent Transportation Systems, and will continue to adapt, changing the way humans and products move around the new smart cities of the future. Autonomous vehicles will communicate with other vehicles and with city infrastructure, profoundly transforming the transportation industry and its constituencies. Smart cities which employ and effectively manage these technologies will improve mobility while reducing pollution, and in so doing will improve quality of life and economic productivity for their citizens (Jimenez, 2017).
Some applications of smart transportation are the control of traffic congestion and the smart parking systems using online maps. They allow users to select the shorter distance and the fastest route and passengers can know the arrival time and schedule their movements more efficiently.
By using these technologies, the time spent on the city trips will decrease while the energy losses will be reduced significantly as well as the CO_2 emissions and other air polluting gases from transportation.

Smart Agriculture

Smart Agriculture is a trend that stresses the use of ICT in the cyber-physical agricultural management cycle.
In the past, the basis of agriculture was intuitive, and farmers relied on empirical experience in preparing the soil and achieving a better yield; sometimes this resulted in crop loss.
With the introduction of IoT devices, the farmers can use sensors for monitoring temperature, moisture level and soil mineral level, pH value of soil and air quality; the associated data can be collected remotely by using IoT on smartphones or computer systems. This is called also "precision agriculture" which ensures that the crops receive exactly what they need for optimizing production while reducing human effort. Therefore, smart agriculture may help in fulfilling the increasing demand of food in the world (Sharma et al., 2019).
However, it should be noted that smart agriculture is not equally widespread in developed and developing countries; furthermore, the adoption of digital agriculture technologies is disproportionate and favourable for global companies compared to the local family-scale farmer. This is affected by financial resources and limited access to appropriate infrastructures and technologies in some rural areas.
A further consideration is that digital agricultural technologies are affected by economies of scale. Indeed, digital transformation and innovative technologies are not always thought for the scale on which small farmers operate, creating obvious business disparities with large-scale farmers (Trendov et al., 2019).

The scope of Smart Farming goes beyond primary production; it is influencing the entire food supply chain. Big data is being used to provide predictive insights in farming operations, drive real-time operational decisions, and redesign business processes for game-changing business models (Wolfert et al., 2017).

1.4 Smart Building overview

In this paragraph we want to introduce some concepts about the Smart Building and the technologies involved in the extended concept.

1.4.1 Definition

The Intelligent Building Institute (IBI) Foundation in 1989 defined an IB as "*one which provides a productive and cost-effective environment through optimization of its four basic elements including structures, systems, services and management and the interrelationships between them*" (Leifer 1988). Later, the European Intelligent Buildings Group (EIBG) in 1998 defined an IB as "*one that creates an environment which maximizes the effectiveness of the building's occupants, while at the same time enabling efficient management of resources with minimum lifetime costs of hardware and facilities*" (Nguyen et al. 2013).

We can say that the concept of smart building has developed since the early 80s when the idea of a building able to think for itself popped up in a New York Times article (Sinopoli, 2010)
After the first decade in which buildings did not have great advancements in terms of "Intelligent Technologies" then thanks to the new waves of innovation emerged, companies started to introduce more advanced pieces of automation inside the building. The most improvement in the concept derived from the research of better management and control of energy and the possibility to use at best energy efficient solutions.
The first historical evolution step has been the introduction of system sensors, actuators and meters installed in buildings. These have provided the ability to manage energy and optimize consumption as well as activating adequate interventions in case of malfunctions (i.e. predictive or preventive maintenance). According to this common sense some definitions have emerged like the one proposed by the online Oxford Dictionary. It defines a smart building as "a building equipped with lighting, heating, and electronic devices that can be controlled remotely by smartphone or computer" (Online Oxford dictionary, 2021).
This definition reflects the current state of the market some years ago, but researchers, startups and also established firms are now developing the idea that a smart building is something more than simple remote control or even building automation.
What we haven't pointed out yet is the difference between the concept of intelligence and smartness.
As Buckman, Mayfield, and Beck noted there is a shared confusion when dealing with these concepts. That is why in the paper Buckman et al. (2014) they tried to tackle the problem. According to them building technologies have undergone a progression in years, starting from "primitive", to "simple", to "automated", to "intelligent", to "smart".
Primitive Building concept is considered as only walls and a roof, when adding manually controlled technologies for fundamental systems like lighting and climate control it assumes the name of "simple" building.
Basically, the introduction of thermostats has enabled the concept of automated buildings in which using timers and central controls, buildings automatically control light and climate and also schedule them. The concept of intelligent building takes what is explained before and combines those capabilities and in order to grasps the difference we provided the words of Hoy et al. (2016):

"(..) The intelligent building combines the best of both simple and automated buildings: systems are still controlled automatically, but sensors allow the building to adjust to user needs in real time. Smart buildings take it a step further, beyond simply turning things on and off. Smart buildings also collect

data about how and when a building is being used and provide a real-time picture of the status of a building. Using networks of sensors and cameras, smart buildings can count the number of occupants in a building at any given time and track that data over time. (..) Using the data from these sensors, building managers can see current and past use and predict future use. They can also adjust traffic flows as needed to reduce congestion and plan staffing levels to meet demand.” (Hoy et al. 2016).

A smart building should be able to understand conditions from the environment, sensing actions performed by the inhabitants (adjusting the thermostat, switching lights on and off), observing the occupancy and behaviour patterns of the inhabitants, and at the end learn to predict future states of the building.
So, the last point in this brief evolution of the concept is the introduction of Artificial intelligence to transform buildings into Intelligent Buildings. This has paved the way towards the implementation of elevated protocols in terms of safety and security as well as improving comfort and life quality.

According to Chiesa et al. (2021) the term Smart Building refers to a building in which the systems included are managed in an intelligent and automated way, through the adoption of a supervision and control infrastructure of the systems themselves, in order to minimize energy consumption and ensure comfort, safety and health of the occupants.
From these definitions some characteristics elements emerge clearly:

- **Automation Technologies**: Elements that includes the sensors to the systems (lighting system, heating system etc...)
    a) **Sensors**. They monitor the environment according to the specifics they are developed for. They measure state variables like temperature, humidity in a non-continuous flow in time. One of the most important aspects of the IoT is *context awareness*, which is not possible without sensors.
    b) **Controllers**. They are a fundamental part of the system that is responsible for elaborating information received from an input and delivering an output command to actuators. Sometimes controller and actuators functions are together in the same device.
    c) **Actuators**. They are responsible for performing actions after receiving the inputs from a controller that has elaborated the information. They could be responsible for switching on and off lights, as well as more complex actions like modulating fans speed in an HVAC system.
    d) **Smart Meters**. A smart meter could be a gas, heat, water or electricity meter. Their role is to establish a communication between the utilities and the building itself. They have the capability to measure flow variables like energy consumption and manage it.
- **Control platform and software**: this element includes platforms, monitoring software and other tools that are able to collect, elaborate and analyse data from building sensors and formulate reports or drive an action.
- **Connectivity:** fundamental and characterizing element for the definition of a smart object. Bus connections are the main architecture used, being wired or wireless.

Last but not least a fundamental difference should be pointed out. The term “Smart Home” often overlaps with “Smart Buildings" in common speech, but the first one refers to homes and private residences while the second usually refers to commercial buildings even if functionalities are more or less the same.
Smart home is a concept that exploits the latest home automation technology in designing home systems for the purpose of providing security, energy efficiency, comfort, and convenience. The ability to

manage electronic systems of consumers/users from one main control system can make their homes run smoother and save energy.

1.4.2 Smart Building functionalities

The growing interest in recent years in technologies included in the smart building paradigm is a direct consequence of the environmental legislation that has been introduced in Europe and in the rest of the world and which will be dealt with in detail in the chapter 4. Technological advancement and the wide range of services offered make the proposition of the main market players increasingly varied. Obviously, the services may vary according to the intended use of the building, the main ones are identified by Chiesa et al. (2021):

- **Safety**
  All the services such as life-saving and fire-fighting systems that are essential for the management and mitigation of risks and to act promptly in situations that may affect the safety of the occupants. This category also includes real time reporting systems for malfunctions.
- **Security**
  Services to manage and prevent situations in which the protection of assets (which are part of the building itself or housed in it) can be compromised. Examples of this type of service can be video surveillance systems, access control, advanced Cyber Security solutions, monitoring and control systems.
- **Comfort**
  All those services whose aim is to improve the comfort conditions of a work or home environment inside the building. Talking about an office environment the main services are management of space occupation, optimization of the flow of people, management and booking of parking spaces. This category of services is destined to expand more and more with even more personalized services, not only in the residential field but also in the offices, tertiary and public sectors.
- **Health**
  The category health includes all the services like management of air fluxes and air quality monitoring whose objective is to preserve or improve the wellbeing of people inside the building. This area has been impacted by the pandemic, in fact, a rapid spread of services in this category is expected, driven by greater awareness of the importance of air monitoring.
- **General Services**
  In this category resides all the service that does not fit in the others, we can think of smart water management systems, waste management systems and smart irrigation.
- **Energy**
  This category includes services aimed at the management and efficiency of energy consumption, with a view to saving money but also reducing emissions. Automatic adjustment of systems and the environment, detection and control of environmental parameters and remote activation of devices could be examples.
  The focus of this thesis falls mainly into this category and is precisely the starting point for the subsequent analysis of the literature.

1.4.3 Energy efficiency in Smart Building

Improving energy efficiency in building is one of the hot topics worldwide when talking of emission and energy consumption. According to Aliero et al. (2021), it is required to make efforts for energy conservation being building structures a major energy consumer. Currently the energy demand in the building sector takes the lead in energy consumption with around 40% across the globe and it is expected to increase by 2% every year.

Looking at the common experience there are several approaches to make buildings more energy efficient: use of modern materials with better thermal characteristics; replacing equipment with more efficient one or use of better control strategy; applying design methods that consider energy efficiency during design phase.

In this paragraph we want to address technologies that consider Smart Objects as the main source for improving efficiency, and we consider the two main areas: lightning and heating.

IoT-based energy management systems consist of a smart object that has the ability to connect to the internet another object as well as interface with people

IoT is a type of technology that has the potential to connect any device that can be switched ON and OFF. This potential can be used to transform homes and buildings into energy-aware environments thereby providing safe, healthy, and cost-efficient residents without compromising the occupant comfort. In order to make a building smart it should be equipped with some tools in order to enable the remote control and autonomous adjustment of building systems.

To control the Lighting system, these components are needed:

Lights should be the first appliance tied to the building automation because of its simplicity and great potential savings:

- With Presence sensors the system is able to understand if the room is empty or not and adjust light consequently;
- Lighting sensor is needed to capture the light intensity of the environment and through an LED actuator drive an action for the LEDs;
- Dimmer actuator is important in the case of dimmable lights, which have the capability of adjusting their intensity.

Venetians should be controlled by a venetian actuator in a shared effort with the lights to adjust and optimize the internal light intensity exploiting at maximum the external one. The actuator enables the automated management of rolling shutters and awnings on a timed basis in relation to the sun's radiation.

Talking about technologies for making smart existing heating system, we have:

- Presence sensors are important to detect if the room is empty and therefore adjust both lighting and heating system;
- Thermal sensors (temperature and humidity) sense the environment conditions, transfer them to the controller that takes an action through an actuator. It could start, stop or adjust the heating system. One of the main strategies that exploits thermostats and separate sensors is the heating management with multi-zone: temperature regulation according to the mode of use and independently for the different rooms of the house;
- Perimeter sensors are useful in homes where there could be heating waste if the doors or windows remain open while the system is running. The role of this type of sensor is to transmit the “open window signal” and switch off the heating system.

In the heating system the differences could be considering the heat pump, air conditioning system or radiators.

- In the case of HVAC, an actuator is needed for a ducted system. It deals with switching fan coils according to the environment requests, as well as adjusting their intensity for the single unit.
- Talking about radiators, the role of controller for the single unit is assumed by Automated Smart Valves. In the market of building automation, it assumes an increasing interest in the market dedicated to smart valves that substitutes the existing ones applied to radiators in order to control them from an interface (be it thermostat, computer or smartphone). The single valves adjust the flow inside the single radiator and as a consequence of this controls the temperature of the single room.

Chapter 2: LITERATURE REVIEW

Any academic assignment requires a thorough literature evaluation. In this chapter, a literature study is conducted to better understand the benefits of Smart Building and to identify potential gaps for additional investigation.

The first section of the chapter describes the steps taken and the analysis performed in order to produce the final sample of papers. Then it shows a descriptive analysis to give the reader all the essential descriptive information about the country, year, type of publication and research method, within the chosen papers. After that, a final subdivision in sub-categories was performed based on the topics of the documents and our purpose of gaining insight from them. Finally, gaps within the literature are exposed and future possible development is provided.

2.1 Introduction to Literature Review

The relation between the Internet of Things, Data and Energy have sparked a lot of attention in recent years, and numerous researches have been performed on the topic.
The field of investigation is wide and full of development opportunities.
As a result, the literature review is even more significant, because it integrates the knowledge of multiple authors to avoid thesis repetition across time, and also puts together consistent aspects across fields.
IoT, Data and Energy may have a wide range of applications, which means there are numerous topics to research on and a focus on a restricted area will be provided along with the following review phases.
The main goal of this literature review is to investigate the state of art and next open possibilities across the Smart Building sector.

2.2 Material Collection

The main sources of information utilized were Journal and Conference papers, being evaluated as the most trustful sources of information in the field.

2.2.1 Source Selection

To be as fulfilling as possible with the research field, three main sources of documentation become the starting point of the collection process:

- Scopus: an abstract and citation database created by Elsevier in 2004. It has roughly 36,377 titles (22,794 active and 13,583 inactive titles) from 11,678 publishers, including 34,346 peer-reviewed journals in top-level topic categories.
- Web of Science: (formerly Web of Knowledge) is a website that offers access to various databases with extensive citation data for a variety of academic fields. The Institute for Scientific Information (ISI) initially created it, and Clarivate Analytics now maintains it.

- Google Scholar: is a free web search engine that indexes the full text or metadata of scholarly literature from a variety of publishers and fields.

2.2.2 Parameters Selection

Keeping in mind our focus of deepening the research related to the relation among IoT, Data Utilization and Energy across the narrower topic of Smart Building, we start investigating our databases with several keywords, years and source combinations.
After several initial attempts, we found the most suitable parameters combination, fulfilling requirements of depth in the specific arguments and broad perspective across multiple papers.
The following parameter combination becomes our starting point:

- Keywords: Smart AND Building AND IoT AND Energy AND Management
- Year: Jan 2015 - Oct 2021
- Search in: Title, Abstract, Keywords
- Source Type: Conference AND Journal

Keywords were covering our research field in a perfect way and the Source Type was securing reliable results.
The years' range was chosen to cover the most recent discoveries and provide an insight into the technologies and techniques diffused in the most recent years.
2015 was set as the starting point in accordance with one of the most important events related to energy consumption: the "Paris Agreement", a legally enforceable international convention on climate change. It was accepted by 196 Parties at the United Nations Conference on Climate Change (COP 21) in Paris on December 12, 2015 and went into effect on November 4, 2016.
Its objective is to keep global warming considerably below 2 degrees Celsius, ideally 1.5, relative to pre-industrial levels.
Countries aspire to attain a worldwide low point of greenhouse gas emissions as soon as feasible to establish a climate-neutral world by mid-century, in order to meet this long-term temperature objective.
According to the International Energy Agency, buildings and buildings construction sectors combined are responsible for over one-third of global final energy consumption and nearly 40% of total direct and indirect CO_2 emissions. For this reason, the Paris Agreement had a great impact on the sector, which needed new innovation strategies to adapt and improve itself.

Stated this assumption, the initial combined results from Scopus, Wos and Google Scholar counted as 1063 papers. Those papers were downloaded and organized in Excel, to further investigation and selection (Polanin et al., 2019).
Firstly, a cross-check among doubles in the database needed to be accomplished and resulted in the elimination of 250 papers, counting for around 23% of the total.
All the 813 remaining papers were put under focus and selected on the basis of 3 main exclusion criteria, chosen to narrower the focus of our analysis around Smart Building Energy optimization thanks to IoT and Data.
The three exclusion criteria were:

- E1: Software focus
- E2: Other focus than Smart Building related to energy (e.g. Smart Grid)
- E3: Focus only on Privacy and Security issues

This screening was done with the analysis of Title and Abstract pieces when the title was not self-explanatory enough. This passage results in a further skimming of 637 sources, leading us to a sample of 176 papers.
Then, to narrow again our focus we chose to proceed with another skimming to eliminate some recurring arguments that were still present in the papers, but not in the focus of our work.
For this reason, we introduced two more exclusion criteria:

- E4: Focus only on a specific algorithm
- E5: Focus on energy consumption prediction and not optimization

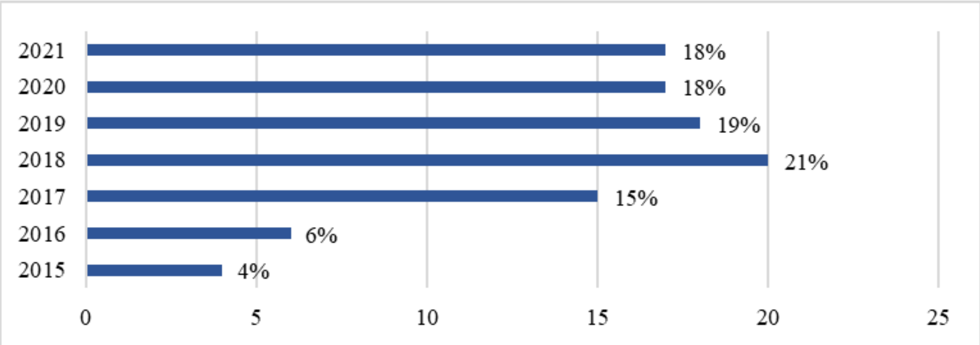
This step result was 97 papers, which became our final analysis pool for the literature review and also the basis of our research scope.

2.3 Paper Analysis and Classification

From this point on, the analysis reaches the final phases, with the disclosure of all the contents in depth (title, abstract and main body) to realize a classification based on: year, continent, country, journal or conference and research method applied.
This classification will be useful to understand the evolution of the Smart Building topic across years and across countries, the most common studied themes and the gaps that need to be filled in the future.

2.3.1 Publication Year

We can start looking at the cross-year classification below represented:

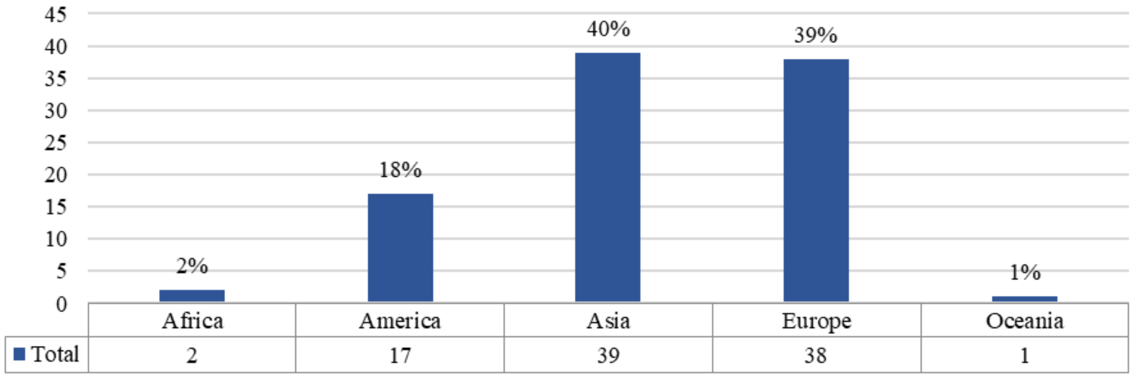


Graph 2.1: Literature Review paper distribution by publication year

Results in the table below show a trend in the last years in respect to the number of publications in the Smart Building field. The interest over selected periods grew a lot with a peak in 2018 with 21% of papers published within the year.
Then, Smart Building keeps being on the edge till today with a balanced distribution of papers being published in 2019, 2020 and 2021, when we can still see a lot of interest in the topic.

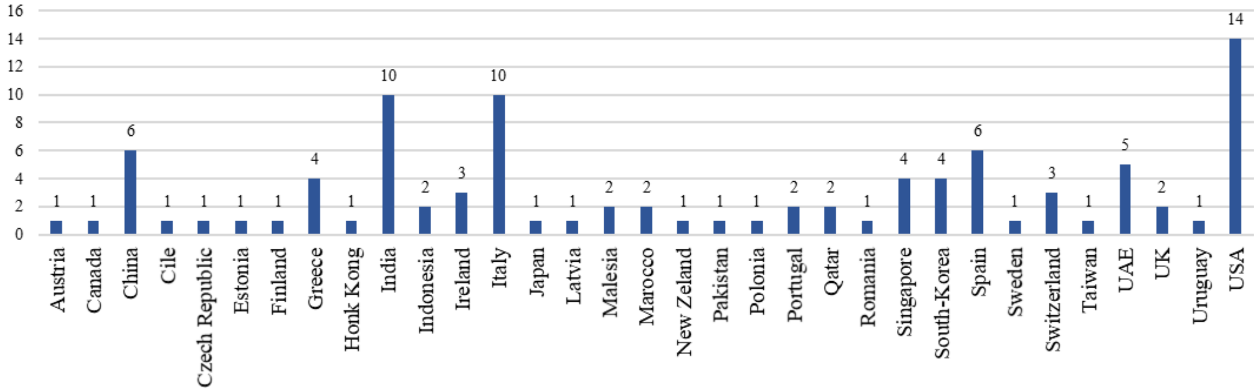
2.3.2 Publication Continent and Country

Switching to Continent and Country classification we can see how the leaders in the research are mainly three continents: Asia (40%), Europe (39%) and America (18%).



Graph 2.2: Literature Review paper distribution by Continent

If the main leaders are taking a big step over Oceania and Africa, the spread inside the single continent, across countries, is balanced.
Taking into account demographic countries' dimensions and interest in the Smart Building field, the distribution of research seems to cover and evolve almost all over the world, making this sector promising and advancing with incredible geographical coverage.
The main "outliers" are the USA (14%), India (10%), Italy (10%) and China (6%).



Graph 2.3: Literature Review paper distribution by Country

2.3.3 Journal and Conference

Across all the 97 sources the classification between Journal Articles or Conference Paper was almost perfectly balanced with 52 papers coming from Conferences (54%) and 45 Articles published in Scientific Journals (46%).

2.3.4 Research Method Applied

Papers have been classified on the basis of the method used by the authors to answer the research objectives and demands.
The classification includes these typologies:

- **Literature Review**: it is the case when the paper analyses the literature, gathering information from other studies and papers previously published about a certain topic (27 papers out of 97).
  An example of Literature Review is provided by Abdul S. et al. (2019) where the author extensively analyses various techniques that have been proposed in the scientific literature, addressing the energy optimization problem, from 1996 to 2018.
- **Conceptual Framework**: method which describes a phenomenon using casual maps, matrices and diagrams (12 papers out of 97).
  Tronchin L. (2018) exemplifies how a Conceptual Framework for Smart Building Technologies can be implemented, creating a framework to have clear boundaries about each single technology application and classification in the bigger Smart Building picture.
- **Analytical Method**: a methodology for scientific analysis which leads to a problem solution using a mathematical process (11 papers out of 97).
  Marc B et al. (2016) is an example of how a mathematical method based on nodes function can be implemented. It shows how the IoT-CSDP solution captures the critical tradeoffs that appear in IoT-Cloud platforms due to the heterogeneity of IoT services, cloud network technologies, and end-user devices. When compared to current solutions, smart IoT services optimized over a fully virtualized IoT-Cloud platform are shown to guarantee stringent QoS requirements in terms of reliability, battery lifetime, and end-to-end latency, while reducing overall power consumption by more than 80%.
- **Simulation**: it is a model of reality which evaluates and forecasts the happening of events and processes, after having imposed certain conditions (11 papers out of 97).
  Banu et al. (2021) provide a software simulation of a smart home energy management system, based on IoT sensors and remote controls. Results coming from the simulation are then discussed against real case study results, with significant consistency.
- **Case Study**: empirical analysis which investigates a contemporary phenomenon in the real world (15 papers out of 97).
  Jasmeet et al. (2016) deployed and tested a smart security system for efficient power management over a home in which 4 220v devices were connected along with the security buzzer and fire alarm system.
- **Survey**: statistical analysis addressed to a selected sample of representative people in order to collect opinions, preferences, or behaviors in relation to a certain objective. It can be structured, semi-structured or non-structured, depending on the needs of the survey (2 papers out of 97).
  Daponte (2018) is a comprehensive survey regarding the adoption of IoT paradigm specific for measurement applications. From this survey, it can be observed that the development of measurement applications using IoT paradigm was possible by using Information Technology, Wireless Sensor Networks, Cloud Computing, Communication Technologies and Cognitive Sciences.
- **Mixed approach**: where a combination of 2 of the previously described approaches has been adopted (19 papers out of 97).
  A significant example of a Conceptual Framework combined with a Case Study is
  Zhang et al. (2017) where the authors summarize their work of developing a framework about the steps needed to build a reliable, cost-effective, and versatile energy management system for

small and medium-sized commercial buildings thanks to IoT, and then apply the framework by effectively building the system.

For a comprehensive view of all the combinations examined, it was identified the following mixed of categories for the final pool of reviewed papers:

- Conceptual Framework and Case Study (9 papers out of 19)
- Analytical Method and Case Study (5 papers out of 19)
- Simulation and Case Study (2 papers out of 19)
- Analytical Method and Simulation (2 papers out of 19)
- Conceptual Framework and Analytical Method (1 paper out of 19)

2.4 Main Themes arising from the Review

Multiple themes have been encountered across the initial phases of the literature review and in particular, some recurrent ones deserve an in-depth analysis, to understand their development and implication across the Smart Building field.
The proposed classification tries to recap the most recurrent and significant themes across different papers and order them by:

- Building typology: Commercial or Residential
- Building technology focus: Water system, Windows and Doors, HVAC, Lighting system, BMS and Control Schema, Appliances and Power Production Systems

The following paragraphs will provide the extensive results for each of the previously mentioned classes.

2.4.1 Commercial or Residential

After having to deepen understanding of the contents of our results, the step needed was to go further in respect of the standard paper categorization.
The first custom classification was made according to the “building typology” treated in the respective paper.
“Building typology” refers to Commercial or Residential buildings focus.

Commercial Building

Commercial buildings include office buildings, warehouses, and retail structures that are utilized for commercial purposes. Essentially, it includes any sort of real estate that is intended to generate revenue, aside from renting purposes.
The number of papers focusing on this building typology is 41 over a total of 97 (42%).
As a geographical economical overview, the worldwide commercial real estate industry was worth over 32.6 trillion dollars in 2020, up 7.6% from the 30.3 trillion dollars in 2019. The largest market was in Europe, the Middle East, and Africa (EMEA), which was valued at close to 10.3 trillion dollars, just slightly more than the Asia Pacific and North American areas. Latin America was the only area whose market size did not rise in 2020, with a size of fewer than one trillion dollars (Statista, 2021).
“This large footprint defines a sizable market opportunity for technical solutions incorporated in Building Management Systems, which are now increasingly based on IoT principles. Inexpensive sensors are emerging, and user-friendly applications are becoming available, often as a Software-as-a-Service (SaaS) cloud-provided service” (Minoli et al., 2017).

Representing the largest part of energy consumption, commercial buildings are a key target for energy optimization strategy thanks to IoT.
Numerous benefits can be achieved thanks to IoT applied in Commercial Building Sector but the two most significant ones are:

- Energy consumption reduction, resulting in a cost and GHG emission cut;
- Comfort for inhabitants increased, resulting in increased overall productivity.

(Hossein et al., 2020)
To reach those objectives the main controlling techniques for data and information are extensively explained:

- Building Information Modelling (BIM):
  is also an integrated design process whose distinctiveness resides in its capacity to gather, consolidate, and combine all data related to building design planning. The area of usage of BIM has an impact on both the execution in terms of timings and techniques, as well as the building's future maintenance and facilities management (Sava et al., 2018);
- Building Automation System (BAS):
  is a computer-based system that monitors and controls the building's mechanical and electrical equipment, such as heating, ventilation, air-conditioning (HVAC) systems, fire systems, and security systems (Hussain et al., 2018);
- Building Energy Management System (BEMS):
  is a comprehensive approach to monitor and control the building's energy needs by collecting the building's energy-related data, analyzing the performance status, and controlling corresponding equipment (Junyon et al., 2016);
- Computerized Maintenance Management Information System (CMMS):
  is utilized by facilities maintenance organizations to record, manage, and communicate their daily operations. The core function of a CMMS is "to manage information related to maintenance, including but not limited to work orders, asset histories, parts inventories, maintenance personnel management and the calculation of maintenance metrics" (Tang et al., 2019).

The combination of these paradigms with the most advanced hardware and software technologies, used to design efficient control and monitoring systems for Smart Building, enables the foundation of all the energy efficiency techniques to cut consumption while retaining or even improving workers' and clients' comforts.

Residential Building

Residential buildings comprehend all the constructions made up of one or more rooms used for housing, with the necessary facilities and utilities that satisfy the living requirements of a person or family. For example, falling under this category we have single houses and multi-level condominiums.
The number of papers focusing on this building typology is 40 over a total of 97 (41%).
Smart Building paradigms inside the Residential Sector, are key enablers of people's life quality improvement.
The integration and development of systems based on IoT thanks to ubiquitous computing techniques, enable and strengthen the interaction between humans and gadgets in terms of:

- Facilitating communication thanks to a collective network intelligence framework between objects and people, as well as between objects and objects;

- Exploiting maximum potential benefits coming from this communications thanks to better general public familiarity with the Information and Communication Technologies (ICT) theme;
- Viewing people and objects as homogenous agents with fixed computational tools in certain ways (Moreno et al., 2015).

Thanks to IoT, Smart Building residents are also exposed to a variety of other benefits.
Smart buildings should prevent users from having to perform routine and tedious tasks to achieve comfort, security and effective energy management.
Sensors and actuators distributed in buildings can make user life more comfortable. For instance, rooms heating can be adapted to user preferences and to the weather; room lighting can change according to the time of the day; domestic incidents can be avoided with appropriate monitoring and alarm systems and energy can be saved by automatically switching off electrical equipment when not needed, or regulating their operating power according to user needs, thus avoiding any energy overuse (Horch et al., 2017).

Commercial and Residential

Some IoT technologies applications could be adapted and applied to both the previous Commercial and Residential building categories (i.e. LED lights installation and automation), for this reason, is also interesting to analyze the amount of paper taking into account both (residential and commercial) at the same time and usually apply a certain single technology to both the contexts.
Overall, the total number of papers treating both the states in the same research was not so significant, reaching the amount of 16 over a total of 97 (17%).

2.4.2 Building Technology Focus

Those categories were chosen to provide a better understanding to the reader about the extensivity of the Smart Building topic, within its all facets.
A single building has multiple parts involved as a single system that needs to be managed with specific technologies in order to optimize both energy and utility.
The main building body parts studied in the research papers can be recapped and divided as:

- Water system (4 papers out of 97)
- Windows and Doors (7 papers out of 97)
- HVAC (46 papers out of 97)
- Lighting system (38 papers out of 97)
- BMS and Control Schema (64 papers out of 97)
- Appliances (40 papers out of 97)
- Power Production Systems (24 papers out of 97)

Papers in the literature reviews focus on different aspects, the majority on multiple technologies within the single study:

- 51 papers on more than one technology in the same paper;
- 46 papers on a single smart building technology focus.

Narrowing the lent on multiple technologies in a single paper we can see how:

- 14 papers focusing on 2 technologies;
- 13 papers focusing on 3 technologies;
- 11 papers focusing on 4 technologies;
- 12 papers focusing on 5 technologies;
- 0 papers focusing on 6 technologies;
- 1 paper focusing on all the 7 technologies.

Results suggest that the two approaches, single technology focus and multiple technology focus, are balanced across the research papers, but tend to slightly move toward the multiple technologies study, usually necessary to have broad perspective results exploiting synergies across smart building technologies.
Zooming on the single technology is interesting to see their details treated in the relative papers.

Water system

Water systems automation thanks to IoT is related to the smart management of water in every aspect of its life cycle in a building.
Water systems enabling the recycling of rainwater are present in the latest commercial buildings, smart water metering can enable optimization techniques for water usage, irrigation systems powered by optimization algorithms to avoid water waste for indoor greenhouses, are a few of the examples where IoT systems can be implemented to improve water usage in buildings.
A focus on a possible deployment for a water management system in residential homes is presented by Rinaldi et al. (2020).
A series of water meters provided by a third-party company emits a number of pulses based on the amount of water passing through the pipe. These water meters are therefore connected to a KNX pulse counter which records home many pulses are sent. Meters are positioned both at the entrance of the water manifold and on each water stream, ensuring that can easily be identified if/where there is a leakage. The user interface is used to monitor the data generated by the smart manifold. It makes it possible to monitor the data generated by the sensors and set up alarms when the values exceed a threshold, defined by the user.

Windows and Doors

Windows and doors can be monitored and actuated very efficiently thanks to IoT technologies.
Windows are one of the first sources of light when we observe commercial or residential buildings. Their optimization with respect to the needs of the building inhabitants is a key aspect to decreasing energy consumption related to artificial lighting systems. A motorized system to partially open venetians/shutters could be a great solution to always have the correct amount of light needed indoors.
Motorized fixtures connected with IoT sensors and a BMS have multiple functions besides the energy optimization one:

- security layer of automatic closing connected to alarms, instead of manual day-to-day action performed by humans;
- opening/closing support for people with walking and movement difficulties, now able to perform these actions in a much simpler way.

An example of a window automation system could be found in Rinaldi et al. (2020) where a prototype designed and implemented wooden frame window unit was equipped with a solar-influx control system

located in the glazing cavity. Multiple sensors were installed: Luxmeter, Passive InfraRed PIR, temperature, relative humidity, and CO2. The window is able to react to the environmental changes through actuators
that enable motorized opening and shading. Thanks to the cognitive layer, the window is also able to automatically define the best opening and shading rules bypassing the local controller on the basis of users' habits and energy efficiency targets.

HVAC

Heating, Ventilation and Air Conditioning systems automation is one the most important achievements in terms of energy efficiency in the field of Smart Building.
HVAC scheduling techniques paying attention to diverse occupancy in the building (diversity in terms of the number of the people inside the building and of their permanence frequency) can reach energy savings up to 30% (Marche et al., 2019)
These techniques need to be combined with parameters taking into account the comfort of residents and workers. This functionality is usually achieved thanks to a preliminary profile user identification, with habits and needs, that is then combined with the optimization function running the HVAC.
The control systems for HVAC are very complex to manage because of the presence of variable frequency drive fans, heating and cooling coils in addition to various random parameters such as outside air temperature, building load disturbance and building occupancy.
In most HVAC systems, the performance of a controller depends on several independent gain values and how often or how accurately these gain values are adjusted. To prevent the complexity of the system from causing poor performance or instability, the whole system needs to be manually adjusted frequently in order to be optimized (Röschlin, 2021).
Another characteristic of HVAC systems is to be able to manage both heating and cooling for a building within the same technology, but this could result in a problem.
Analyzing the other side of the coin, Caleb et al. (2018) provided an extensive case study related to HVAC Systems applied inside the electrical engineering building at Texas Tech University, where the traditional controlling system was activating at the same time heating and cooling functions, resulting in an energy waste from 5% to 20%. A solution to this problem was then provided by the authors, with a more efficient control schema able to do auto-tuning of PI controllers, drastically reducing energy waste previously observed.

Lighting system

The lighting system is one of the most affected ones when we talk about energy efficiency reached thanks to automation and technology improvements.
An incredible achievement of up to 70% electrical energy reduction can be achieved by switching from a traditional bulb, to a LED light incorporated with IoT communication technologies for dimming management (Yaïci et al., 2021).
Lighting systems are extensively utilized both in residential and commercial buildings, providing artificial light to people when it's needed. The key factor to assess is the concept "when they need it".
Usually, a poor evaluation of when and how we need to switch on/off building lights is a major cause of energy waste.
A lot of situations brings a lights management system to have poor performances, and some examples are reported below:

- Groups of lights are switched on together because build within the same circuit when as little as one bulb was sufficient;
- Lights are left switched-on during intervals of no human presence;

- Lights are not dimmable, resulting in a scattered lumen intensity function during the day, unable to meet the optimization level required of lower lumen intensity when natural light is present;
- Lights are not controlled by a central BMS, able to perform all the solutions to the previous problems in an automatic way.

An example of an implemented autonomous LED lighting system managed by a HEMS for a smart home is provided by AlFaris et al. (2017).
Lights connected were dimmable LED luminaries. Smart home's system has used a DALI gateway to control the luminance level for each luminaire based upon the demand. DALI system is a digital control system for lights that control the status and the lumen level for each lamp according to the occupancy rate and the daylight. This control measure by the DALI system may save the lighting power consumption from 40%-60% as per recent studies.
The intelligent home's perspective is not an advanced technology for modernization only, but it is a smart way to optimize the energy performance and to operate the house's energy systems in a smart and efficient way.

BMS and Control Schema

A Building Management System is a control and management system for buildings, or parts of buildings, which controls and monitors mechanical and electrical systems and equipment and offers the ability to manage them, on-site or remotely, through a single interface (Tanasiev et al., 2021).
It collects under its umbrella the management mode of all hardware (control sensors and monitoring and management equipment) through software elements, different from one BMS to another (different algorithms and communication standards).
BMS and Control Schema represent the heart of the IoT Building deployment paradigm, the one way to make all the technologies work synergically together (Verma et al., 2019).

Multiple papers put a focus lens on this aspect and how to manage it, being a backbone for every system. In particular, an extensive review of algorithms and techniques implemented in BMS to obtain energy optimization has been performed by Shah et. al. (2019), resulting in discovering the latest algorithms in energy optimization: earthworm optimization algorithm, Firefly, bat algorithm, anarchic society optimization (ASO) algorithm, cuckoo optimization algorithm (COA), league championship algorithm (LCA), and crow search algorithm (CSA).

Appliances
Appliances and devices are not defined properly as "smart building parts" but they remain a core aspect of investigation when coming to the real deployment of a smart home or a smart office.
Examples of smart devices are Smart Speakers, Smart Kitchen appliances, Smart TVs and Media Kits, Smart Security objects and in general other secondary connected tools that do not deploy a core role function inside a building.
Particular attention should be provided to smart assistants and smart speakers, as suggested by Deloitte (2019). Having increased their diffusion thanks to increasing utility in recent years, Amazon Alexa, Google Echo Dot and Apple HomePod are able to integrate their system with almost all the smart parts of your house, providing a comfort increase for the final user, that can now control his appliances thanks only to his voice, or automate their function through intelligent scenarios.
Smart speakers are gaining traction also in the non-residential context. The operation and use of service devices in smart offices show how smart devices can be integrated into an existing office environment and how they can be controlled by a network calendar and voice services.

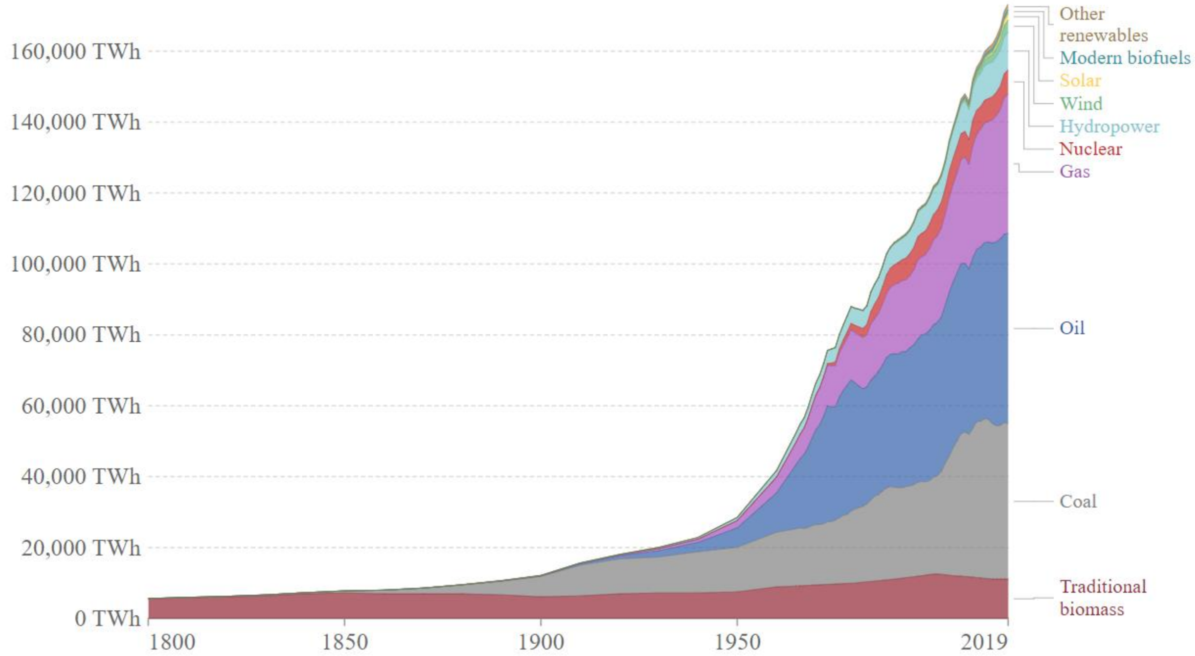
This concept shows the successive opening up of closed platforms, like those of Amazon Alexa, for the development of solutions for smart IoT solutions in order to unleash the full potential of the internet of things (Horch et al., 2017).

Power Production Systems

The last one investigated aspect regarding Smart Building that popped out from the research papers is the best method to provide energy to the building under investigation.
Is useful to remember the classical definition provided by energy sources:

- Renewable Energy: the useful energy collected from renewable resources, which are naturally replenished on a human timescale, including carbon-neutral sources like sunlight, wind, rain, tides, waves, and geothermal heat.
- Non-Renewable Energy: is the energy obtained from sources that will run out or will not be replenished in the near future. Most non-renewable energy sources are fossil fuels: coal, petroleum, natural gas and nuclear energy fall under the non-renewable basket.

Buildings are among the most electricity consumers especially from non-renewable sources that make a huge amount of greenhouse gas emissions (Attia et al., 2018), for this reason, the deployment of smart systems to cut energy consumption inside the building is also usually combined with energy production systems that are able to provide clean renewable energy.
Looking at the map below of primary energy consumption by source at a world scale, we can see how the global population is still very dependent on non-renewables.



Graph 2.4: Global primary energy consumption by source

Focusing only on electricity production we can see how it is instead taking a big step forward to renewables sources. Hydropower, Wind, Solar and Other Renewables accounts for the 36.7% of electricity production source wordwide (Ritchie et al., 2020).

A specific mention needs to be made talking to this aspect, reflecting on how important and diffused Photovoltaic and Solar Panels are becoming to provide energy to smart buildings.

Those solar systems not only provide green energy but enable energy independence for buildings situated in remote areas, difficult to reach by traditional energy grid and with high energy transportation costs.
Those systems make building owners independent from the grid, but dependent on solar light conditions, usually scarce and available only for a few hours a day. For this reason, a well-deployed IoT system is essential in this field in order to obtain the maximum energy conversion and storage from sunlight, with minimum effort and in an autonomous way (Aliero et al., 2021).

Most diffused technologies combination
All the single technologies work for a smart building like body parts in a human being, each one specialized on a single function but usually installed together to better exploit potential synergies to reach higher energy and cost savings.
Looking at paper technology arguments, a narrow down on the "couple of building technologies" has been performed, representing which technologies are usually investigated together in the same paper for a joint result.
Applied the same smart building technology classification as before, a cross-check count of technologies has been carried out with the following results.
In the matrix below Lighting Systems and HVAC are the most diffused systems to be studied and deployed together for the same SB (34 couples over 281).
Following most research combined fields are the HVAC and BMS (32 couples over 281), run after by Lighting System and BMS (31 couples over 281).

	Windows and Doors	Water System	Lights	HVAC	BMS and CS	Appliances	Energy Production
Windows and Doors		3	5	4	5	6	2
Water System	3		4	4	4	3	3
Lights	5	4		34	31	30	15
HVAC	4	4	34		32	26	15
BMS and CS	5	4	31	32		27	17
Appliances	6	3	30	26	27		11
Energy Production	2	3	15	15	17	11	

Table 2.1: Technology couples combination presence in the Literature Review

2.5 Literature Review Conclusions

As final evaluations of the Literature Review, we obtained interesting insights.
The panoramic view on the scientific research carried out since 2015 on the topic of Smart Building has brought to light many considerations that can be summarized in two main points.

First of all, the papers dealing with this topic often make a clear division on the scope of research. Many papers deal with issues in the residential sector and as many in the commercial sector, but few do so jointly, exploiting and evaluating mixed situations in IoT technology adoption. During the entire literature review process, no model was ever found that calculated the benefits of the IoT in a "Mixed Smart Building" with a dual purpose: both residential and commercial.
As a second point, the majority of the papers are focused on a limited number of technologies and those that deal with multiple of them simultaneously are related to literature reviews or general market analysis. The application of a quantitative method, like a mathematical model or simulation, that considers in an extensive way multiple technologies in a single building has been found only in very few cases.
The usefulness of the Literature Review will be found in the subsequent research steps and in the drafting of the model, which will have part of its roots in the just exposed Literature Review's conclusions.

Chapter 3:
OBJECTIVES and METHODOLOGIES

The objective of this thesis is to fill the gaps seen in the literature about Smart Buildings, estimating the economic impacts deriving from the implementation of innovative solutions for energy efficiency. The gaps identified are basically two, summarized in the following lines.
Many papers deal with the topic in the residential sector and as many in the commercial sector, but few do so jointly, exploiting and evaluating mixed situations in IoT technology adoption. During the entire literature review process, no model was ever found that calculated the benefits of the IoT in a "Smart Mixed Building" with a dual purpose: both residential and commercial.
Moreover, the majority of the papers are focused on a limited number of technologies and those that deal with multiple of them simultaneously are related to literature reviews or general market analysis. The application of a quantitative method, like a mathematical model or simulation, that considers in an extensive way multiple technologies in a single building has been found only in very few cases.
This chapter has been developed to make clear what are the research questions and how we intend to answer them. The methodologies involved in this work are described and the approach explained. The thesis is included in an important line of research of the Internet of Things Observatory of Politecnico di Milano that tries to investigate the current status of the overall IoT market in all its facets.

3.1 Research Questions

After having performed a literature review considering Smart Building and energy efficiency as the main keywords, it has been defined the final direction of our work. The outcomes of the previous chapter are the literature gaps and starting from that two research questions have been formulated:

RQ1. What is the current Smart Building state of the art?
This first question has been developed to understand what are the main trends in the market, what startups are doing and the main existing successful projects.

This first question has been split:

> ***RQ1.1 What is the application scenario and the technological frontier?***
> What are the peculiarities of the offer and the current state of the market is investigated considering what is going to be implemented right now and what in future.
> ***RQ1.2 What are the current data valorization strategies implemented in Smart Building?***
> Looking at our initial focus of extracting valuable information from IoT data, our aim is to understand how Smart Building players intend to use the enormous quantity of information gathered to produce value.

RQ2. Which are the IoT-enabled benefits and costs of the IoT solutions for energy management in Smart Buildings?
This second question is tied to the analytical model methodology. We want to dig deeper into an analysis of what could be quantitative costs and benefits of introducing IoT solutions in a building retrofitting intervention.

3.2 Methodologies

To adopt the right approach and obtain realistic results we followed complementary methodologies looking at the different parts we were dealing with. We decided to include in our work both qualitative and quantitative tools that are:

- **Literature Review:**
  97 articles related to Smart Building, IoT and Energy Management were analyzed in order to identify the state of art of scientific research. Several research papers coming from scientific Journal and Conferences, combined with white papers from leading components companies (i.e. Schneider Electric, ABB, BTicino), helped us deepen our understanding on topics such as Smart Building, IoT and Smart Energy Management. Relating to Smart Building, the Literature Review helped us in understanding the main related gaps and creating the first track for our work.

- **Analysis of secondary sources:**
  We scanned 307 Startups and this analysis was useful to get information about how new technologies in Smart Building are deployed to challenge the status quo. Further review of 11 Smart Building examples was also useful to get insights about latest smart constructions. Our main source of information was the well known startup web database “CrunchBase”. Specific gaps were filled thanks to single research for certain startups. Main parameters analysed were in terms of startup demography, finance and application field, to have a 360° general comprehension at a worldwide level about this evolving ecosystem.

- **Quantitative Cost and Benefit model:**
  We set an analytical model for computing the main costs and benefits of a smart mixed building. This methodology is important for us because we are able to give a quantitative assessment of a retrofitting intervention for a typical city building composed of both offices and homes. Even if the smart components included in the two different environments are not the same, their goal is similar. We take into account heating, lighting and energy management. After assessing the base case of 4000 m2 considering Italian averages in terms of climatic regions and energetic performances, we drafted a sensitive analysis varying the most peculiar characteristic of the building. This has been done to understand what the optimal situations to develop the project could be, at the end a final table with the variables crossed is shown to graphically understand the main outcomes of the dissertation.
  The model drafted in this way could be useful for a hypothetical investor who wants to know whether the investment is convenient or not before taking part in the project. The aim of the cost-benefit model is to act as a support tool for the strategic decision-making process.
  The actors that can receive advantages from this model are four:
    - Private Building owners and Public Administrations.
    - Regulators that should understand the size of the investment. They have to decide how to encourage these initiatives with actions aimed at overcoming barriers that prevent people from investing money.
    - Companies that own an office, or even the whole building.
    - Homeowners that are interested in building automation want to understand the economic feasibility of a plug and play solution.

Chapter 4:
SMART BUILDING STATE OF THE ART

The following paragraphs try to sum up all the most important topics, trends, and considerations about Smart Building. It is used to answer the research question 1.1 linked to the current state of the art and future evolution of the sector. Once having understood the numbers we develop an analysis related to what are the current projects in paragraphs 4.3 and the technological frontier in paragraph 4.4. In the last paragraph, we try to answer the research question 1.2 related to the IoT data valorization strategies in the field of Smart Building.

4.1 Smart Building Market

Before entering the Italian market and numbers we want to give an overview of the international market structure considering both quantitative and qualitative aspects to get the real possible evolution of the market.

4.1.1 Worldwide Smart Building Market

For the analysis we take as a reference two reports, the first one is Smart Buildings Market by Component, Building Type, Region - Global Forecast to 2025 by marketsandmarkets and the other is the "Smart Building Market - Growth, Trends, Covid-19 Impact, and forecast (2021 - 2026) of Mordor Intelligence.

Numbers

We want to first tackle the numbers of the phenomenon worldwide and then dive into the main factors affecting the market. According to our first source the Smart buildings market is projected to grow from 66.3 billion USD in 2020 to 108.9 billion USD by 2025, at a CAGR (Compound Annual Growth Rate) of 10.5% during the forecast period (marketsandmarkets, 2021). Growing energy concerns, increasing government initiatives on smart infrastructure projects, and rising awareness of space utilization are driving the market's growth positively.

PESTEL

As said in the chapter introduction we want to address the main trends that affect the market and make a synthesis of those. The considerations made are general and valid for the world as well as for the Italian market. To better frame them we take one of the most important tools used for understanding the competing industry: the PESTEL analysis.

- POLITICAL - LEGAL
  - The increasing number and importance of government initiatives to reduce energy consumption have been one of the primary factors for adopting smart building solutions, that speed up the market. It is worth mentioning here all the plans that the EU commission has set up to reduce emissions and improve energy efficiency in their territories.

  - Cooperation is required among standard bodies, city governments, and other stakeholders for IoT and existing smart-building technologies to work together. The cooperation in the building of smart cities is vital in bringing out the maximum potential of these technologies, the main example here is the cooperation for the introduction of smart grids.

- SOCIAL - ECONOMICAL
  - The first aspect considered is the advent of COVID-19 with its structural changes in how the people conceive society and economy, the awakening of consciousnesses that has caused. We do not want to spend too much time here since we have already mentioned the pandemic in previous chapters and its major outcomes in terms of economic stop and then rapid acceleration.
  - Environmental issues are a major concern today, that is why the whole world is in an effort towards transforming its economy into a greener one. As a consequence of this, it is inevitable that at least for a transactional period energy costs are rapidly increasing. The reasoning is concluded by saying that for this reason in the market there is increasing pressure to provide more energy-saving solutions and save money.
  - A problem that is at the intersection between economy and society is represented by the lack of competent experts skilled in assessing smart solution systems. Failure in having competent professionals may lead to complications in the smart building's constant growth.

- TECHNOLOGICAL
  - In the common-sense Smart Buildings are mainly because of their capacity for energy management even if they are more than that.
    The IoT technology provides owners with an opportunity to have direct conversations and relationships with building users along with their tenants. Let's think about IoT-enabled BMS, they can be used for various purposes such as repairing and maintaining building systems and cutting down administrative costs. For instance, property owners use the data collected from various sensors, such as indoor-air quality and space utilization at the building level to regulate air-conditioning and lighting systems in real-time, thereby reducing energy costs and optimizing the internal environment for its intended purpose.
    The second example here is the role of sensors in shopping malls, which can help owners connect directly to various customers and provide their services, resulting in building relationships with customers.
  - Of course, IoT used alone cannot be as effective as it if used together with other technologies like Cloud, AI, Blockchain, etc. Those technologies are affected by an exponential evolution that seems almost uncontrollable and that is what is driving the smart buildings market.
  - The introduction of 5G technology enhances new and powerful intelligent building capabilities. A huge amount of data is generated thanks to IoT-enabled devices in smart buildings, and in this scenario, 5G technology enables quick data transport, processing, and consequently faster and more effective actions taken. 5G will enhance the occupant's experience.
  - The concept of Smart Building is strictly tied to IoT and sometimes cannot be divided. However, the adoption of these technologies poses a security threat to the building. Most IoT devices and sensors have weak security built-in, unpatched software running,

or use non-standard communication protocols, which could expose smart buildings to various vulnerabilities. Skilled hackers' modus operandi is always to scan targets for technological weaknesses to infiltrate and steal valuable data or take control of a facility.

- ECOLOGICAL
  - Finally, a large part of the interest in smart building solutions can be attributed to the need for appropriate and tailor-made solutions for optimized energy performance to reduce building energy consumption without compromising comfort or security.
  - Enhancing the energy performance of commercial buildings and offices is fundamental for the worldwide emission reduction because buildings generate more waste in the form of carbon and other solid wastes.

4.1.2 Italian Smart Building Market

The analysis about data on the Italian situation starts from the updated “Smart Building Report 2021” of The Energy and Strategy Group of Politecnico di Milano.
In 2019, with over € 8 billion invested in the Smart Building sector, the market for smart components reached € 2 billion, equal to approximately 25% of the overall investments made in the sector. 75% of this value relates to the building devices and solutions category, while the residual share is distributed evenly between Automation technologies (13%) and Management and control platforms (12%) (Chiesa et al., 2021).
Twenty-five percent of "smart" investments include those components that have the characteristics necessary to transform or equip a building with intelligence and management autonomy, hence the definition and the name. According to the authors of the report, this data seems to be related to the reduced awareness of end-users about the potential that this paradigm has both in terms of energy-saving and, above all, in terms of occupants' safety, health and well-being.
Moreover, the analysis of the working group shows that heat pumps, photovoltaic systems, solar thermal systems, and locks are mainly addressed to the residential market. On the other hand, video surveillance systems, fire and intrusion detection systems, emergency lighting and lighting, cogeneration and IAQ systems are solutions typically installed in the tertiary sector.

4.2 European and Italian Legislation for Smart Buildings

The numbers are useful to understand the size of the market but then we should investigate what are its boundaries and opportunities. This paragraph is aimed at presenting the main European and Italian legislation regarding smart buildings in the field of energy efficiency. Starting from the European directive and Italians "decreto legislativo" we analyze obligations and the most updated forms of the post-pandemic incentives.

4.2.1 Climate Change

To understand the actual legislative framework and incentives introduced by the governmental organs we should start from the climatic situation.
According to WWF (2021), the climate crisis is now a fact. The past five years have been the hottest in history and the 2010-2019 decade has also been the hottest since there are reliable and regular records of temperature.
The instrumental measurements, the frequency and violence of climatic events that we are observing, the changes in behavior, in the migratory and reproductive habits of many animal and plant species leave little room for interpretation.
The scientific community is unanimous in indicating human activities as responsible for the climate crisis, in particular, due to the increase in greenhouse gases released into the atmosphere. The concentration of greenhouse gases in the atmosphere has reached record levels, if compared to pre-industrial levels the increase is impressive (WWF 2021):

- Carbon dioxide has increased by 147%
- Methane by 259%
- Nitrous oxide by 123%

These changes directly affect the structure of the atmosphere and induce floods, droughts, hydrogeological instability, the spread of diseases, the crisis of agricultural systems, water crisis and extinction of species more and more frequently.
The only way to deal with this type of problem is to search for a solution in a systemic way, considering all the countries worldwide. The Paris Agreement is the first-ever global climate change agreement (which is also legally binding), adopted at the Paris climate conference (COP21) in December 2015.
The main outcome of the Agreement was to create a global framework to limit global warming below 2°C. The signatories are committed to avoiding dangerous climate change and pursue efforts to limit global warming to 1,5°C. The framework helps the countries to deal with the consequence of the climate change as well as support them in real terms.

4.2.2 European Initiatives

All the following laws have a common backbone that is represented by the European initiatives and medium/long-term plans to achieve sustainability.
We are talking about the 2020 Climate & Energy Package, 2030 Climate & Energy Framework, and the comprehensive 2050 long-term strategy.

- 2020 Climate & Energy Package
  European policy makers have defined in 2008 a set of goals to be achieved within 2020, in doing so a set of laws has been defined to ensure the EU meets its climate and energy targets. The main pillars are:

1) To reach a 20% cut in greenhouse gas emission from the baseline levels (1990 levels).
2) To obtain at least a share of 20% of EU total energy consumption from renewables.
3) To make improvements in energy efficiency (that could be translated into a reduction in energy consumption) of 20% compared to the projection for 2020.

The progress made in these years are relevant, in particular, EU greenhouse gas emissions were reduced by 24% between 1990 and 2019, while the economy grew by around 60% over the same period according to the EU climate action progress report of November 2020 and it is also important to underline that from 2018 to 2019, emissions declined by 3.7%.
Data about 2020 are not statistically relevant since the COVID-19 pandemic has completely cleared all the time series, even though we can see that CO2 emissions have had a steep decline. According to the carbon monitor in Europe + United Kingdom, CO2 emissions registered -10,3% in 2020 compared to 2019 considering all sectors with aviation as the one with the most impact (Commissione europea et al., 2020).

- 2030 Climate & Energy Framework
  The 2030 represents an intermediate target point for the EU towards the 2050 ambitious goals of climate neutrality. This is why in September 2020 decided to raise the greenhouse gas emission reduction target, to at least 55% compared to 1990.
  The objectives of 2020 were amplified in terms of increasing the share of renewable energy on the total energy consumption and to make improvements in energy efficiency.

- 2050 long-term strategy
  The union aim is to be climate-neutral by 2050. The EU is committed to developing a sustainable, secure and decarbonised energy system by 2050. It is important to underline that member states should find a competitive equilibrium reducing energy consumption and decarbonising energy supplies. The objective to have an economy with net-zero greenhouse gas emissions is in line with the commitment towards the global climate action under the Paris Agreement and at the center of the European Green Deal.

4.2.3 Building Legislation

Having understood the big picture about energy and emission we can now dig deeper into the specific sector. What is important to underline are the drivers that push the interest for legislators around smart buildings.
As said in numerous papers buildings are responsible for 40% of energy consumption in the US (Majumdar et al., 2016), Moreover, according to Aliero (2021) "*Currently the building structure sector takes the lead in energy consumption across the globe and is expected to increase by 2% every year".*
Consequently, being a major energy consumer, it's required to make an effort for consumption reduction in this field.
But not only this consideration is sufficient to understand because the most important thing is the opportunities enabled by a better management and conservation of energy in buildings.
Around 75% of the current EU housing stock is considered to be energy inefficient and annual renovation rates are low (0,4-1,2%).
There is a clear need to accelerate and finance building renovation investments and leverage smart, energy-efficient technologies.
To boost energy performance of buildings, the EU has established a legislative framework, the legislation that represents the solid fundamentals are the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU.

Energy Performance of Buildings Directive 2010/31/EU (EPBD)

The main outcomes of the European directive that must apply in all the EU countries are the following

- EU countries must establish strong long-term renovation strategies, aiming at decarbonising the national building stocks by 2050.
- The application of minimum requirements to energy performance of new buildings, existing buildings subject to renovation activities or building parts undergoing replacement or retrofit of heating and cooling systems, rooms or walls etc...
- According to the legislation, all new buildings must be nearly zero-energy buildings (NZEB) from 2021 onwards. Since 31 December 2018, all new public buildings already need to be NZEB.
  The EU parliament defines ‘nearly zero-energy building’ as: “a building that has a very high energy performance”. “*The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby*”; the energy performance instead is defined as all the annual energy needs for a building to heat or cool down and maintain the envisaged temperature conditions.
- The general common framework of a methodology for calculating the integrated energy performance of buildings and building units.
- The promotion of smart technologies, building automation and control systems as well as devices to control heating systems with the aim to regulate temperature at room level. Not only temperature but also health and well-being should be addressed (for instance through air quality monitoring or ventilation).
- EU countries must set up lists of national financial measures and incentives to improve the energy efficiency of buildings.

Energy Efficiency Directive 2012/27/EU

Directive 2012/27/EU established a set of measures to help the EU reach its energy efficiency target by 2020 and to lay the groundwork for further efficiency energy improvements beyond that date.
The directive together with the previous described one represent a turning point for Europe's economy and approach towards energy consumption, demonstrating the strong effort UE puts in developing a greneer Europe and less polluted cities for all of its citizens.
The Energy Efficiency Directive defines a number of important measures that have been adopted to improve energy efficiency in Europe, including:

- New policies to achieve energy savings equal to a reduction of 1,5 % in the annual energy sales to final customers of all energy distributors each year.
- EU countries should make energy efficient renovations to at least 3% per year of buildings owned or occupied by central governments in order to respect minimum requirements established under the national level application of 2010/31/EU.
- Under this directive, EU countries must draw up National energy efficiency action plans (NEEAPs) every three years, and also report their progress in terms of energy efficiency targets through annual reports. In NEEAPs countries must define their expected energy consumption level, energy efficiency measures and long-term renovation strategies with intermediate milestones.
- Products like boilers, household appliances, lighting etc... should be provided with minimum energy efficiency standards and energy labels as well as information about energy consumption printed on the product.

- Smart meters are considered a central part in building energy measures and that is why this directive has a planned rollout of close to 200 million devices for electricity and 45 million for gas by 2020. Smart meter diffusion is continuously spreading and talking about more recent data a study (European Commission, 2020) on the deployment of smart meters in the EU found that a number close to 225 million smart meters for electricity and 51 million for gas will be rolled out in the EU by 2024. This means that a percentage of almost 77% of European consumers will have a smart meter for electricity. About 44% will have one for gas.

Both directives were amended, as part of the Clean Energy for all Europeans Package, in the last few years. In particular, the Directive amending the Energy Performance of Buildings Directive (2018/844/EU) introduces new elements and sends a strong political signal on the EU’s commitment to modernise the buildings sector in light of technological improvements and increase building renovations.
First of all, it is important to underline that the new directive arises from the need to encourage the achievement of new efficiency and energy performance objectives, namely:

- To reduce greenhouse gas emissions by at least 40% by 2030
- To foster the development of a sustainable, competitive, secure, and decarbonised energy system by 2050.

To achieve the objectives, some innovations are therefore introduced, among the most important:

- It is required to provide national strategies for the renovation of buildings. The update of the directive requires Member States to develop long-term national strategies to support the efficient renovation of residential and non-residential, public and private buildings, with the aim of reducing emissions in the EU by 80-85% compared to baseline levels.
- The standard addresses the issue of introducing an "indicator of the predisposition of buildings to intelligence". The commission defined, by 31 December 2019, a common optional European system to assess the readiness of buildings for intelligence. A new useful tool for understanding the ability of buildings to use new technologies and systems to adapt to the consumer's comfort needs, optimize their operation and consumption and interact with the network from a smart grid perspective.
- Support is provided for the development of charging infrastructures for electric vehicles in an effort to push sustainable mobility. In particular, forms of incentives are envisaged for the construction of infrastructures for recharging electric cars both in new buildings and in those subject to major renovations.

Obligations

Decreto legislativo 28/2011 (Integration from renewable energy sources)

The legislation establishes the minimum percentages of integration from renewable energy sources for both "thermal" and "electrical" needs.
In the case of new buildings or buildings undergoing major renovations, the decree establishes that the thermal energy production plants must be designed and built in such a way as to ensure simultaneous compliance with the roof, through the use of energy produced by plants powered by renewable sources 50% of the thermal energy requirement for the production of domestic hot water. For heating and cooling, the coverage with renewable sources of an amount of energy is calculated on the overall needs

of the property, with a percentage of at least 50% when the application for the building permit is issued from 1 January 2017.
Concerning electricity, the power of plants powered by renewable sources that must be installed on top of or inside the building or in its appurtenances, measured in kW, is calculated according to a formula: $P = S / K$,
where: $K = 50$, when the application for the building permit is issued from 1 January 2017.

Standard UNI EN 15232 and Decreto ministeriale del 26/05/2015

The standard, introduced in 2012, emphasizes that the introduction of control and automation systems leads to a reduction in energy consumption in all the parts of the building with a particular focus on Heating, Cooling, Ventilation, and Lighting.
It represents one of the standards to apply the EPBD directive about building energy efficiency and consumption reduction. It has been slightly modified in 2017.
The BACS (Building Automation and Control Systems) and HBES (Home and Building Electronic Systems) automation systems have the function of maximizing the energy efficiency of the building systems in relation to the external/internal environmental conditions and to the different and variable scenarios of use and occupation of the individual rooms in the building itself while providing the highest levels of comfort, safety, and quality. Thanks to its features, it can improve energy consumption, sometimes managing to correct the user's bad habits.
The most important part of the standard is the one that defines 4 Energy efficiency classes valid both for the classification of residential and non-residential building automation systems:

- Class D "NON ENERGY EFFICIENT": includes traditional technical systems without automation, which are not efficient from an energy point of view.
- Class C "STANDARD": corresponds to automated systems with traditional control devices or with BUS systems (BACS / HBES). It is considered the reference class because it corresponds to the minimum requirements required by the EPBD directive.
- Class B "ADVANCED": includes systems controlled with a bus automation system (BACS / HBES) but also equipped with centralized and coordinated management of functions and individual systems (TBM, Technical Building System: this is a BAC system evolved, including data collection, reporting, consumption accounting, operational and management activities including infrastructures, in support of building management activities).
- Class A "HIGH ENERGY PERFORMANCE": in this case there is a management system similar to class B that allows high levels of energy performance of the system thanks to high levels of precision and completeness of the automatic control.

In particular, the savings allowed by a management system concern all the main sources of consumption of a building, namely heating, cooling, ventilation, solar shading and building lighting.
In commercial buildings or offices, they can achieve savings of between 40% and 50%, therefore extremely high. Not surprisingly, the Ministerial Decree "Requisiti Minimi" of 26/05/2015 prescribed, for buildings for non-residential use and in the case of new constructions or major renovations, a minimum level of automation corresponding to class B of UNI 15232, testifying to the importance assumed by automation and control systems.
In 2017, the standard was updated with the addition of a structured list of control functions and additional methodologies for defining the minimum requirements or other specifications regarding control and automation functions.

Decreto Legislativo n 257/2016 (Charging Infrastructures)

The decree deal with the predisposition for the possible installation of infrastructures that allow the charging of a car an open or covered parking space and from each garage for a number of parking spaces and garages equal to at least 20% of the total.
The decree applies to newly built buildings or buildings undergoing a renovation with at least 10 residential units. What should be said is that the installation of charging infrastructures in existing condominiums is not regulated.

Decreto sblocca Italia DL 133/2014 - DL 33/2016 (Broadband Infrastructure)

The management of the broadband infrastructure, useful for enabling high-performance connected services, is managed by these two different decrees. In general, they require passive multiservice physical infrastructure inside the building, consisting of adequate installation spaces and high-speed fiber optic communication systems up to the network termination points.
By multiservice physical infrastructure it is meant all the installations inside the buildings containing wired access networks in optical fiber with fixed or wireless termination that allow access to ultra-broadband services and to connect the access point of the building with network termination point.
The decree is applied at all new buildings and constructions subject to significant building renovations, which lead to a building organization, in whole or in part, different from the previous one.

Post-Pandemic Incentives:

After the first waves of the Pandemic and the great difficulties introduced in the economy worldwide, all the national governments and international institutions have defined recovery plans that were unimaginable months before. Even if the COVID-19 has been one of the greatest catastrophes the world has ever faced, now it could become a unique opportunity to revise and change things and our behavior in more sustainable ways. The great investments decided by the European Union are part of these visionary interventions and in Italy has been created the PNRR (Piano Nazionale Ripresa e Resilienza).

The PNRR has defined the guidelines on which the economy will develop after the crisis caused by the pandemic. An overall investment of nearly 200 billion euros is the greatest opportunity that could be hoped for to realign the country to the more developed economies.
Not everyone will jump on the tram of economic growth and benefit from it; precisely the structure of the PNRR indicates the leading sectors, with digitalization and ecological transition assuming the most relevant position, together with those on education and research.
If we talk about digitalization and the green revolution we are talking about the conversion of the old economy into a new economy with a high rate of sustainability, and all this requires skills and new professionalism, even in traditional fields like that of construction.

We are referring mainly to energy consumption reduction when talking of buildings, but also to the introduction of new technologies to manage all the processes that a building normally handles.
The focus of our dissertation is on Smart Building and Energy efficiency and so we dig deeper into the adoption of governmental incentives like the recent “SuperBonus 110”.

SuperBonus

The 110% Superbonus is provided for by the “Decreto Rilancio” allows for the tax deduction, over a period of five years, of a series of redevelopment interventions on the building stock.
The “Decreto Rilancio” is mainly aimed at the residential sector and concerns interventions for the improvement of thermal insulation, the replacement of heating systems and the reduction of the seismic

risk, possibly combined with the installation of photovoltaic systems, storage systems or electric charging columns.

An increase to 110% of the deduction rate for expenses incurred in the period between 1 July 2020 and 30 June 2022 is established, to be divided into five annual installments of the same amount, for interventions aimed at:

- Increase the energy efficiency of buildings
- Promote the installation of photovoltaic systems connected to the electricity grid
- Promote the installation of charging stations for electric vehicles
- Reduce the seismic risk

Article 119 of the "Decreto Rilancio" contains indications relating to the type of efficient interventions energy and the minimum requirements to be met to access the deduction at a higher rate.
The interventions considered are of two types: the driving interventions and the driven interventions.
The 110% subsidized rate also applies to the interventions contained in Legislative Decree no. 63 of 2013 if carried out in conjunction with the driving interventions, described in the next paragraphs, and the demolition and reconstruction of buildings, as long as they maintain the pre-existing volume.
For access to the deduction, the interventions must ensure the improvement of at least two energy classes or the achievement of class A +, to be demonstrated through the energy performance certificate.

Driving interventions
The so-called "driving" interventions included in the decree concern:

- Thermal insulation interventions on the envelopes (thermal insulation of opaque surfaces affecting the building envelope (the so-called thermal coat), including the insulation of the roof.
- Replacement of the winter air conditioning systems on the common parts
- Replacement of winter air conditioning systems on single-family buildings or on real estate units of multi-family buildings that are functionally independent.
- Anti-seismic interventions

Driven interventions
In the case of carrying out one of the aforementioned energy redevelopment interventions, the expenses for interventions carried out together with at least one of the main thermal insulation interventions, replacement of winter air conditioning systems, or reduction of seismic risk are also included in the Superbonus. Taxpayers can also realize the following, deducting expenses to 110%, but on condition that their realization (and expense) takes place within the time horizon provided for the SuperBonus and within the work start and end dates.
Driven interventions are identified as:

- Energy efficiency interventions
- Installation of photovoltaic solar systems
- Infrastructure for charging electric vehicles

Home automation and smart home
In the case of building automation systems, installed in the house jointly or independently of the replacement interventions of winter air conditioning systems, the certification or suitable documentation specifies that the technology should refer at least to class B of the standard EN 15232 and allows customized automatic management of heating systems or production of domestic hot water or summer air conditioning in a manner suitable for:

- Show energy consumption through multimedia channels through the periodic supply of data (i.e. through smartphone apps)
- Show the current operating conditions and the regulation temperature of the systems (the system is on, off, is producing heating);
- Allow remote switching on, switching off and weekly programming of the systems.

If home automation and smart home interventions are carried out alone, they benefit from the 65% deduction; if they are combined with "driving" interventions, they enjoy the total deduction (from 100 to 110%). The owner of the apartment, or building, in fact transfers the credit acquired from the tax authorities to the company that carried out the work or to a bank that finances the entire amount. In this case, 100% is recovered, since the 10% more goes to the person who acquires the credit. However, this means carrying out important building modernization works at no cost.

4.3 Smart Building Examples

The characteristics of the market have been explained as well as its size and opportunities, we want to provide some examples of already implemented projects.
In this historical period, building innovation has reached an exponential bent. In fact, smart buildings, which use technology to optimize performance, communicate with various technology systems, and improve daily processes of building occupants, are constantly evolving.
The technologies used in smart buildings can work together to manage and control everything from a building's lighting and HVAC systems to a building's security.
With current sustainability initiatives and the refurbishment of the office sector, the market evaluation of the smart building industry is estimated to quadruple by the year 2023.
Here below there are some examples of Smart Buildings in the world.

Oakland City Center (Oakland, California)

Oakland City Center is an office, shopping and hotel complex in Downtown Oakland, covering twelve city blocks.
A building like 1111 Broadway serves prominent law firms, financial advisors, government agencies, and construction companies with particular attention to the areas of energy efficiency.
In 2019 Oakland City Center became a pilot site for Siemens Dynamic VAV Optimization (DVO). DVO is an HVAC optimization strategy that relies on a cloud-based, artificial intelligence (AI) powered algorithm to automatically control fan speed, supply temperature, and humidity levels for centralized air handling units.
Oakland City Center is well known for its advanced variable air volume (VAV) system. It collects temperature and humidity data and learns how the system responds to changes in demand.
The operating data are evaluated by an AI-powered algorithm that sends setpoints to the building's HVAC system to cost-effectively and sustainably ensure better occupant comfort.

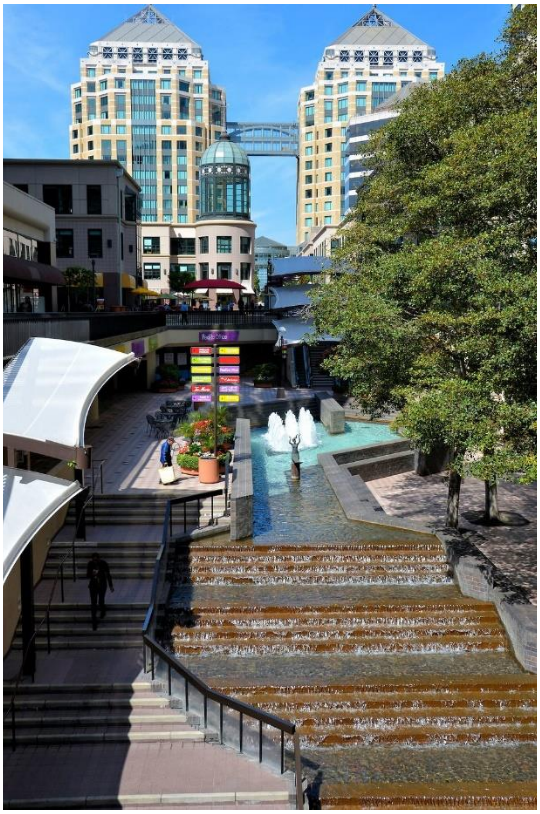


Figure 4.1: Oakland City Center

Another relevant advantage of this dynamic VAV system is its ability to control air quality efficiently at different settings, which was particularly valuable during the pandemic year.
A general "green mode" setting optimizes temperature, pressure, and humidity in a normal environment, and when a virus has been introduced, its "decontamination mode" helps minimize virus transmission by increasing the temperature during the unoccupied building, and accelerating decay of the virus.
This was one of the features that made it possible to safely reopen the building, for any work that requires a physical presence on site.

Frasers Tower (Singapore)

Frasers Tower is an exclusive 38-storey Premium Grade A office development situated within Singapore's core Central Business District Completed in mid-2018. Frasers Tower has a total net lettable area (NLA) of around 685,000 sq ft and was 93% leased as of March 31, 2019.

Designed to meet the demands of the workforce of tomorrow, Frasers Tower features future-focused workspaces built to foster team collaboration, nurture employee well-being, and support technology integration.

Frasers Tower offers a sustainable work-life environment equipped with energy-efficient and smart building features. Besides Low-emissivity double-glazed glass, it was invested in the latest destination control system for the lifts as well as in the rainwater harvesting used in irrigation of plants and NEWater to serve the cooling towers.

The building has a BCA Green Mark Platinum rating, which is the highest accolade in sustainability. Singapore awards The BCA Green Mark Platinum to exemplary green projects that effectively demonstrate 30% energy and water savings, as well as environmentally sustainable building practices and innovative green features.

Figure 4.2: Frasers Tower Singapore

At Frasers Tower in Singapore, Microsoft worked closely with Bentley Systems and Schneider Electric to implement sensors and telemetry to create a connected workplace allowing to adjust the space based on usage, therefore improving energy efficiency.

At the Microsoft offices in Frasers Tower, data is collected in real-time using a mix of 179 Bluetooth beacons in meeting rooms and 900 sensors for lighting, air quality and temperature by Schneider Electric. The platform generates nearly 2,100 data points, that are connected to the cloud on Microsoft Azure, enabling the holistic management of the environment. The sensors enable monitoring of facilities usage, energy and utilities. They optimize space utilization, air conditioning and lighting adjustments. All these provide a comfortable and productive space for employees while increasing overall energy efficiency.

Employees and staff use Smart Building CampusLink, an application that is fully integrated with Microsoft Outlook and Microsoft Office 365, taking navigation to the next level by enabling employees to find directions, determine room occupancy and book facilities in real-time.

The sensors could potentially also monitor carbon dioxide levels in the air that negatively affect work performance and neural activity, noise levels and energy usage, which can result in savings of up to 25%, as experienced at Microsoft's Headquarters located in Redmond, Washington.

The partnership of Bentley Systems with Microsoft offers a real model on how connected devices combined with contextualized sensor processing can deliver smart building systems that do not intrude on the privacy of individuals and can be applied beyond offices, to buildings, shopping malls and even homes of the future.

Fulton East Chicago Center (Chicago, Illinois)

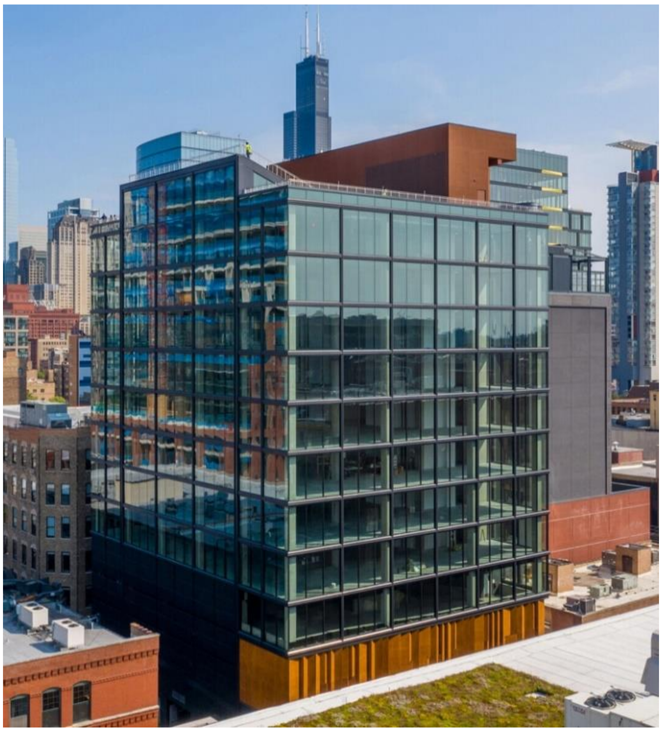


Figure 4.3: Fulton East Chicago Center

Fulton East offers 85,000 square feet of floor-to-ceiling glass skyspace providing spectacular views throughout the city while allowing optimal daylighting to the building's interior spaces, both optimal conditions for stimulating a creative environment.

Fulton East is the first office building designed and constructed for employee health, safety and wellness in the post-COVID-19 business environment. Besides prioritizing energy efficiency, Fulton East features a number of state-of-the-art health innovations.

The building includes the world's first new-construction installation of Canada-based MAD Elevator Inc.'s Toe-To-Go (T2G) contactless elevator system. In addition, Fulton East is the first multi-story office building to employ airPHX ("air fix") non-thermal, plasma technology throughout the entire building to help reduce cross-contamination risks by eliminating bacteria, viruses and other harmful organisms found on surfaces and in the air providing employees with cleaner air and work surfaces.

Fulton East received LEED certification for the project's reduced urban heat island effect by installing reflective roofing vegetated space on the amenity deck, and locating all building parking undercover. The project also achieved 79% baseline reduction in outdoor water use via effective irrigation methods, and 31% baseline reduction in indoor water use via low flush/flow fixtures, and achieved maximum points in the Low Emitting Materials credit occupant health was a priority in the material selection.

Vodafone Group Global Headquarters (London, England)

Figure 4.4: Vodafone Group Global Headquarters

In 2020, Vodafone Group Global Headquarters, specialized in software and telecommunications equipment for stores and Mobile phone stores, won the Smart Building Innovation Award. This is an impressive international award, assigned by the independent research firm Verdantix that recognizes organizations that have implemented innovative technologies to improve their facilities.

Vodafone Group won the Corporate Headquarters Retrofit category for its innovative collaboration with General Electric. Together they developed and deployed an IoT platform that delivered a single integrated view into air quality, energy usage, people movement, noise levels, room bookings and space utilization. This allows employees working in an office with different kinds of workspaces like collaboration, interviews, quiet work, to find the appropriate workspace on the basis of real-time data availability. The integrated view of the environment and operations as well as the smart use of the data concurred to have a building more energy-efficient.

Corning Optical Communications Headquarters (Charlotte, North Carolina)

Figure 4.5: Corning Optical Communications HQ

Corning Optical Communications Headquarters is a smart building example for its smart enterprise network solution. It was built in 2019 with a fiber and power-to perimeter network which laid the foundation for a smart building prepared for the future. From a single room on the first floor, more than 460 fiber runs leave the Main Distribution Frame and span the six floors.

This is the Fiber Deep concept: taking fiber and DC power deep into the building, feeding electronics that power edge devices like cameras, printers, Wi-Fi access points, and more.

This building served as a pilot for SPIRE smart building program that is

based on six main criteria: power and energy, health and wellbeing, life and property safety, connectivity, cybersecurity and sustainability.
The connectivity is performed through high-end fiber-optic networks, digital health tools like sensors that monitor overcrowded spaces and air quality issues, data collection and processing technology to manage energy consumption properly, and upgraded cybersecurity systems. In addition to that, the building meets LEED, Fitwel, and WELL Building Standards.

U.S. Green Building Council Headquarters (Washington, D.C.)

The U.S. Green Building Council (USGBC), is a private non-profit organization founded in 1993 with the aim to create a new concept of building design and construction as well as a new way of communities operation based on LEED (Leadership in Energy and Environmental Design).
The certification gives the conceptual structure for creating highly efficient, healthy and wellness, and cost-saving green buildings and is the most widely used certification in the world for the green building rating.
USGBC as the creator of the LEED rating system for sustainable buildings developed the project of a new national headquarters: the 2101 L Street NW office space.
It was intended to improve 30% air quality, save 40% water, and reduce more than half the energy in comparison with a traditional equivalent office space.
Sensors and automatic controls are the main features of the project and allow optimizing the performance of the building. The outdated lighting control systems were improved by adopting Legrand's digital lighting management solution working in parallel with auto-controlled window systems detecting the sun intensity and adjusting blinds accordingly. Additionally, circadian programming and smart time scheduling were implemented using occupancy sensors that turn off the electronic devices out of the business hours and adjust the temperature depending on the occupation of the offices and workstations. These acts reduced lighting electricity costs and increased employees' satisfaction ratings concerning comfort.

Figure 4.6: U.S. Green Building Council HQ

The Sinclair Hotel (Fort Worth, Texas)

After a major refurbishment, this 1920s-era structure was transformed from an office building to a Marriott Autograph Collection luxury hotel. The new Sinclair represents the landmark building downtown for its technology innovation and authenticity.

It has been retrofitted with Power-Over-Ethernet connectivity solutions, the first LG Li-Ion Energy Storage System in the U.S., and VoltServer's patented Digital Electricity.

In addition to being energy-efficient, it has been described as the world's first digital hotel that offers a personalized experience for everything from water temperature to lighting preferences.

Starting from the sensors in the rooms that are customized for occupants' movements to the deployment of Digital Electricity as well as the use of energy-conserving diesel replacement technology, the Sinclair is a fully innovative hotel in Fort Worth (Texas) and in the world.

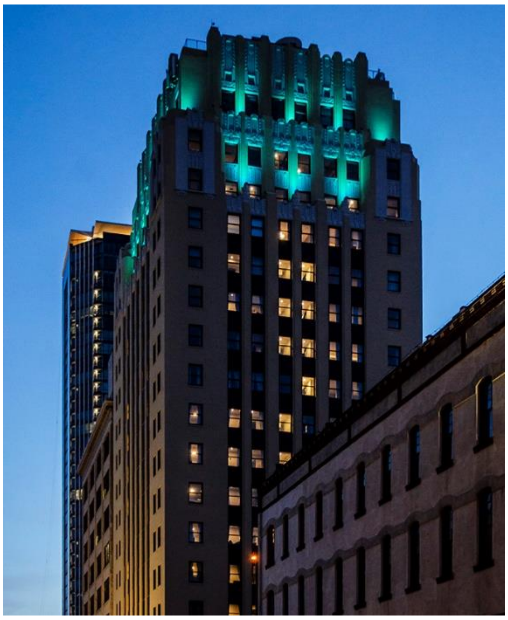


Figure 4.7: The Sinclair Hotel

Bosch Campus (Singapore)

Bosch Singapore campus is a typical example of a smart building concept that becomes reality. Bosch firmly sustains the use of its own technologies in collaboration with other companies' expertise.

Bosch provides smart building solutions with open Application Programming Interface (API) by enabling exchanging data and functionality with third-parties solutions, Building Information Models (BIM) and Building Management Systems (BMS).

This concept was applied to the Bosch Singapore campus where IoT sensors and cameras were installed in a decade-old building and integrated with the Bosch Connected Building software.

Figure 4.8: Bosch Campus

The SenseAgent installed is a multifunctional IoT sensor designed specifically for smart buildings that avoid the need to install multiple ones. It can control lights directly while tracking the main building parameters related to ambient noise level, position via Bluetooth beacons,

occupancy via Passive Infrared, air pressure, vibration and air quality (temperature, humidity, CO_2 and total volatile compounds concentrations).
The integrated Bosch Connected Building software creates a common data lake, where data is analyzed and shown graphically giving an immediate picture of the functionality of the entire building.

Bloomberg European HQ (London, UK)

Bloomberg Unveils New European Headquarters in the City of London is the most sustainable office building that has been developed in the world.
The building achieved a BREEAM Outstanding rating with a 98.5% score, the highest design-stage BREEAM score ever achieved by any major office development.
The environmental strategies of the new building allow saving about 73% in water and 35% in energy consumption in comparison to a traditional office building.
A water conservation innovative system that uses rainwater from the roof, cooling tower blow-off water and greywater sources allows saving 25 million liters of water each year.
Innovative power, LED lights and natural ventilation systems are the main features for energy savings. The system utilizes 40% less energy than a normal fluorescent office lighting system and includes 500,000 LED lights. The airflow adjustment in accordance to the number of people in each zone of the building is made possible using smart CO_2 sensor controls.

Figure 4.9: Bloomberg European HQ

Locally produced combined heat and power (CHP) centers reduce carbon emissions by combining heat and electricity into a single, efficient system. This technique generates waste heat, which is recycled for cooling and heating and is estimated to save 500-750 metric tonnes of CO_2 per year while in operation.

Ankara City Hospital Campus (Ankara, Turkey)

The Ankara City Hospital is a completely digital hospital developed with the Smart Infrastructure of Siemens. It is based in the Bilkent district and with nearly 4000 beds and more than 130 operating units is one of the largest hospital campus in the world as well as one of the most modern.

It is equipped with an intelligent interconnected ecosystem focused on safety and comfort of patients and staff. The 22 hospital subsystems are controlled and monitored through the integrated building management platform Desigo CC.
The control and monitoring of around 800,000 data points, coming from energy supplies, fire protection, HVAC lighting access control, enable the critical infrastructure to run smoothly during the whole day.
The operational efficiency is improved through the latest Energy Automation technology provided by Siemens that guarantees the energy blackout prevention, serves as load shedding and feeding controller, and allows several options, for instance the connection of peripheral devices.

Faria Lima B32 Office Tower (São Paulo, Brasil)

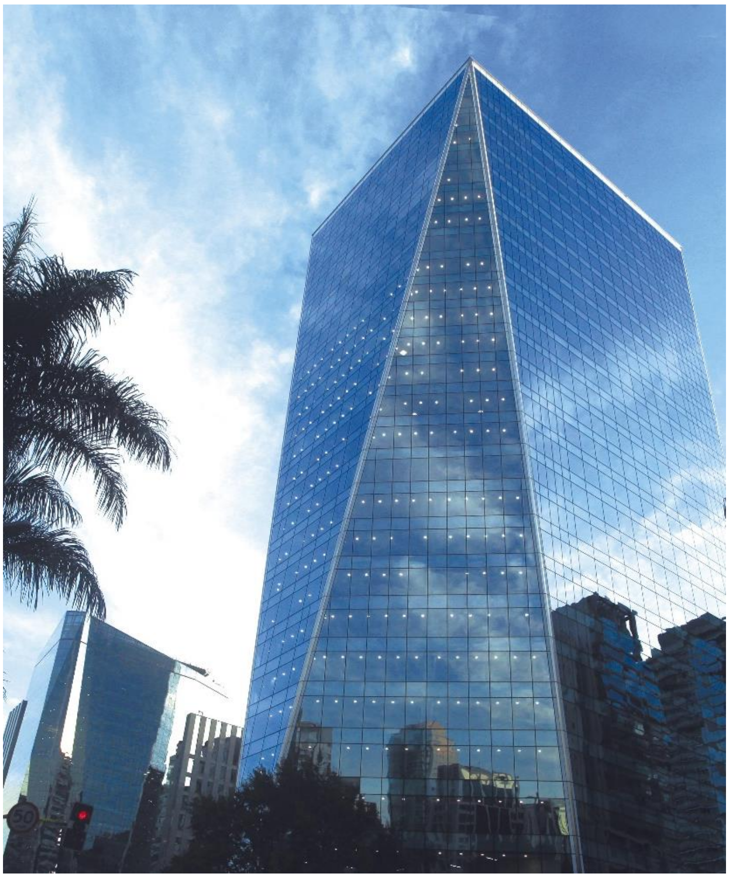


Figure 4.10: Faria Lima B32

In São Paulo, the Faria Lima Birmann 32 Tower was started to be constructed in 2013 and was completed in 2020.
Designed by Pei Partnership Architects it was intended to become the reference point of the city with Brazil’s fastest elevators at 7 meters per second.
To ensure the seamless connection of its 27 floors this office building is integrated with AGILE Destination Controls in the turnstiles with card and touch screen terminals. The AGILE Management Center is installed to schedule the use of elevators and the MAX innovative maintenance solution is also used.
After an initial delay, several Latin America cities are now adopting smart technologies embedded in the Internet of Things and big data to face critical points like mobility. The ultra-modern elevators, as applied in the Faria Lima Birmann 32 Tower, allow to obtain the highest levels of energy efficiency and services together with smart solutions.

Sharing Cities Milano (Milano, Italy)

Sharing Cities is a project funded under the H2020 Smart Cities and Communities call which involves more than 30 partners from 6 European countries (United Kingdom, Portugal, Italy, France, Bulgaria and Poland) with the aim to create smart districts in 3 "lighthouse cities" (London, Lisbon, Milan) and three "follower cities" (Bordeaux, Burgas, Warsaw) that will replicate the models proposed by the cities leading the consortium.
A total contribution of 25 million euros was assigned to the project with approximately 8.6 million allocated to the local partnership of the city of Milan.

Sharing Cities aims to adopt an innovative approach to respond to some of the main environmental challenges facing our cities, such as reducing the carbon emissions of buildings and means of transport and improving air quality. Initiatives for smart cities and communities that integrate the energy, transport and ICT sectors were the lead features of the project.
Innovative and smart solutions about electric mobility, building refurbishment, public lighting, ICT, citizen engagement were designed, implemented and tested in each city, ensuring effective results and great reproducibility. Concerning the mobility measures, services and infrastructures relating to electric car-sharing, electric bike-sharing, smart parking, e-logistics (with e-vans and e-bikes) were the main characteristics of the project.
The Italian team, made up of public and private partners, worked in the model district of Porta Romana Chiaravalle in the field of mobility and sustainable living, public lighting and environmental quality, data sharing through interoperability to achieve the creation of an almost zero energy-smart district.
Virtuous behavior was also encouraged thanks to the SharingMI app, which allowed users to earn rewards thanks to sustainable actions.
The project started on January 1, 2016, and ended on December 31, 2020, taking 3 years for the implementation of the interventions and 2 years for the monitoring of the deployed actions.

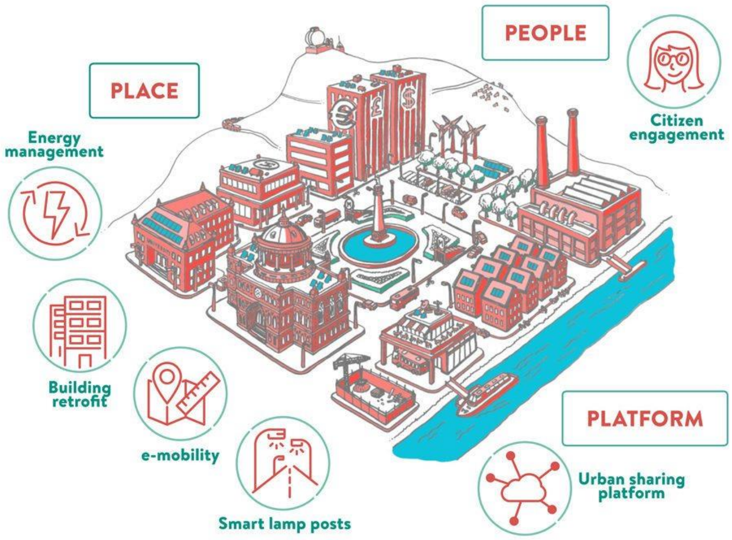


Figure 4.11: Sharing Cities concept

The obtained results of the Sharing City Milano are as follows:

- active participation of citizens and planning for the co-creation of sharing services to integrate the urban platform layer;
- development of a neighborhood reward system to encourage change in behavior;
- energy requalification of 4,633 square meters (2 multi-storey public buildings) and 20,000 square meters (buildings with mixed ownership);
- creation of a micro-grid (information and intelligent electricity distribution network) capable of using the demand for energy supply in real-time;
- provision of 62 electric vehicles, 150 electric bikes / 7 stations, 76 points of
  recharge: 60 for car-sharing (20 fast), 10 for bike-sharing, 1 for eLogistics vehicles, 5 will be available near the Symbiosis area, 125 parking bays, 11 shared electric vehicles for the distribution of goods: 9 vans and 2 electric bikes;
- construction of 300 wi-fi lampposts equipped with various types of sensors;
- development of a shared urban platform that uses a common standard to be replicated in different cities

4.4 Startup Analysis

If in the previous paragraph we were talking about already existing projects to define the current state of the art in technologies and buildings, this chapter aims at analyzing the overall status of startups exploring the technological edge of the smart building sector.
Having a panoramic look over the startup ecosystem of a selected sector is useful to understand where the sector is moving and where technological boundaries are being pushed.

The methodology adopted to perform this startup analysis is the following:

- A reference site, as CrunchBase, has been chosen for its popularity and completeness.
- The selected sector of “Smart Building” has been chosen as the main and only keyword.
- The year range have been selected according to Literature Review one (Jan 2015 - October 2021).
- Geographical coverage was not selected, aiming at having the widest possible one.
- All the CrunchBase presented startups have been selected and summarized on a database, resulting in 307 startups.
- On the columns, different parameters have been selected to perform the relevant analysis:
    - Company Name
    - Industry
    - HQ Location
    - Description
    - Company Type
    - Foundation Date
    - Number of Fundings Rounds
    - Top Investors
    - Most Recent Valuation range
    - Last funding date and last funding amount
    - Total funding amount
    - Number of investors

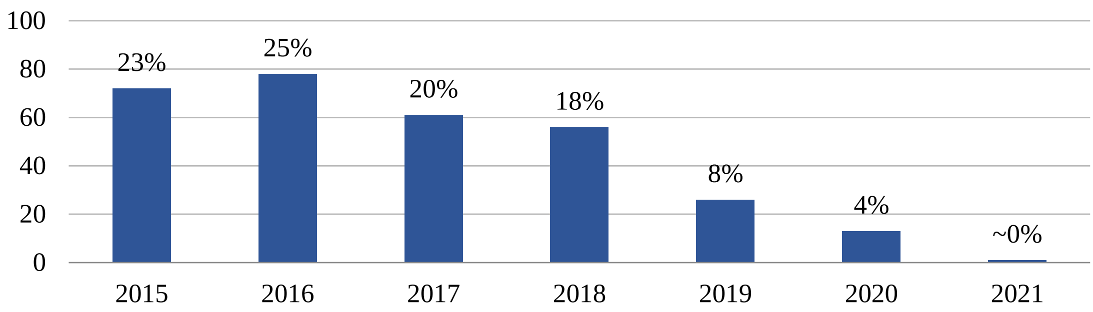
The analysis methodology is not fulfilling and covers all the startups operating in the Smart Building sector all over the World since the main source of information was CrunchBase and with it, the bias of only startups that submitted their presence to this tool can be considered. On the other hand, using this tool as the main source we are sure that we can rely on trustful and verified information from still a very wide range of countries and startups, being the recognized top information site for cross-sector startup tracking.

All the information obtained has been carefully analyzed and exposed below, also thanks to graphic tools that will give us the current evolution of Smart Building startups ecosystem, till our latest days.

4.4.1 Foundation Year

The range of official day-one foundation dates for the startups under exam goes from Jan 2015 to October 2021. The foundation date overview is useful to understand trends and patterns that can be possible observed across different years.
The graph below shows us how the bigger amount of startups was founded in 2015 and 2016 (72 and 78 respectively), with a decreasing trend till 2021.

However, an interpretation specification must be done: part of the startups founded in recent years (2018,2019,2020,2021) could still be too small to be under the radar of Crunchbase. This could create a distortion in the graph where the numbers of startups from 2018, 2019, 2020 and 2021 could be much higher in number in respect to the numbers reported in the graph.

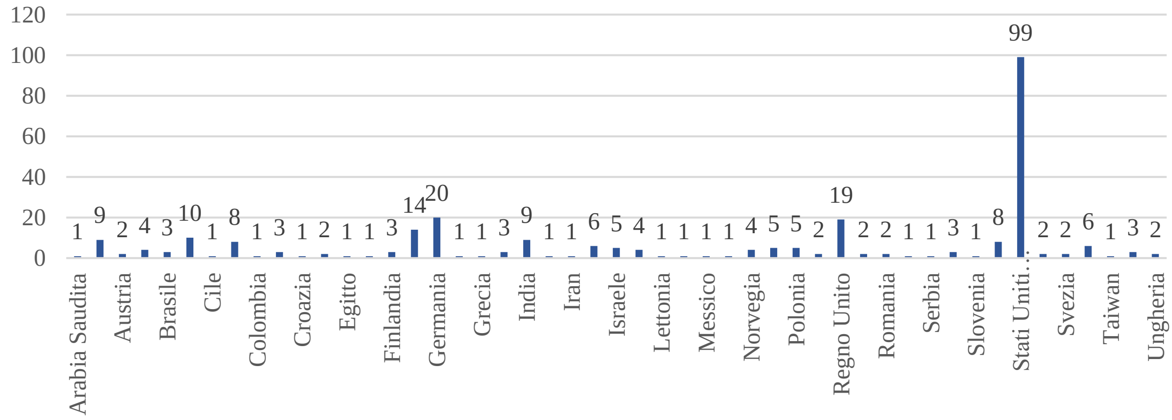


Graph 4.1: Startups distribution by foundation year

4.4.2 Geographic Area

Another crucial aspect to consider in order to have a thorough picture of a market sector is the geographic dispersion of the players involved.
Looking and the following graph, the dominance of Europe and North America is clear within the Smart Building sector, even if Asia is gaining traction.
It's useful to precise that those numbers are in strong concordance with what is stated in chapter 3 about the Literature Review and the papers' country of origin.

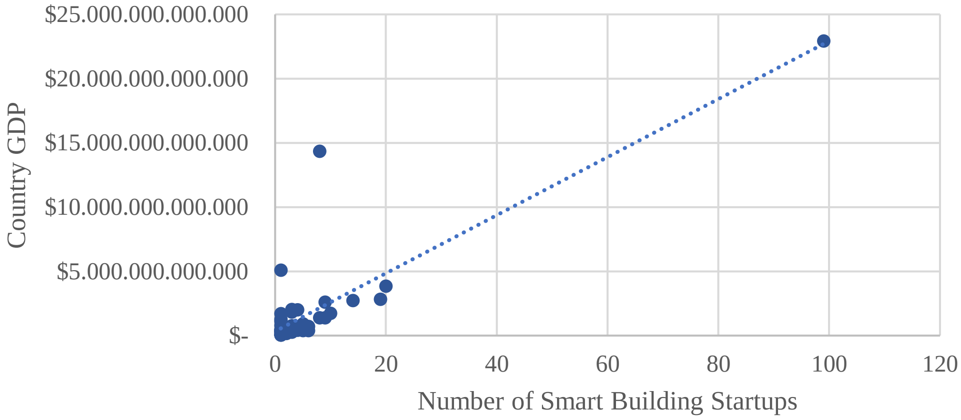
Deepening the research area inside the single country, we can see how the United States takes the lead, followed by Germany, UK and France.



Graph 4.2: Startups distribution by country

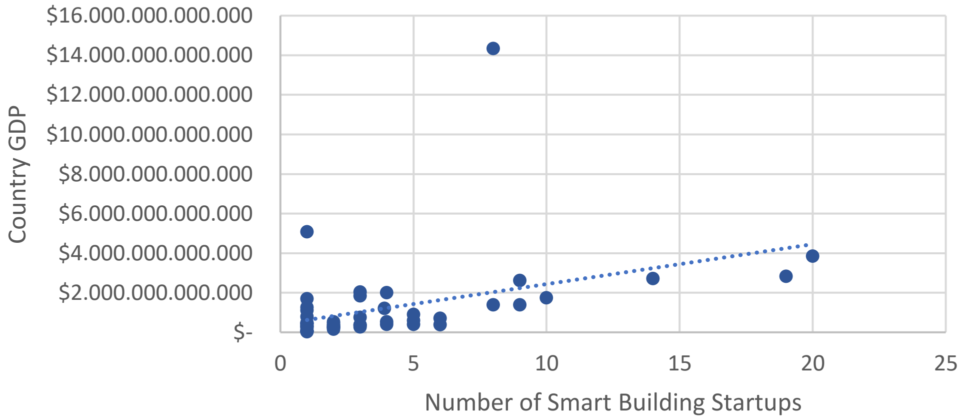
Other pieces of relevant economic information related to the geographical area are considerations of startup number per country connected with gross domestic product.
Considering the relation between Smart Building startups and GDP, the following results have been achieved after correlating the number of startups and the respective country's gross domestic product.

The two factors seem to be positively correlated, showing a positive trend. Higher the GDP, higher the number of startups and vice versa.
This relationship is tight. Startups represent the new class of companies that will provide the main contribution from the economic point of view for a country. The smaller sub-category of Smart Building new companies seems to represent this phenomenon in a relevant way.
A dispersion graph of the normalized number of SB Startups against normalized GDP is presented below.
The first one represents the overall picture with a resultant correlation factor (ρ1) of 0.85.
As a reminder, the correlation coefficient is a statistical measure of the strength of the relationship between the relative movements of two variables. The values range between -1.0 and 1.0. A correlation of -1.0 shows a perfect negative correlation, while a correlation of 1.0 shows a perfect positive correlation. A correlation of 0.0 shows no linear relationship between the movement of the two variables.



Graph 4.3: Startups per country VS Country GDP

The second one instead represents the same data as before but depurated by the United States, representing a significant outlier. The resultant new correlation factor (ρ2) is 0.40.



Graph 4.4: Startup Number per Country VS Country GDP (no US)

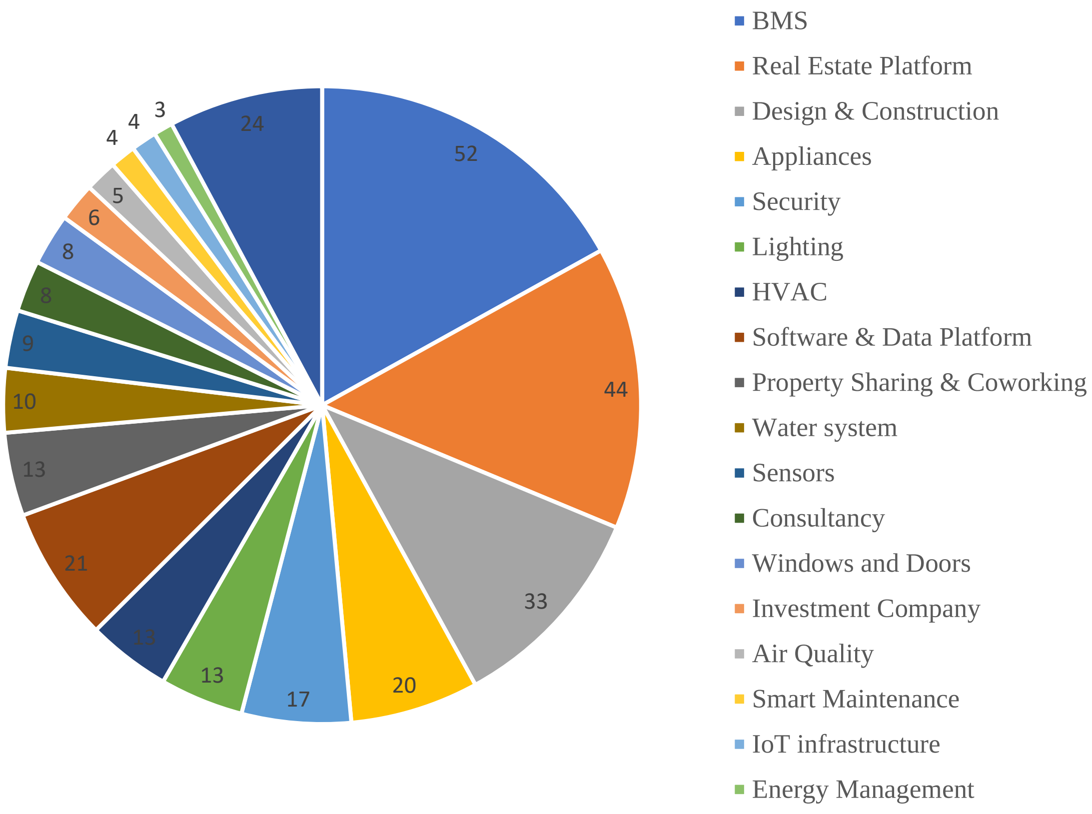
4.4.3 Startups Field

Analysing all the different startups within the Smart Building ecosystem is also fundamental to understanding which of the specific topic is tackled by each startup.
To perform this deep dive all the startups were categorized according to:

- **BMS:** Software/technology to implement/control/optimize the Energy Management System
- **Real Estate Platform:** Platform to manage trading operations, for businesses or private users, regarding buildings (e.g. Building Services buying/selling app)
- **Design & Construction:** From design to construction services.
- **Appliances:** Smart general products for buildings.
- **Security:** Security product and services (e.g. Smart surveillance cameras)
- **Lighting:** Lighting products/optimization services.
- **HVAC:** Heating, Ventilation and Air Conditioning products/optimization services.
- **Software & Data Platform:** Platforms to trade/use software services related to Smart Buildings (e.g. API for smart sensors)
- **Property Sharing & Coworking:** Shared building units management.
- **Water system:** Water system products/optimization services.
- **Sensors:** Sensor producing and/or deploying.
- **Consultancy:** Specialized and customized building services.
- **Windows and Doors:** Smart Windows and Doors production and/or deployment.
- **Investment Company:** Accelerator, Incubator, VC, Private Equity and other investment entities.
- **Air Quality:** Air Quality products/optimization services.
- **Smart Maintenance:** Smart Maintenance thanks to IoT sensors.
- **IoT infrastructure:** Deployment and management of IoT sensors and connectivity.
- **Energy Management:** Energy Management aside from BMS (e.g. Smart Grid management)
- **Others:** Category collecting various other startup typologies with more specific scope (i.e. recycling system, mobile toilets, smart acoustic solution, smart gardening, parking marketplace, smart concierge, smart locker, smart road, smart hotel, location detection, power transmission)

This categorization made it possible to discover that the field covered by several startups is the development of BMS solutions. The result is consistent with the fact that energy optimization and remote control of building technologies is the beating heart of any Smart Building solution. HVAC and Lighting Smart solutions were also investigated by several startups together with the companies taking care of effective building construction (Design & Construction). It was interesting to notice how the development of Smart Building improved also the diffusion of Real Estate Platforms, where users can manage properties, and related services, as items on a marketplace.

Below is the sample of 307 startups divided by application field:



Graph 4.5: Startups distribution by field of focus

Energy optimization of building systems remains the most tackled topic with almost 40% of startups in the field over the total.

4.4.4 Finance

Multiple financial factors are available to evaluate the SB Startup ecosystem. The main relevant ones are presented in the following paragraphs, useful to have a deep dive inside the ecosystem mechanisms.

Evaluation

In order to start having dimensional ideas about the market, powerful insight is the startup evaluation. Only one company is valued at over $1B (Verkada), reaching the ambitious status of "unicorn".
The jump is then large to the second band where only three companies are evaluated between $10M and $50M (Plant Prefab, Deako, Site 1001).
The evaluations for those cited companies are all "post-money" ones, meaning that the valuation method bases its roots on the investments done during investing rounds and the relative shares sold.
The majority of players stand inside the range valuation below $10M, with the remaining 303 companies in the dataset occupying this set.

Top Investors

Investors putting their money in startups are from a wide range, going from Venture Capital Firms to Banks and Institutional funds, from Private Equity Funds to Incubators and Accelerators, and more.
For Smart Building a total of 54 different investors have been found, with 18 investing in two companies, one investing in 4 companies, 3 investing in three companies and a top investor in terms of the number of startups invested in has been identified with a total of 9: Techstars.
Techstars is an American seed accelerator founded in 2006 in Boulder, Colorado. As of 2019, the company had accepted over 1,600 companies into its programs with a combined market capitalization of $18.2bn USD.

Looking at which type of investor is the most active in the sector, we can see below how Venture Capital Firms are on the edge with 9 companies in the list of overall 21 investors falling under this typology.
Bank and Governments Agencies with Incubator and Accelerator come after with 5 each and in the end, there are 2 Private Equity firms making their bets on the Smart Building sector.
From the type of investor, we can have a small hint of trends regarding the financing preferences on the market.
The most active types of investors are those in the extreme ends of the life cycle of a startup: Pre-Seed/Seed (i.e. Venture Capital, 9 investors, and Incubator and Accelerator, 5 investors) and Latest Rounds (Institutional Funds and Banks, 5 investors).
Investments in the intermediate stages seem to be lacking, with the little presence of classic investors in this range, such as Private Equity companies (2 investors of this type).
A precision remark should be made regarding the number of investors which could be higher due to either Angel Investors, privately-held investments or small investments not detected by the sources.

Another interesting indicator is the number of rounds of investment a startup is usually gathering in this specific sector.
Most startups get only 1 round of investments, as expected, but a consistent amount of companies are getting from 2 to 5 rounds. The outliers are the ones with more than 6 rounds, with a top of 9 for Carbon Analytics.

Total Investments

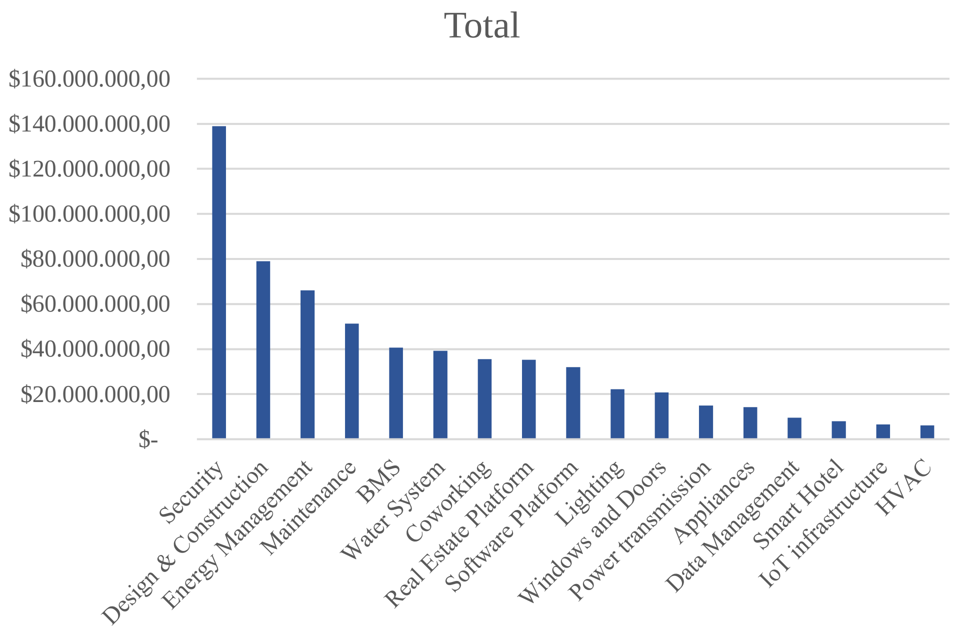
Last, but not for less important, is the analysis of the total investments received by each startup based on the geographical region.
The disclosure of investment data is available only for a part of the total data set. This will be the base for this part of the analysis.
All the investments amount in different currencies from $USD (GBP, EUR, AUD, PLN, SEK, NOK, CNY, RUB) are converted at the average change value to $USD within the current year. This clarification is needed because the total amount of investment usually comes from the sum of single investments in different years, a type of detail not available from the current data set. However, the change value from those currencies does not change drastically from 2015 till now, meaning still reliable results.
Total fundings received from Smart Building Startups born from 2015 ahead is $725 824 077,7 (results coming from 106 startups having total investments >0).
The startup with the higher value in investments is Verkada (US) with $138.900.000,00 (last round 2020), followed by Voltus (US) with $66.100.000,00 (last round 2021) and at the 3rd place WeMaintain (France) with $46.269.000,00.

The table below reports the status of the top 25 Startups per investment amount.

Name	Startup Field	HQ	last funding year	total funding amount ($)
Verkada	Security	US	2020	138,900,000
Voltus	Energy Management	US	2021	66,100,000
WeMaintain	Maintenance	France	2021	46,269,000
Flo Technologies	Water System	US	2019	39,250,000
Plant Prefab	Design & Construction	US	2021	38,642,297
Habyt	Coworking	Germany	2021	35,536,500
Manufaqtury	Software Platform	Russia	2021	32,006,759
Deako	Lighting	US	2021	22,220,000
Crown Electrokinetics	Windows and Doors	US	2021	20,750,000
Site 1001	BMS	US	2018	17,275,000
PowerScout	Real Estate Platform	US	2018	17,074,500
Infogrid	BMS	UK	2020	15,500,000
GuRu	Power transmission	US	2019	15,000,000
ROOM	Design & Construction	US	2020	14,500,000
Lampix	Appliances	US	2017	14,200,000
Dvele	Design & Construction	US	2019	14,000,000
HABX	Design & Construction	France	2018	11,925,000
Kasita	Real Estate Platform	US	2016	10,890,000
Mapped	Data Management	US	2021	9,499,988
JiaChang Group	Smart Hotel	China	2015	8,000,000
Enerbrain	BMS	Italy	2021	7,949,536
Convendum	Real Estate Platform	Sweden	2018	7,253,649
Zeetta Networks	IoT infrastructure	UK	2020	6,590,061
Arloid Automation	HVAC	UK	2021	6,100,000
Shepherd Network	Maintenance	US	2020	5,115,236

Table 4.1: Top 25 Smart Building Startups by funding amount

As a remark, we should notice how startups categories of Security, Design & Construction, Energy Management, Maintenance and BMS were the top funding receiving ones. These values could be representing a strong signal of investor interest in those specific sectors. Nevertheless, investments are driven mainly by single startups and not large samples, deviating also the previous takeout to another direction: investors are not investing in a specific smart building category but more on a specific team, idea and market strategy.

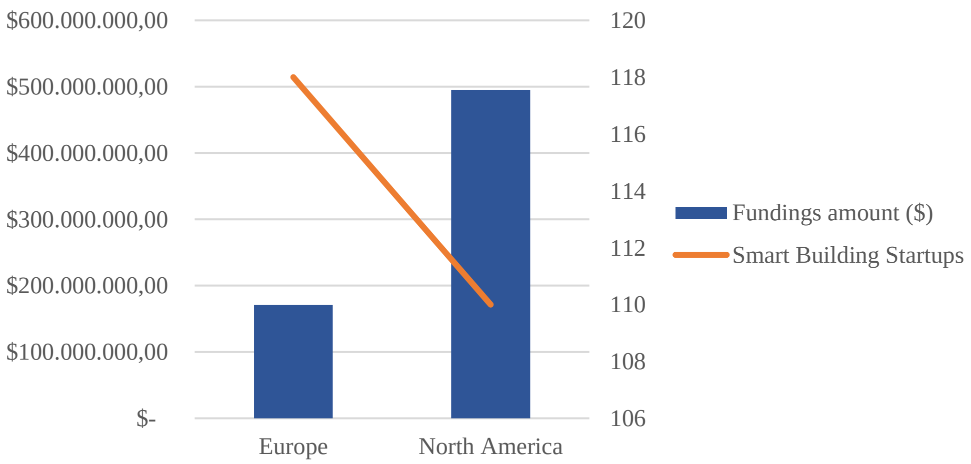


Graph 4.6: Top 25 Startups' fields by funding amount

Total investments - Europe VS North America

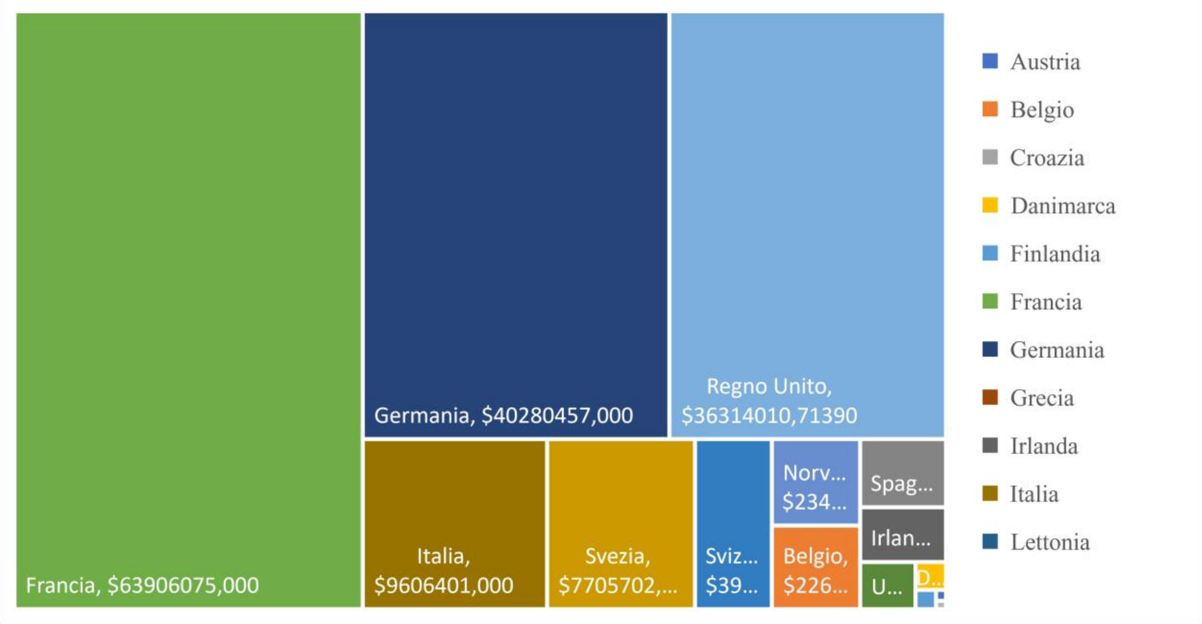
An interesting deep down could be performed a comparison on investments in Europe and North America, the two most active eco-system coming out from the previous analysis.
As a first estimate, we can see the total amount of investments received from startups in the two zones, looking at the outperformance of North America. The performances of NA should be attributed almost completely to the United States, representing 99 startups over a total of 110 for this Continent.

Comparing the Total Funding amount with the number of startups we can achieve the average amount of investment received by every single entity, looking once again at a better performance by North American companies with $1,448,136 received by European companies against $4,503,310 of NA based ones.



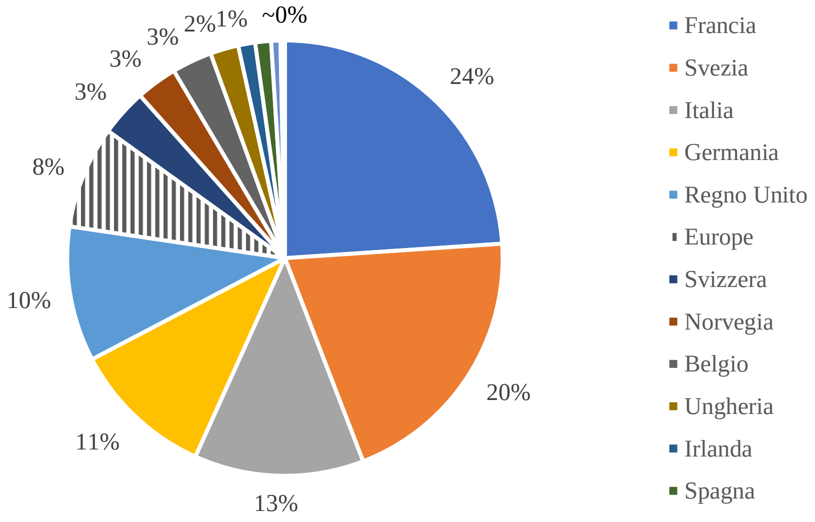
Graph 4.7: Overall fundings amount received VS Number of SB Startups

Focusing instead only on Europe, Germany, UK and France not only have the higher number of startups, but they also have the highest amount of total investment raised.
An overall comprehension graph about Europe is shown below.



Graph 4.8: Total investment amount in EU SB Startups by Country

The average amount received per startup in a single country within Europe sees almost the same result as the overall country values, but Sweden takes second place thanks to high amounts raised by Convendum ($7,253,649).
Also, Italian startups in Smart Building are a relatively low number but raising amounts over the average: EnerBrain ($7,949,536) and Jarvis ($1,656,865).



Graph 4.9: Average investment amount per SB Startup in EU

4.4.5 Most Innovative and Significant Startups

This last part focuses on in-depth descriptions and analyses of some of the most financed and innovative start-ups in the sample. It attempted to choose companies from all the most important country eco-system that emerged from previous analysis, with a focus also on the most interesting and selected Italian companies.

Verkada

HQ	San Mateo, US
Foundation Year	2016
Employees	501-1000
Total Funding Amount	$138,900,000
Last Funding Amount	$80,000,000
Last Funding Date	29 Jan 2020

Verkada Inc. is a cloud-based building security system developer situated in San Mateo, California. Security equipment including video cameras, access control systems and environmental sensors are combined with cloud-based machine vision and artificial intelligence by the firm.
Verkada creates cloud-managed business building security solutions that include security cameras, door access control systems, and environmental sensors that work in tandem.

Main Products:

- Cameras: company's cameras combine edge processing and storage with a centralized web-based platform to provide advanced physical security across numerous sites. The cloud-based system allows rapid sharing of video feeds via SMS text or weblink, such as with offsite law enforcement personnel or company management;
- Access control systems: Verkada's cloud-managed access control systems are integrated with its security cameras, which can be centrally managed remotely over the cloud, across all sites. The systems allow security personnel to remotely monitor entryways, provision badges and unlock doors without requiring IT involvement;
- Environmental sensors: Verkada develops indoor environmental sensors that measure air quality, temperature, humidity, motion and noise. The sensors are integrated with security cameras, and send alerts when a threshold reading is exceeded, allowing operators to view the area of interest;
- Alarms: Verkada’s Alarms product analyzes information from the company's cloud-based physical security products including video security, door-based access control, and environmental sensors.

Voltus

HQ	San Francisco, US
Foundation Year	2016
Employees	101-250
Total Funding Amount	$66,100,000
Last Funding Amount	$31,000,000
Last Funding Date	13 May 2021

Voltus provides cash-generating energy products to commercial, institutional, and industrial customers. Their technology enables the identification, rationalization and collection of every dollar from every type of distributed energy resource across every electricity market in the US and Canada. Thanks to their unique energy management platform they can connect those distributed energy sources, with relative estimated costs, to your plant/building. This system eliminates complexity while minimizing business owners' energy-related costs. The platform gives also you real-time value about expenditures, energy consumption and energy performances by source. Every step of the process is automated and thus largely increases the customer adoption process speed.
Main product: Distributed Energy Platform for Businesses.

Deako

HQ	Seattle, US
Foundation Year	2015
Employees	11-50
Total Funding Amount	$22,220,000
Last Funding Amount	$12,500,000
Last Funding Date	15 Mar 2021

Deako provides an easily upgradable lighting system that allows people to be able to control the switches with or without their mobile devices. The Deako Lighting system is typically installed during the construction phase of new-build homes. It consists of three elements. The first is the Deako backplate which an electrician wires into a junction box just like any other light switch. Second is the Deako Simple Rocker Switch, which can easily be switched out by anyone with any other Deako plug-n-play switch. Last, is the screwless faceplate. This lighting system makes it easy for homeowners to personalize their homes with the switches they want.
Main products:

- Simple Motion Sensor / Timer Switch;
- Simple Dimmer / Smart Dimmer;
- Smart Switch / Smart Plug.

Every smart product can be integrated into the Deako App and with all the Voice Assistants on the market.

WeMaintain

HQ	Paris, France
Foundation Year	2017
Employees	51-100
Total Funding Amount	$44,430,000
Last Funding Amount	$34,350,000
Last Funding Date	29 Jun 2021

WeMaintain rethinks the model in place to develop a new standard for building elevators.
They are building in parallel, hardware and software, in order to provide reliable and complete data to optimize the management of building elevators.

The intervention process is divided into 6 steps:

1) Inventory: a commercial proposal based on the technical characteristics provided.
2) Transition: support in the decision-making process (defense, discussions with purchases, etc.) physical or online.
3) Interventions: speakers for each geographic area, parts storage in Île-de-France and contact persons dedicated to customer support.
4) Lifting of reservations: real-time updates about intervention.
5) Modernization: small works for the elevators system up to total modernizations.
6) CAPEX: by improving preventive maintenance, they extend the life of elevators. With the IoT technology, they help you anticipate modernization expenses for the assets you manage.

IoT Sensors are installed on each elevator system and transmit data useful to build preventive maintenance models, but also derive useful insights about elevator performances and utilization.

DrizzleX

HQ	Tel Aviv, Israel
Foundation Year	2019
Employees	1-10
Total Funding Amount	$1,020,000
Last Funding Amount	$1,020,000
Last Funding Date	1 Nov 2020

DrizzleX is a ground-breaking smart water metering technology for residential buildings that allows water reduction.
DrizzleX's solution combines the unique, maintenance-free, easy-to-install, and cost-effective FlowDXTM smart water sensors with a sophisticated SaaS dashboard that provides statistics, comparative trends, warnings, and AI-powered insights to the final user. This process creates data-driven transparency about water consumption.
DrizzleX encourages tenants to take responsibility for their water usage and positively affect the environment while allowing property managers and owners to monitor and reduce water bills and property expenses by measuring individual units' water consumption in multi-family homes.

The solution could be articulated in 3 main steps:

1) Metering: DrizzleX's FlowDx sensors are the world's only local water-meters specifically designed for the needs of multi-family properties with hundreds of units and, as such, are maintenance-free, plug & play, cost-effective, and tamper-free. The water sensors measure individual units' water consumption in multi-family properties and upload data to the cloud.
2) AI: Data is analyzed by machine learning algorithms that instantly identify misuse and leaks.
3) SaaS Dashboard: A dashboard and a mobile app enable property managers and owners to manage and decrease water expenses, while real-time alerts and recommendations empower tenants to take responsibility for their water consumption.

Main products:

- FlowDX water meter;
- DX Energy Dashboard.

Wattsense

HQ	Dardilly, France
Foundation Year	2017
Employees	11-50
Total Funding Amount	$4,160,000
Last Funding Amount	$3,320,000
Last Funding Date	2 Oct 2019

Wattsense is a plug-and-play energy management solution for commercial buildings (BMS). The Wattsense Box, which is meant to be simple and quick to install, makes connecting apps to buildings much easier. The building manager gets access to the building data via the Wattsense user console after the box is set up.

Multiples connected equipment could be connected to the Box (e.g. boilers, heating network, gas meter, electric pumps) with their own different communication protocols. Wattsense integrates all those protocols and with the purpose of to universalize the field communication protocols used in building management.

Products:

- Box: 4G data plan included, LoRaWAN, 11 wired network ports, 10 communication protocols till now, managed device;
- Hub: the Wattsense Hub is distinguished from traditional gates by its ease of use, sophisticated capabilities, and adaptability. From one project to the next, connect it all with an IoT gateway that will keep you in control;
- Mini-BMS: Edge device, Mini-BMS Console, Configuration Wizard, 10 communication protocols and counting, Schematics, Alarms, Graphs.

Infogrid

INFOGRID

HQ	London, UK
Foundation Year	2018
Employees	11-50
Total Funding Amount	$15,500,000
Last Funding Amount	$15,500,000
Last Funding Date	30 Nov 2020

Infogrid was created with simplicity in mind to overcome the constraints of traditional sensor technology. The end-to-end system monitors buildings in real-time with the world's tiniest sensors. The variety of sensors are low-cost, low-maintenance, and wire-free, making IoT simple to set up, economical, and scalable.

Main products: Air Quality sensor / People counting sensor / Pipe Monitoring sensor / Humidity sensor / Temperature sensor / Proximity sensor / Touch Response sensor / Water sensor / Desk Occupancy sensor / Building Sensors Platform

The platform is built to easily grow throughout the whole estate. It has easy user interfaces, adjustable alarms, one-click reporting, and an open API, ensuring that the building owner begins to see value as soon as the first sensor is installed.

Arloid Automation

arloid.

HQ	London, UK
Foundation Year	2019
Employees	11-50
Total Funding Amount	$6,100,000
Last Funding Amount	$3,600,000
Last Funding Date	22 Jan 2021

Arloid.ai is a UK-based autonomous cloud-based solution that continuously and precisely optimizes HVAC settings depending on internal and external conditions.

The intervention process follows 4 steps:

1) Building Assessment: They conduct a remote building evaluation based on the information given.
2) Building Connection: They were able to connect to the building in less than an hour.
3) Building Simulation: They give you expected savings for the next 12 months, baselines, and insights for each building zone based on the generated Digital Twin and simulation.
4) AI Launch: Arloid.ai continually adjusts the HVAC parameters of your building with a high level of granularity. Customer service is also available 24 hours a day, seven days a week.

Building applications are various: Data Centers, Hotels, Airports, Hospital, Shopping Malls and Universities.

Breeze Technologies

HQ	Hamburg, Germany
Foundation Year	2015
Employees	11-50
Total Funding Amount	$343,845
Last Funding Amount	-
Last Funding Date	1 Sep 2020

Breeze Technologies is a market leader in air quality sensors, data, and software for air quality analytics. The startup uses artificial intelligence and the internet of things to assist cities and companies in developing stronger clean air action plans and a more liveable environment. Small-scale air quality sensors can monitor common pollutants including carbon and nitrogen oxides, ozone, particle matter, and many more, allowing them to achieve their aim. Then, using a combination of Breeze air quality sensors and external data sources, the environmental analytics cloud platform collects real-time data. They employ their unique Adaptive Cloud Calibration Engine, which is based on machine learning and big data technologies, to improve data dependability and accuracy. The Breeze cloud platform enables users to obtain very high data resolutions, which may help facility managers, environmental scientists, and even municipal management and governments better understand air quality.
Main products:

- Breeze Air Quality Sensors;
- Breeze Environmental Intelligence Cloud.

DABBEL

HQ	Dusseldorf, Germany
Foundation Year	2018
Employees	1-10
Total Funding Amount	$4,400,112
Last Funding Amount	$4,120,000
Last Funding Date	18 May 2021

DABBEL Automation Intelligence GmbH was formed with the goal of creating the most scalable, cost-effective, and long-lasting software to rapidly cut CO2 emissions in commercial buildings throughout the world.
The DABBEL AI is a software add-on that replaces the current Building Management System's (BMS) manual control with Artificial Intelligence, which manages energy systems independently and in real-time. Their estimates say that the AI algorithm can save up to 40% of HVAC energy use in commercial buildings without any hardware or upfront investments.
The startup software will boost your Heating, Ventilation and Air Conditioner system's performance and eliminate human control dependencies.

The solution can be installed remotely and without hardware within one week and is compatible with most building automation systems. The AI technology self-adapts to your building's dynamics and characteristics. Self-Learning with each decision ensures the perfect balance between energy consumption and a healthy indoor environment and maintains the sustainability of your building over time.
Product: AI algorithm to HVAC consumption optimization.

EnerBrain

enerbrain® For an intelligent use of energy

HQ	Torino, Italy
Foundation Year	2015
Employees	11-50
Total Funding Amount	$7,949,536
Last Funding Amount	$5,950,000
Last Funding Date	2 Aug 2021

Enerbrain, thanks to hardware and software technology-based on IoT and AI, optimizes energy consumption for air conditioning, improving environmental comfort and reducing CO2 emissions.
Enerbrain collects building data, processes them thanks to machine learning logic in the Cloud and provides the best output according to your objectives.

Enerbrain provides a complete package consisting of:

1) Inspection and energy analysis: a team of experts collects, processes and analyses data relating to the architectural, plant and energy characteristics of each building
2) Installation: the installed monitoring system is able to acquire the environmental parameters and energy consumption related to the building. The collected data is sent to the Cloud.
3) Calibration: The Cloud receives the data and, using machine learning algorithms, builds forecast models by developing efficiency strategies for all energy vectors.
4) Optimization: the algorithm defines the adjustment methods of the elements in the field so that maximum comfort can be maintained with the minimum expenditure of energy.
5) Data visualization in real-time: the interface provided allows you to view, analyze and download monitoring data and to set the control parameters of the systems.

Main products:

- Man in the Middle: if you already have a BEMS and you can't modify it, Enerbrain will intervein punctually on the single components to optimize the whole system;
- Enerbrain as-a-service: if you already have a BEMS and you can modify it, Enerbrain enables the existing control system to receive advanced commands processed by their algorithm;
- BEMS Cloud: if you don't have a BEMS, Enerbrain creates ad hoc your new local control system which, thanks to the Cloud connection, receives advanced commands processed by their algorithm.

Jarvis by IOOOTA

HQ	Bologna, Italy
Foundation Year	2015
Employees	1-10
Total Funding Amount	$1,656,865
Last Funding Amount	-
Last Funding Date	27 Jan 2021

Jarvis is a smart-objects hub that allows you to connect smart objects in the home, from household appliances to thermostats of different brands, and bring them back to a single remote-controlled centralized hub. The IOOOTA smart-hub recognizes any dangerous situations (gas leak, flooding or if something is going on or on fire), monitors any inefficiencies and sends notifications directly to the smartphone.

Its main functions are:

- Control and Management: interaction with your smart home directly from the app, with the ability to manage all connected objects directly from the phone;
- Savings: monitoring of consumption and single item-related expenses;
- Scenes: the coordinated management of multiple smart objects to create customized scenarios.
- Multi-User: multiple users can have different same home set-ups
- Multi-hub: possibility to check more than one home in the same app.

4.5 Data Valorisation Strategies in Smart Building

In this paragraph, we want to address the main concepts related to the data valorization strategies in the Smart Building sector. We decided to start from the outcome of the startups analysis in which we found some great insights looking at the approach adopted by the newcomers. The main startups chosen as a reference are also big players in the ecosystem with millions of funding, meaning that data exploitation strategies are a good way to monetize through IoT, and it is appreciated by investors.

As the ultimate resume of the strategies they adopt, we can say that the most exploited is the exploration of a software business model as defined in Gebauer et al. (2020).
This concept is related to the fact that the company value proposition is related to obtaining and analysing data about customer processes. We can see this approach in Arloid Automation, whose objective is to optimize HVAC consumption. They build an AI solution that is trained to automatically change HVAC settings based on a calculated comfort index in real-time. As a result, it leads to less energy consumption while keeping an optimal level of comfort. Which is the way they are able to transform IoT data into tangible results, even in monetary terms. The solution works with the existing HVAC infrastructure of the building and doesn't require the installation of additional hardware devices.

A similar approach is the one adopted by another startup already described. DABBEL provides software that replaces the manual control of the existing Building Management System (BMS) with Artificial Intelligence, which operates the energy systems autonomously and in real-time. It models the building at all times, recognizes the context of each room/area of the building in real-time, and adapts the control decisions of the HVAC systems accordingly. The result is interesting and consists in improved performance with each iteration of the AI, ensuring a healthy indoor environment, and reducing unnecessary energy waste and CO_2 emissions. Without any hardware or upfront costs, the AI can save up to 40% of HVAC energy usage in commercial buildings. Meaning a useful and clever use of the IoT data.

Both the strategies adopted can be reconciled to the Process Optimization way of monetizing IoT data. This strategy was identified by Tumino et al. (2012) in their 5-strategy framework already explained in paragraph 1.2.2. The main consideration here is that when talking of Smart Building and in particular energy management, which are the topics of our thesis, the only strategy that can be found in the market is the “Process Optimization”. This is the main approach because it consists in using data obtained from Smart Objects to improve internal processes with the objective of increasing efficiency (time or cost reduction) or effectiveness (client service).
In the category of “Process Optimization” is included also the predictive maintenance approach which can be found in WeMaintain. Their proposal is based on the installation of IoT Sensors on each elevator system and the transmission of data useful to build preventive maintenance models, but also to derive useful insights about elevator performances and utilization.
The monetization of this IoT strategy can be estimated in the improvement of preventive maintenance, extending the life of elevators. With the IoT technology, they help the user to anticipate modernization expenses for the assets he manages. Moreover, it provides access to complete transparency of the maintenance and repair process, detailed usage analysis for preventive maintenance, this is translated into higher service provided to the clients. The tailor-made service they provide can be associated with another strategy of data valorization that is the “Customised product or service”. The strategy is about the use of IoT data to obtain user profiling, through analysis of the data collected. In this case we are talking of objects and not people but the concept is the same.

An intelligent way of exploiting data measured from the Smart Objects is the strategy adopted by Youtiligent. Thanks to their machine learning technology they create usage fingerprints based on electric consumption patterns or external signals from devices. According to an algorithm they translate all the consumption data into meaningful business insights such as new sales opportunities, consumption preferences, and scheduled maintenance services.
Data are gathered through smart plug on which the user should connect appliances or machines.

A similar approach is performed by Drizzle X but related to Water Management, the use of advanced analytics on data is directed towards the instant identification of water leaks and misuse.

At the end it should be reported the example of the two Italian startups analyzed. Enerbrain and IOOOTA.
Both are very similar and can be reconducted to “Process Optimization” valorization strategy.
Enerbrain thanks to sensors, actuators, a control panel and software technology based on AI can optimize energy consumption for air conditioning, improving environmental comfort and reducing CO2 emissions. Thanks to the analysis they made on data gathered it is able to reduce wastes with the constraint of maintaining a comfortable environment. The monetization phase is obtained by a consumption reduction of ⅓ and in making people spend more time in commercials.
Jarvis by IOOOTA, instead, is a plug & play IoT solution for smart buildings that enables energy efficiency, comfort, safety and automation, even remotely. A smart solution not only for the management of multiple objects and HVAC systems but which dynamically regulates and automates the execution of rules and scenarios based on events and third-party services, with the main objective of reducing waste and consumption, CO2 emissions.

After this brief analysis about the startups we can say that the main strategies in Smart building can be reconciled to Process Optimization as the main way to gain money from the IoT data. The outcome was probably predictable because it is the simplest way to monetize data but also buildings have high requirements in terms of privacy and security of its inhabitants and therefore some strategies are difficult to apply, remaining inside the legislation. Moreover, if we consider the framework provided by Gebauer et al. (2020) we can say that the direction of software-based services is predominant in the offers of startups, and this reflects the trends of the other tech sectors.

To provide a further analysis regarding the strategies of optimization for the building systems that a lot of startups are making, we tried to find concepts in the literature.

In Daissaoui et al. (2020) the focus is on the use of IoT to open new opportunities, in particular the use of large volumes of data collected from sensor networks feeds Big Data databases. This opens up the way for in-depth analysis to identify the optimization strategies of smart buildings based on models.
They identify 4-ways through which IoT data can be exploited:

1) **Facilities Management**: The category includes preventive maintenance and detection of building equipment defects to ensure the optimal condition of the building. An effective Facility management will bring many benefits, improving the overall quality of installation services but also reducing the cost of repairs and energy consumption of buildings.
   The paper proposes also a comprehensive building maintenance platform developed with a set of contextual intelligent maintenance applications that used environmental sensors to monitor related variables, such as temperature and humidity, and automatically report feedback.
   For example, if an error is received by an indoor unit, a message is generated. The platform is able to detect the location and possible defective equipment, in this case the HVAC system, and

to alert the human operator suggesting a corrective intervention to facilitate the repair process. The idea of the platform is a very promising exploitation of data and it is one of the main typologies of IoT valorisation identified in Gebauer et al. (2020).

2) **Energy Management**: These systems already exist in commercial buildings that control, monitor the current energy consumption of buildings. These systems usually install non-intrusive meters on electrical circuits to collect energy consumption data for users. However, the potential for improvement is still very significant. Smart buildings require customization according to specific requirements, which requires a certain level of contextual knowledge. The HVAC system needs adjustment according to the number of people in the room and the lighting system must monitor the light intensity outside the building and adjust the lighting inside accordingly. In this way data collected assumes a total new value that can be translated in monetary terms if looking at the bill reduction.
3) **Occupants and resource location tracking**: The location inside is of great value for improving building performance. Data about location of assets or people inside the building could enhance the comfort and improve the energy management. These data can be used for two things mainly:
    - Occupancy information acquired from location information could be used to distribute the resource in a balanced manner;
    - Occupant location will help to understand occupant behaviours and make predictions about the use of the floors or the single rooms within buildings.
4) **Comfort enhancement inside the building**: people spend on average 80% of their lives in buildings according to Yang et al. (2012), so a healthy and comfortable indoor environment is important for the well-being and productivity of occupants. At an advanced level, smart building systems, such as HVAC, will integrate sensors and actuators, so that temperature and other variables will be set according to occupants' preferences and needs based on historical information and through empirical learning automatically configured. The smart home is generally the first type of building that has started with research on occupant comfort using an IoT system.

Talking about energy management that is the focus of our thesis we want to provide a deeper analysis about how these systems are controlled inside a building.
A first distinction should be done between methods of data exploitation to control the system. In Yaici et al. (2020) there are predictive and adaptive methods which are investigated in IoT applications.
The primary purpose of predictive control algorithms is to create energy usage forecasting models based on past energy usage behavior (historical data) as well as different factors such as weather and individual comportment.
In contrast with predictive technologies, adaptive technologies focus on changing the energy consumption of a building based on live feedback if the predictive algorithm is not sufficient.
We have two ways of exploiting data, and according to the type of data its specific application is provided.

Continuing our analysis inside the strategies for consumption reduction inside smart building systems we can now deal with more specifics approaches.

The greatest savings can be achieved in smart building according to control strategies applied to the existing assets of the building. These strategies are enabled by sensors and actuators but have to be set according to some procedures and principles. The following approaches we report do not always exploit the analysis of data as the main aspect to generate value but, they are useful to understand the trajectory of energy efficiency using IoT. We reported all the classes of approaches to give a complete overview.

Lighting Strategies

In the paper Bannamas (2016), the lighting management system has been described highlighting the six major functions that can be used for reducing electrical energy consumption.

1. **Occupancy Control**
   We are talking of an automatic lighting system which detects occupancy inside a room. In this function lights will be automatically turned on when movement is detected and turned off after the last occupant leaves the room. The need for sensors or cameras is fundamental.
2. **Time Scheduling**
   The name of the function is self-explaining. The system can be programmed to automatically turn on or off lights for the required period of time.
3. **Daylight Control**
   In this function dimmable lights are needed as the system exploits the benefit of sunlight. A room is divided into groups based on the distance from windows, sections are separated based on the different amount of sunlight they receive.
   The different sections are then programmed to adjust the intensity of lights to guarantee the needed comfort and lumens standard. According to this scheme, power usage can be saved while ensuring the right light intensity. The light sensors are a central part of the system together with the dimmer actuators.
4. **Task control**
   The characteristic of this function is that the areas are divided into small sections in order to control lights only in specific working areas or bathrooms etc… Lights can be switched on and off only in the area where people are working or staying
5. **Personal Control**
   This way of managing and controlling lights is especially used in large buildings where the energy conservation strategies are more effective. As the name suggests it consists in using software to control and adjust the lighting system.
6. **Variable Power Shedding**
   Starting from the maximum power required for a building, the user sets the default setting of power usage. The program is allowed to warn the user when the decided power consumption is achieved. The software then allows the user to switch off luminaries or let the system cut off unnecessary ones automatically. The default power is calculated by setting a load factor, which is 80% during typical days.

Heating Strategies

Improving HVAC system management to be more energy efficient by use of modern control techniques can be a non-invasive and cheaper approach towards energy efficiency. Not only lighting systems, also in heating systems different management strategies are fundamental to control energy consumption while at the same time ensuring the right amount of comfort for occupants.

Looking at the paper Mařík (2011), a simplified classification of the control strategies can be found. Even if the research is ten years old it is able to identify the main areas in which controls type are split:

1. **Performance Monitoring**
   Performance monitoring strategy is achieved by passively observing the system and notifying the system about possible problems or environmental conditions, so that the user or the software can take action. This represents an important step towards better HVAC control.

One example of strategies included in the performance monitoring category is thermal comfort monitoring.
Thermal comfort in a zone is traditionally used for HVAC control. The strategy is based on the requested comfort level defined by the facility manager, or the occupants and it is used as a target setpoint for the HVAC settings. The acceptable comfort level can typically be achieved by various combinations of different factors like temperature, air speed, humidity etc.

2. **Rule-Based control**

   The basic functioning of the control system is based, as the name claims, on basic rules that drive actions based on data gathered by sensors. The rule-based approach is used mainly for better scheduling like improved pre-cooling setup or optimal start and stop of the heating system.
   These methods are relatively simple, and although they are capable of finding a suboptimal solution, quite significant energy savings can be achieved if they are properly implemented. According to the numerous authors many buildings are poorly controlled, thus even a simple enhancement of control strategy would reduce operating costs.
   An example of rule-based control system is the Demand Control Ventilation (DCV): Thinking of high occupancy spaces like multipurpose rooms, theatres or conference rooms, DCV can be used to reduce ventilation when spaces are not used or lower than the peak occupancy. These places are designed for a high occupancy that rarely occurs and when ventilation is reduced, less outside air is heated or cooled which results in energy savings.

3. **Model predictive control (MPC)**

   The main objective of any HVAC control system is to maintain predefined comfort levels in rooms, while minimizing the overall costs and consumption. An MPC-based solution addresses this goal by modelling the relations between different variables, zone comfort, setpoints and inputs.
   In the paper Belic et al. (2015), is given an overview about predictive control strategies. Predictive control techniques rely on predicting the dynamic behaviour of the system in future and adjusting the response of the controller accordingly. This type of control solves an online optimization problem to perform an action at each time, with the prediction of future evolution of the process, the model should be subject to some constraints on control inputs and states.
   Usually this means some variation of Model Predictive Control (MPC), where prediction is performed based on an explicit model of building. These kinds of methods can achieve very good results, but often have problems with complex implementation. Moreover, the paper Kwadzogah et al. (2013), provides some insights about the strategy saying that Model predictive control (MPC) has shown great potential in comparison with Rule Based Control.
   MPC does not represent a single strategy, it is a vast class of control methods that use a model to control the system by minimizing cost function subject to some constraints.

Chapter 5:
MODEL FORMULATION

The core and central part of our Dissertation is the formulation of a model that considers a retrofitting intervention for a building with the application of IoT-based technologies aimed at obtaining energy savings, optimization, and consumption reduction. Our model will be useful for understanding the main costs and benefits of the intervention for whoever wants to enter into such an investment.

5.1 The Model

The peculiarity of the model is that it considers three different parts (apartments, open space offices, and offices of professionals) for the same building with the application of different technologies according to the type of floor, even if they have the same objective of energy saving.

We consider only those components needed to increase the level of smartness of a system (heating and lighting), meaning actuators, sensors, controllers, and software. This decision was taken to understand the impact of an IoT- focused intervention. For instance, we do not take into consideration Solar Panels which would have had a great impact on energy savings, but they would have made us lose the IoT focus.

We consider the owner of the building as the one who should invest, but then we estimate all the benefits of these interventions for occupants, being companies or families. The approach taken, puts the building at the centre and tries to estimate what’s all around it in terms of acquisition costs, technologies adopted, related savings, installation costs and additional period costs.

The capital expenditure of this type of project depends on the technology and the building dimension. The technology installed refers mainly to all the necessary components needed to increase the smartness of existing systems, considering mainly two types: lighting and HVAC.

In the offices the energy savings due to lighting systems are driven by new LEDs with dimmable function, equipped with lighting sensors and actuators and also the shading system with venetian actuators.

HVAC system in offices is composed of indoor units powered by heat pumps. Thanks to the technologies we decided to use, we want to make it “Smart” in order to obtain benefits related to the control strategies. We included sensors with multiple functions, new types of thermostats, and HVAC actuators. In the calculation of the number of actuators needed we also reported all the estimations of the number of internal HVAC units that the building is supposed to have.

The control system is implemented in the KNX and DALI standards. The architecture of the control system is based on three protocols: DALI protocol for the luminaires, KNX protocol for commands, sensors, and actuators, TCP/IP protocol when the internet connection is needed for monitoring and remote control.

The main thing to underline in our set up is that the products we took are all KNX or DALI compatible according to the system to be managed. In fact, we decided to take as a reference the common standard to define the components needed.

We decided to also include the DALI standard because it can enable daylight-linked lighting control. This strategy can be used to either switch lights on and off, or it can be used with dimmable systems to provide artificial light when daylight is present. This technique is of particular interest for us as most

commercial and office spaces have sufficient daylight from windows to strongly reduce the need for electric lighting.
These energy-saving smart lighting systems are generally installed in office buildings as they have the highest potential for power consumption reduction and are relatively straightforward to retrofit.
In the smart home part of our thesis the lighting and heating systems have been considered like in the offices part even if the components are not exactly the same. The first difference is about the communication protocol, which in the case of the residential part is ZigBee.
The largest share of solutions in the field of smart home is based on radio communication protocols since domotics in houses are conceived by components makers in order to be plug and play. With a small investment in terms of money and effort, a house owner could have a complete system with lots of benefits.
The homes in the model are equipped with smart sockets, smart switches, a gateway, windows/doors sensors for the lighting system. Contrary to the offices, the residential part of the building is heated by radiators. Therefore, automated thermostatic valves have been considered to automate the system in strict correlation with sensors and smart thermostats.
We dimensioned all the components starting from the real need of a hypothetical building, we considered the typical need for heating and cooling per square meter in offices and the lumens required per square meters given by law. The components we choose are taken from real catalogs on the market and have been dimensioned according to their specifics. No big differences between offices and homes even if the residential computations were simpler because we base them on the requirements of the single house, like the number of rooms.
We calculated savings considering two main things:

- The percentage savings on the total initial energy consumption that can be obtained from the technologies and strategies we implemented. Those values are obtained from the literature.
- Average consumption of residential and commercial buildings, that could vary according to the case.

Investment is calculated as a sum of the acquisition costs of single pieces and the installation costs. Acquisition costs are taken from real market products but are influenced by economies of scale that we introduced according to the number of pieces needed and therefore the building dimension.
The final aim of our Dissertation is to obtain real outcomes of an investment like this for the building typology. With this in mind, we decided to adopt the Payback time as the final indicator for the estimations. The results are obtained by actualizing the value of savings and costs during the years by adjusting them with inflation.
In the next few paragraphs, we dive into the descriptions of the formulas we used, both for costs in paragraph 5.2 and benefits in 5.3. Those formulas will be the model itself and their application is delegated to chapter 6.

5.2 Cost Structure

In this section of the model our objective is to explain how we set up the computation of costs. In the cost's computation part, we considered three main cost typologies:

1) Acquisition Costs

   These are usually calculated as the multiplication of unitary costs, taken from real references, times the quantity of the single piece. The values obtained are then decreased by the percentage we assume to have, considering possible synergies and scale economies among the different systems installed. We obtain at the end the Discounted Acquisition Costs.

   The economies of scale are included together with the assumption that higher volume would cause a reduction in the unitary price of the single piece. This relation is not linear but depends on the single provider and its cost structure. The main driver for defining economies of scale is the quantities, the higher they are the higher the bargaining power of the buyer.

2) Installation Costs

   Are calculated multiplying the Acquisition Costs with a percentage Installation costs on Acquisition Costs. According to the type of floor we consider two types of percentage: 10% for residentials and 20% for Offices. This percentage is composed of two addends: 10% + 10%. The first one considers the costs for installing the single components by a professional technician and it is obtained from mail requests to experts, we use this value also for smart home installations. The other, instead, is related to all the costs for acquiring and installing necessary components of the KNX bus, we consider in this percentage components like: Power Supply of the line, Line Coupler, IP Router and cables.

   We used this methodology because computing Installation Costs punctually would be strictly tied to the single case and the single component in the specific building, and a model in this way wouldn't be useful. As already stated, houses components are based on Zigbee protocol with no wired system to be installed, therefore as installation percentage we consider only the first 10%.

3) Period Costs

   These are considered annual costs, which include running costs. We take into account the Appendix A of EN15459 and we adopt the same approach as installation costs.

   The document has been prepared under a mandate by the European Commission and the European Free Trade Association, and supports essential requirements of EU Directive(s). They provided period costs as a percentage of the initial investment, this value includes the single component's annual preventive maintenance (operation, repair, and servicing costs).

The sum of Discounted Acquisition costs and Installation Costs is represented by the Initial Investment. In the following paragraphs we show the formulas to estimate the costs in our model. The next paragraph is about the lighting and HVAC system for offices with all the technologies involved, while the following one computes the costs for the Smart Home system.

5.2.1 Offices Cost Computation

The main characteristic of our model is the presence of a mixed building which includes three types of different environments: The Professional Offices, The Open Space offices, and the Smart Home. While the difference between Residential and Office are relevant, not so obvious are those between Open Space and Office of Professional. We consider in the first case a large environment with no boundaries to divide the zones, let’s think about the offices of large tech companies, which could also have separations, but the system is managed like one single zone.

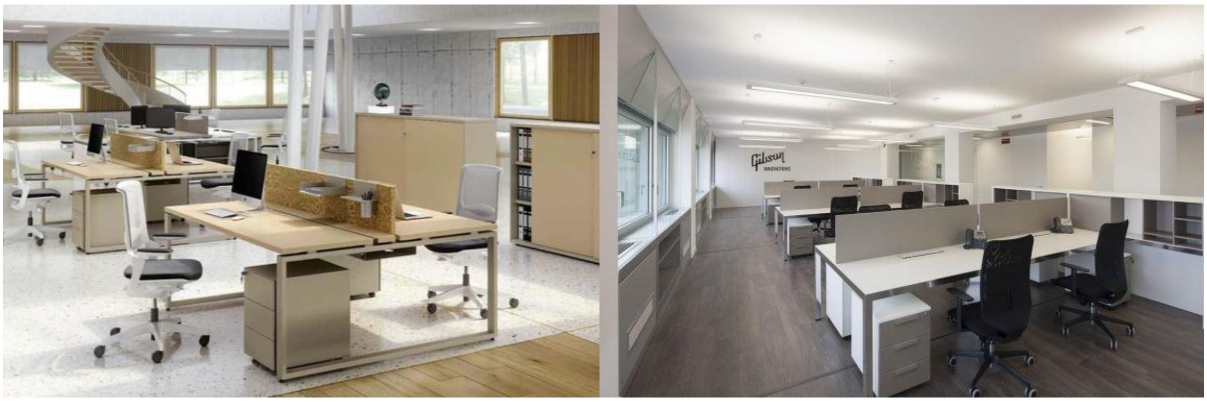


Figure 5.1: Open Space Offices

The Office of Professional are considered as a floor divided in single closed offices of different size, each on with its requirement in terms of light and HVAC.
As a consequence of this, differences between the two types of offices are not linked to the technologies employed but in the dimensioning phase with the quantification of components.
Since the cost computation formulas for Open Space Offices and Professional Offices are the same, we do not replicate them twice, but we will calculate different values in the model application parts for the two environments. The formulas are shared, but the costs aren’t.

LIGHTING SYSTEM

The lighting system in the model is composed of different parts: LED Lights, DALI lighting Sensors, Dimmer Controller/Actuator, Venetian Actuator.
The Venetian Actuator is considered in this part because it is important to control the shading system and therefore adjust the level of intensity by external sources of light.
The increased utilization of daylight in buildings is an increasing trend as sunlight has been known to have a positive effect on the health and well-being of occupants. One such benefit is its effect on the regulation of human circadian rhythms, which can increase worker alertness during working hours.

CEILING LED LIGHTS

We decided to substitute all the ceiling lights in the offices because we need dimmable lights for the control strategies we want to implement. We take as a reference a LED light panel from the Ikea catalogue with a Luminous flux of 4000 lumen, which is DALI compatible. This item has a unitary cost of 100 €.
We performed the calculation about the number of led lights needed in the building starting from a law about the office environment. According to UNI EN 12464 in offices there must be 500 lux, a lux is equal to 1 lumen/m^2.

$$Lumens\ for\ one\ Office\ =\ Lumens\ Required\ per\ m2\ \cdot\ Office\ surface\ = \\ =\ 500\ lumens/m2\ \cdot\ Office\ surface$$

Lumens required are provided by the lights we install, and considering the specifics of the product we calculate:

$$N°\ LED\ lights\ in\ one\ Office = \frac{Lumens\ for\ one\ Office}{Lumen\ of\ one\ LED\ light} = \frac{Lumens\ for\ one\ Office}{4000\frac{lumen}{LED\ light}}$$

$$N°\ LED\ lights\ for\ all\ Offices\ =\ N°\ LED\ lights\ in\ one\ Office\ \cdot\ N°\ Offices\ in\ the\ Building$$

After calculating the lights in offices, in the building floors there are also common areas which we should evaluate in the same way:

$$Lumens\ for\ Common\ Areas \\ =\ Lumens\ required\ per\ m2\ \cdot\ Common\ Areas\ Surface\ in\ one\ Floor \\ \cdot\ N°\ floors \\ =\ 500\ lumens/m2\ *\ Common\ Areas\ Surface\ in\ one\ floor\ *\ N°\ Floors.$$

$$N°\ LED\ lights\ in\ Common\ Areas = \frac{Lumens\ for\ Common\ Areas}{Lumen\ of\ one\ LED\ light} \\ = \frac{Lumens\ for\ Common\ Areas}{4000\frac{lumen}{LED\ light}}$$

$$N°\ LED\ lights\ for\ the\ Building\ =\ N°\ LED\ lights\ for\ all\ Offices\ + \\ N°\ LED\ lights\ in\ Common\ Areas$$

Acquisition costs are a function of the unitary costs, the number of pieces, and the economies of scale applied according to the quantities. For the estimation of installation and period costs we took the acquisition costs and the percentages costs on the acquisition ones.

$$Acquisition\ Cost\ for\ LED\ Lights =\ Unitary\ LED\ Cost\ \cdot\ N°\ LED\ for\ the\ Building \\ =\ 100\ €/LED\ \cdot\ N°\ LED\ for\ the\ Building$$

$$Discounted\ Acquisition\ Cost\ for\ LED\ Lights \\ =\ Acquisition\ Cost\ for\ LED\ Lights \cdot\ (1 - Ec.Scale)$$

Different formulas are used for the bathroom areas. In these areas we adopt Led lights specifically designed for baths because what is only needed is a sensor that is able to sense when someone is entering to automatically switch on the light. When the movement sensor perceives that no one is in the bath it switches off the light, saving electricity. The price considered is 50 €.

The formulas are similar to the previous calculation with the exception that lumen is not taken as the main parameter in the dimensioning because now it should be one ceiling light per single bath. In our model we set up the bathrooms dividing them in subareas, each with their lights.

Figure 5.2: Ceiling LED Light

$$N°Baths\ LED\ Lights\ =\ N°\ Bathrooms\ in\ one\ Floor\ \cdot\ N°\ Floors\ \cdot\ N°\ Subareas\ in\ Each\ Bathroom$$

Acquisition costs are then calculated:

$$Acquisition\ Cost\ for\ Baths\ LED\ Lights = \ Unitary\ LED\ lights\ Cost\ \cdot\ N°Baths\ LED\ Lights = \ 50\ €/LED\ \cdot\ N°Baths\ LED\ Lights$$

$$Discounted\ Acquisition\ Cost\ for\ Baths\ LED\ Lights = \ Acquisition\ Cost\ for\ Baths\ LED\ Lights \cdot\ (1 - Ec.Scale)$$

Having the installation costs for both Bath Areas, offices and Common Areas we can estimate period and installation costs:

$$Light\ Installation\ Cost = \ 20\%\ \cdot\ (Acquisition\ Cost\ for\ Baths\ LED\ Lights + \ Acquisition\ Cost\ for\ LED\ Lights)$$

$$Light\ Period\ Cost = \ 2\%\ \cdot\ (Acquisition\ Cost\ for\ Baths\ LED\ Lights + \ Acquisition\ Cost\ for\ LED\ Lights)$$

After summing up the discounted acquisition for lights in offices, common areas and baths we can calculate the initial investment.

$$Initial\ Investment\ Bath\ LED\ Lights = \ Discounted\ Acquisition\ Cost\ Bath\ LED\ Lights + \ BAth\ LED\ lights\ Installation\ Cost$$

DALI LIGHTING SENSORS

This section of the model computes the number of DALI sensors needed in the building, which depend on the area to monitor, and the surface covered by each sensor. Our setup needs a lighting sensor for understanding the luminous flux inside a building and transmitting the signal to the controllers/actuators. We need sensors which are DALI compatible because they are included in the daylight-linked lighting control strategies based on this protocol. We decided to take as a reference "DALI light and presence sensor" by OSRAM which has a market price of around 80 €. The percentage period costs considered is about 5%.
The sensor is installed on the ceiling, and it covers a height of 3 meters with a diameter long enough to cover a square area of 8x8 meters. The number of sensors strictly depends not only on the surface to cover but also on the shape of the zone.

$$N°\ DALI\ Sensors\ in\ One\ Office\ = \frac{Office\ Area}{Area\ covered\ by\ one\ Sensor} =$$

$$N°\ DALI\ Sensors\ in\ the\ Office\ Floor = \ N°\ DALI\ Sensors\ in\ One\ Office\ \cdot\ N°\ Offices\ in\ the\ Floor$$

$$N°\ DALI\ Sensors\ in\ the\ Floor\ for\ all\ Offices = \ N°\ DALI\ Sensors\ in\ One\ Office\ \cdot\ N°\ Offices\ in\ the\ Floor$$

$$N°\ DALI\ Sensors\ in\ Common\ Areas\ in\ one\ Floor\ = \frac{Common\ Areas\ m2}{Area\ covered\ by\ one\ Sensors}$$

After calculating the number of sensors for offices and common areas we can come up with a final number:

$$Total\ N°\ DALI\ Sensors = (N°\ DALI\ Sensors\ in\ the\ Floor\ for\ all\ Offices + N°\ DALI\ Sensors\ in\ Common\ Areas\ in\ one\ Floor) * N°\ Floors$$

Then costs are calculated considering the three main types of costs:

$$Acquisition\ Cost\ for\ DALI\ Sensors = Unitary\ Cost\ for\ DALI\ Sensors \cdot Total\ N°\ DALI\ Sensors = 80€/unit \cdot Total\ N°\ DALI\ Sensors$$

$$Discounted\ Acquisition\ Cost\ DALI\ Sensors = Acquisition\ Cost\ DALI\ Sensors \cdot (1 - Ec.Scale)$$

$$DALI\ Sensors\ Installation\ Cost = 20\% \cdot Acquisition\ Cost\ DALI\ Sensors$$

$$Sensors\ Period\ Cost = 5\% \cdot Acquisition\ Cost\ DALI\ Sensors$$

The initial investment required for this type of component is finally calculated:

$$Initial\ Investment\ for\ DALI\ Sensors = Discounted\ Acquisition\ Cost\ DALI\ Sensors + DALI\ Sensors\ Installation\ Cost$$

DIMMER ACTUATORS

Considering Lights Actuator we took as a reference KNX-DALI light controller 8-fold, DLR/S 8.16.1M from ABB, which is one of the main players in the market with high market share in the field. The product acts as a dimming actuator compatible with the bus system KNX, it integrates devices with DALI interfaces into a KNX building installation. Up to 64 DALI devices can be connected to the DALI output. The 64 DALI devices should be assigned to 8 lighting groups with the ETS-independent Software Tool (which is the software able to configure the system KNX).

Control of the 64 DALI devices via KNX is exclusively group-oriented and individual lighting groups can be switched or dimmed.

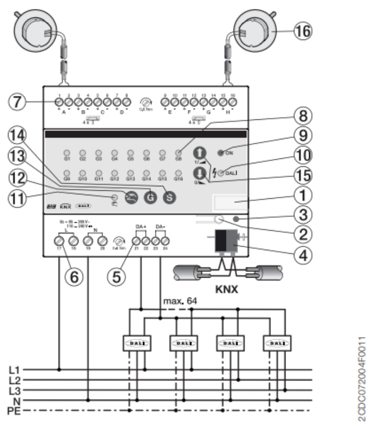


Figure 5.3: Dimmer Actuator

For the calculation we consider three parameters which strictly depend on the specifics of the product:

- Max n° of input sensors per dimmer = 8
- Max n° of output lighting groups per dimmer = 8
- Max n° of lights connected = 64
- Unitary cost = 365 €
- Period cost Percentage = 3%

Having the number of sensors per floor from the previous paragraphs we can estimate the actuator's quantities making a maximum function between the values obtained considering input and the values obtained considering outputs:

$$N° \ of \ Dimmer \ Actuators \ per \ floor \ (output) = RoundUp\left(\frac{Total \ n° \ of \ LED \ Lights \ per \ floor}{Max \ n° \ of \ LED \ Lights \ connected}\right)$$
$$= RoundUp\left(\frac{Total \ n° \ of \ LED \ Lights \ per \ floor}{64 \ LED \ Lights/Dimmer}\right)$$
$$N° \ of \ Dimmer \ Actuators \ per \ floor \ (input)$$
$$= RoundUp\left(\frac{Total \ n° \ of \ Light \ Sensor \ per \ floor}{Max \ n° \ of \ input \ sensors \ per \ Dimmer}\right)$$
$$= RoundUp\left(\frac{Total \ n° \ of \ Light \ Sensor \ per \ floor}{8 \ Light \ Sensor/Dimmer}\right)$$

$$N° \ of \ Dimmer \ Actuators \ per \ floor$$
$$= MAX \ (N° \ of \ Dimmer \ Actuators \ per \ floor \ (output); \ N° \ of \ Dimmer \ Actuators \ per \ floor \ (input))$$

The total number of Dimmer Actuators needed can be obtained multiplying times the number of floors:
$$Total \ n° \ of \ Dimmer \ Actuators = N° \ of \ Dimmer \ Actuators \ per \ floor \cdot N° \ of \ Floors$$

All the specific costs needed are calculated as follows:
$$Acquisition \ Cost \ of \ Dimmer \ Actuators$$
$$= Unitary \ Dimmer \ Actuators \ Cost \cdot Total \ n° \ of \ Dimmer \ Actuators$$
$$= 365 \ €/Dimmer \cdot Total \ n° \ of \ Dimmer \ Actuators$$
$$Discounted \ Acquisition \ Cost \ of \ Dimmer \ Actuators$$
$$= Acquisition \ Cost \ of \ Dimmer \ Actuators \cdot (1 - Ec.Scale)$$

$$Dimmer \ Actuators \ Installation \ Cost = 20\% \cdot Acquisition \ Cost \ of \ Dimmer \ Actuators$$
$$Light \ Period \ Cost = 3\% \cdot Acquisition \ Cost \ of \ Dimmer \ Actuators$$

Initial Investment can be found using this formula:
$$Total \ initial \ Investment \ for \ Dimmer \ Actuators$$
$$= Dimmer \ Actuators \ Installation \ Cost$$
$$+ Acquisition \ Cost \ of \ Dimmer \ Actuators$$

VENETIAN ACTUATORS

Venetian Actuators are useful for controlling blind/shutter mechanisms (awnings, blinds, shutters and various sun and visibility protection devices).
We take as a reference the Venetian blind Actuator from Siemens, which is KNX compatible.
For the calculation of the number of actuators we considered that each actuator could control 4 different groups. Venetian Actuator unitary cost = 352 €. Period cost Percentage = 3%.
There are two constraints to be satisfied in the calculation of this quantity:

1) Connectable objects per one actuator = 249 Venetians
2) Max n° of groups to be controlled by one actuator = 4 Groups / Actuator

At the end it should be taken as the maximum between these estimations.

The first constraint is satisfied starting from understanding the number of windows in the building. To make estimations general, as the model nature claim, we decided to calculate the number of windows considering the Italian “Decreto Ministeriale 5 Luglio 1975” which says that the “Rapporto

Aeroilluminante" (i.e. the ratio between the surface of the floor and that of the windows) must be higher than 1/8.
Starting from that we calculate the number of windows as:

$$Area\ of\ Windows\ for\ the\ Building\ =\ 1/8\ \cdot\ Building\ Surface$$

The area of windows for the building glass area in one window is 1,5 m^2, and we need it to calculate how many windows the offices have:

$$N°\ of\ Windows\ =\ \frac{Area\ of\ Windows\ for\ the\ Building}{Glass\ Area\ in\ one\ Window}\ =$$
$$=\frac{Area\ of\ Windows\ for\ the\ Building}{1{,}5\ m2}$$

$$N°\ of\ Windows\ =\ N°\ Venetians\ to\ Control$$

$$N°\ Venetians\ Actuators\ (Connectable\ Objects)\ =\frac{N°\ Venetians\ to\ Control}{Connectable\ Objects\ per\ one\ Actuator}=$$
$$=\ \frac{N°\ Venetians\ to\ Control}{249\ Devices/Actuator}$$

The second constraint to be satisfied to estimate actuators is the one considering controllable groups:

$$N°\ of\ Venetians\ Actuator\ (Groups) = RoundUp\ \left(\frac{Total\ n°\ of\ Venetians\ groups\ to\ control}{Max\ n°\ of\ Venetians\ groups\ controllable}\right)$$
$$= RoundUp\left(\frac{Total\ n°\ of\ Venetians\ groups\ to\ control}{4\ Groups/Actuator}\right)$$

We have our final estimation for the number of Venetians Actuators needed that is:

$$N°\ of\ Venetians\ Actuators$$
$$= MAX\ (N°\ of\ Venetians\ Actuators\ (Connectable\ Objects);\ N°\ of\ Venetians\ Actuators\ (Groups))$$

As usual costs are calculated as follows:

$$Venetian\ Actuators\ Acquisition\ Cost\ =\ N°\ Venetians\ Actuators\cdot\ Unitary\ Cost\ =$$
$$= N°\ Venetians\ Actuators\cdot\ 352\ €/unit$$

$$Discounted\ Venetian\ Actuators\ Acquisition\ Cost$$
$$=\ Venetian\ Actuators\ Acquisition\ Cost\ \cdot\ (1-Ec.Scale)$$

$$Venetian\ Actuators\ Installation\ Cost\ =\ 20\%\ \cdot\ Venetian\ Actuators\ Acquisition\ Cost$$
$$Venetian\ Actuators\ Period\ Cost\ =\ 3\%\ \cdot\ Venetian\ Actuators\ Acquisition\ Cost$$

For a total required initial investment of:

$$Total\ initial\ Investment\ for\ Venetian\ Actuators$$
$$=\ Discounted\ Venetian\ Actuators\ Acquisition\ Cost$$
$$+\ Venetian\ Actuators\ Installation\ Cost.$$

WINDOW SENSORS

The Window contact detects open windows and immediately sends a signal in the system. The system through the controller is able to perform actions so that indoor units do not continue to heat unnecessarily, while the user ventilates. In this way, the intelligent window sensor ensures energy efficiency in the office.
The unitary cost of 30 € is taken from real products, the item should be KNX compatible. The percentage period costs is considered 5% as the other sensors.

To calculate the quantity of sensors to install we should have the actual number of windows. The estimation has been already performed in the previous paragraph and we report here the main formulas:

Figure 5.4: Windows Sensor

$$Area\ of\ Windows\ for\ the\ Building\ =\ 1/8\ \cdot\ Building\ Surface$$

$$N°\ of\ Windows\ =\ \frac{Area\ of\ Windows\ for\ the\ Building}{Glass\ Area\ in\ one\ Window}\ = \\ = \frac{Area\ of\ Windows\ for\ the\ Building}{1{,}5\ m2}$$

$$N°\ of\ Windows\ =\ N°\ of\ Window\ Sensors$$

The related costs are then computed:

$$Window\ Sensors\ Acquisition\ Cost\ =\ N°\ Window\ Sensors \cdot\ Unitary\ Cost\ = \\ = N°\ Window\ Sensors \cdot\ 30\ €/unit$$

$$Discounted\ Window\ Sensors\ Acquisition\ Cost \\ =\ Window\ Sensors\ Acquisition\ Cost\ \cdot\ (1 - Ec.Scale)$$

$$Window\ Sensors\ Installation\ Cost\ =\ 20\%\ \cdot\ Window\ Sensors\ Acquisition\ Cost \\ Window\ Sensors\ Period\ Cost\ =\ 5\%\ \cdot\ Window\ Sensors\ Acquisition\ Cost$$

HVAC SYSTEM

In this part we want to address the main formulas to calculate the requirement of the HVAC system. We describe all the components needed to automate it and enable remote control, including: sensors, actuators, and thermostats.

TEMPERATURE SENSORS

The first component of the heating and cooling systems is the sensor. We considered as a reference a sensor able to measure temperature, humidity and movements, which is able to sense the important information needed to optimize consumption and increase energy savings. From this moment on we refer to it as Multisensor.

As in the previous case for the DALI sensors, the quantity computed depends on the area to monitor, its shape and the surface covered by each sensor. Contrary to the first type of sensor described, this one is installed in the KNX bus; therefore, it should be KNX compatible.
We considered a market price of around 120 €. The percentage period costs considered is about 5%.
The sensor is installed on the ceiling, and it covers a height of 3 meters with a diameter 12 meters

$$N° \ Multisensors \ in \ One \ Office \ = \frac{Office \ Area}{Area \ covered \ by \ one \ Sensor} =$$

$$N° \ Multisensors \ \ in \ one \ Office \ Floor$$
$$= \ N° \ Multisensors \ in \ One \ Office \ \cdot \ N° \ Offices \ in \ the \ Floor$$
$$N° \ Multisensors \ \ in \ one \ Floor \ for \ all \ Offices$$
$$= \ N° \ Multisensors \ in \ One \ Office \ \cdot \ N° \ Offices \ in \ the \ Floor$$
$$N° \ Multisensors \ in \ Common \ Areas \ in \ one \ Floor \ = \frac{Common \ Areas \ m2}{Area \ covered \ by \ one \ Sensors}$$

After calculating the number of sensors for offices and common areas we can come up with a final number:

$$Total \ N° \ Multisensors$$
$$= (N° \ Multisensors \ in \ the \ Floor \ for \ all \ Offices$$
$$+ N° \ Multisensors \ in \ Common \ Areas \ in \ one \ Floor) * N° \ Floors$$

Then costs are calculated considering the three main types of costs:

$$Acquisition \ Cost \ for \ Multisensors$$
$$= \ Unitary \ Cost \ for \ Multisensors \ \cdot \ Total \ N° \ Multisensors$$
$$= \ 120€/unit \ \cdot \ Total \ N° \ Multisensors$$
$$Discounted \ Acquisition \ Cost \ Multisensors$$
$$= \ Acquisition \ Cost \ DALI \ Sensors \ \cdot \ (1 - Ec. Scale)$$
$$Multisensors \ Installation \ Cost \ = \ 20\% \ \cdot \ Acquisition \ Cost \ Multisensors$$
$$Multisensors \ Period \ Cost \ = \ 5\% \ \cdot \ Acquisition \ Cost \ Multisensors$$

The initial investment required for this type of component is finally calculated:

$$Initial \ nvestment \ for \ Multisensors$$
$$= \ Discounted \ Acquisition \ Cost \ Multisensors$$
$$+ \ Multisensors \ Installation \ Cost$$

HVAC ACTUATORS

Hvac actuators' role is to transform the heating system into a smart one and their number is defined based on the number of indoor units in the office floors. The office floors were already equipped with a HVAC system powered by a heat pump and our goal is to transform the existing system by applying additional components (it is a renovation intervention of something already functioning). Our main and important assumption here is that we do not have to change neither indoor units nor outdoor ones, since from a market review, we saw that products in this category are compatible with this type of technology. To consider an almost real case we started from the definition of the power requirement for the offices from this table drafted by ENEA.

m^2	kW HEATING	kW COOLING
5	0,63	0,45
10	1,155	0,9
15	1,575	1,35
20	2,1	1,8
26	2,73	2,34
30	3,15	2,7
35	3,675	3,25
40	4,2	3,6
45	4,725	4,05
50	5,25	4,5

Table 5.1: ENEA Offices kW requirement per m^2

In order to adopt the proper technology, we consider a VRF heat pump from Yanmar as a reference for the power production and also compatible indoor units.
Characteristics of the heating system were considered to estimate the number of smart equipment needed, therefore, Yanmar split had been selected as reference because it can communicate with sensors and remote controllers, meaning that it is suitable for being part of the automation system included in our model. Data about the power production of each unit was needed to count and define their number according to the heating and cooling requirements of each room.
The indoor unit chosen as a reference is the 4-way cassette unit by Yanmar, which can be seen in the figure 5.5. It has 4 kW of maximum heating power and 3,6 kW in cooling power.

Figure 5.5: HVAC Indoor Unit

First of all, the number of splits has been defined using Table 5.1 that summarizes the average power required by the office according to their dimensions.
The number of 4-way cassette units (also called Splits or Indoor Units) is calculated by finding the maximum between the quantities of splits calculated by using the kWh of cooling and heating.

$$N° \ indoor\ units\ in\ one\ Office\ (Heating) = \frac{Heating\ kWh\ Required\ in\ one\ Office}{kWh\ Prvided\ by\ the\ System} = \\ = \frac{Heating\ kWh\ Required\ in\ one\ Office}{4\ kWh/Split}$$

$$N° \ indoor\ units\ in\ one\ Office\ (Cooling) = \frac{Cooling\ kWh\ Required\ in\ one\ Office}{kWh\ Provided\ by\ the\ System} = \\ = \frac{Cooling\ kWh\ Required\ in\ one\ Office}{3{,}6\ kWh/Split}$$

$$N° \ indoor\ units\ in\ one\ Office\ = \\ MAX(N°\ indoor\ units\ in\ one\ Office\ (Cooling);\ N°\ indoor\ units\ in\ one\ Office\ (Heating))$$

$$N°\ indoor\ units\ in\ Office\ floors\ = N°\ indoor\ units\ in\ one\ Office\ \cdot N°\ Offices\ in\ the\ floor$$

$$N° \, indoor \, units \, in \, office \, in \, the \, building \; = \; N° \, indoor \, units \, in \, Office \, floors \; \cdot \; N° \, floor$$

The same calculation is repeated for common areas and baths and then the results are summed up:

$$\begin{aligned} &Total \, N° \, of \, Splits \\ &\quad = \; N° \, Splits \, in \, all \, Offices \; + \; N° \, Splits \, in \, Common \, Areas \\ &\quad + \; N° \, Splits \, in \, Baths \end{aligned}$$

After having understood the number dimension of the HVAC system, we used this number for obtaining the number of actuators needed. We take as a reference the "Spacelogic KNX Valve Drive Controller" from Schneider Electric. The product acts as both controller and actuator and can be connected to a max number of 4 split per channel and a max number of 6 channels per actuator. Each channel can be managed in a different way while the indoor units connected to the same channel are actuated in the same way, that is why we should create groups according to the same needs. Groups of indoor units are considered for simplicity as those acting in the same room, because they should provide an equal workload.

Figure 5.6: HVAC Actuator

The formulas are as follows:

$$N° \, of \, channels \, needed \, in \, one \, Office \; = \; \frac{N° \, of \, indoor \, units \, in \, one \, office}{Max \, n° \, of \, units \, connected \, per \, channel} = \\ = \frac{N° \, of \, indoor \, units \, in \, one \, office}{4 \, indoor \, units/channel}$$

$$\begin{aligned} &Total \, n° \, of \, channels \, needed \, in \, one \, office \, floor \\ &\quad = \; N° \, of \, channels \, needed \, in \, one \, Office \; \cdot \; N° \, of \, Offices \end{aligned}$$

$$\begin{aligned} &Total \, n° \, of \, actuators \, needed \, in \, one \, office \, floor \\ &\quad = \frac{Total \, n° \, of \, channels \, needed \, in \, one \, office \, floor}{Max \, n° \, of \, channels \, per \, actuator} \end{aligned}$$

$$\begin{aligned} &Total \, n° \, of \, actuators \, needed \\ &\quad = \; Total \, n° \, of \, actuators \, needed \, in \, one \, office \, floor \cdot N° \, floors \end{aligned}$$

The investment necessary for this big purchase has been calculated according to the reference price of their catalogue. We consider 400 € as market price for this controller/actuator.

$$Total \, Actuators \, Cost \; = \; N° \, Actuators \cdot \; Unitary \, Cost \; = \; N° \, Actuators \cdot \; 400€/unit$$

$$Discounted \, Actuators \, Acquisition \, Cost \; = \; Total \, Actuators \, Cost \; \cdot \; (1 - Ec. Scale).$$

$$Actuators \, Installation \, Cost \; = \; 20\% \; \cdot \; Actuators \, Acquisition \, Cost$$

$$Actuators \, Period \, Cost \; = \; 3\% \; \cdot \; Actuators \, Acquisition \, Cost$$

Finally, we obtain the total initial investment needed for those types of components, which we calculate taking into account both installation and acquisition costs.

$$Total\ Initial\ Investment\ for\ Actuators = Discounted\ Actuators\ Acquisition\ Cost + Actuators\ Installation\ Cost$$

THERMOSTATS

Smart thermostats represent a potentially attractive short/mid-term measure to increase energy efficiency in residential buildings. Compared to energetic refurbishment or the replacement of an outdated heating system, the acquisition of a smart thermostat is a small-investment, low-effort measure with a potentially shorter payback time. It may be particularly appropriate for the energy-inefficient building stock.

This device is able to guarantee the right temperature in Heating and Cooling plants. It is equipped with room control functions for switching, dimming, room temperature control, manual or automatic ventilation control and scenario management.

Figure 5.7: Office Thermostat

Since it was decided to have one control point per each office, the number of thermostats was imposed equal to the number of offices, while it has been assumed to set and control the temperature of common areas and bathrooms from the central panel. People, even in a small office, can separately control the heating and cooling system to maximize comfort as well as reducing energy wastes.

$$N°\ Thermostats = N°\ Offices$$

After this assumption we can go straight to the costs' calculations:

$$Acquisition\ Cost\ for\ Thermostats = N°\ Thermostats \cdot Unitary\ Cost = N°\ Thermostats \cdot 200€/unit$$

$$Discounted\ Acquisition\ Cost\ Thermostats = Acquisition\ Cost\ for\ Thermostats \cdot (1 - Ec.Scale)$$

$$Thermostats\ Installation\ Cost = 20\% \cdot Acquisition\ Cost\ for\ Thermostats$$

$$Thermostats\ Period\ Cost = 3\% \cdot Acquisition\ Cost\ for\ Thermostats$$

$$Initial\ Investment\ for\ Thermostats = Discounted\ Thermostats\ Acquisition\ Cost + Thermostats\ Installation\ Cost$$

BMS SOFTWARE

A BMS is a piece of software whose role is to monitor and control a building's equipment. The equipment cited is used to manage loads, improve efficiency and reduce the energy needed to illuminate, heat and cool the building. A BMS interacts with controllers, sensors and actuators to monitor and modulate in real time the energy used.

What can BMS do?

1) Sets up lighting and HVAC systems to operate on an intelligent/efficient schedule.
2) Tells when HVAC is running both heating and cooling, to reduce utility costs.
3) Identifies who and when someone is entering and leaving a building (if combined with CCTV cameras)
4) Coordinates components and facilities to work together for greater efficiency.
5) Senses emergencies and turns off facilities that could endanger occupants (if combined with safety and security systems).

Why is it useful?

- Unique Interface
  The use of a BMS allows the management staff to keep the systems and equipment under control through a single software and a single interface.
- Consumption Optimization
  This is the most important characteristic for the model, in particular the use of a BMS allows the user to save on operating costs thanks to the ability to adjust the air conditioning and lighting by sector and by need, keeping peaks under control and avoiding unnecessary waste.
- Safety
  The use of a BMS allows to keep under control fire systems, intrusion alarms and energy overloads, offering the possibility to intervene promptly and avoid emergency situations that could cause damage to sensitive areas like server rooms. This functionality is not considered in our dissertation but is very important for what concerns the occupants' comfort.
- Keep track of events
  The use of a BMS allows the users to log every single event relating to the function of systems and equipment: the availability of data allows to plan interventions to obtain efficiency plans, eventually to apply predictive and preventive maintenance.

In this paragraph we want to show our reasoning for the cost estimation of this software component. First of all, we do not want to build it in house but rather we adopt a software as a service approach. We decided to include in our model the calculation of the BMS cost as an annual fee to have the possibility to update the software without the need of in-house developers. From market research we considered the costs taken from Schneider electric website which is about 200 €. Since there could be the possibility that each floor system is managed in a different way because of different occupants' companies, we consider one software license per floor.

$$BMS\ Costs\ =\ N^{\circ}\ of\ Offices\ Floors\ \cdot\ Unitary\ license\ costs$$

5.2.2 Smart Home Cost Computation

The residential part of the thesis is different from the previous paragraphs because it considers the whole IoT-based system and the calculation of all the costs is explained in this section.
For the smart home we consider:

- Presence & Motion Sensors
- Windows Opening/Closing sensors
- Automated TRVs
- Smart Socket & Smart Switch
- Smart Thermostat
- Gateway Zigbee

PRESENCE & MOTION SENSORS

We took a reference sensor from Bticino and to simplify the calculation to make it more general we decided to include only one sensor per room. The percentage period costs on the total acquisition costs were 3%.

Figure 5.8: Presence & Motion Sensor

Calculation of the number of sensors needed were as follows:

$$N° \; of \; sensors \; per \; house = N° \; of \; sensors \; per \; each \; room \cdot N° \; of \; rooms \; in \; one \; house$$
$$N° \; of \; sensors \; per \; floor = N° \; of \; sensors \; per \; house \cdot N° \; of \; houses \; in \; one \; floor$$
$$N° \; of \; sensors = Total \; n° \; of \; sensors \; per \; floor \cdot N° \; of \; residential \; floors$$

And the costs were calculated as in the other parts of the model:

$$Sensors \; Acquisition \; Cost = N° \; Sensors \cdot Unitary \; Cost = N° \; Sensors \cdot 22€/unit$$
$$Discounted \; Sensors \; Acquisition \; Cost = Total \; Sensors \; Cost \cdot (1 - Ec. Scale).$$
$$Sensors \; Installation \; Cost = 10\% \cdot Sensors \; Acquisition \; Cost$$
$$Sensors \; Period \; Cost = 3\% \cdot Sensors \; Acquisition \; Cost$$

With a final estimation of the investment of:

$$Initial \; Investment \; for \; Sensors$$
$$= Discounted \; Sensors \; Acquisition \; Cost + Sensors \; Installation \; Cost$$

WINDOWS OPENING/CLOSING SENSORS

The presence of these sensors is aimed at enabling controlling strategies for heating and cooling systems that save energy while windows or doors are open. Those sensors sense the situation and signal it through the system, which is able to switch off heating or cooling.
We take as a reference for the price information a sensor from Aqara.

Figure 5.9: Window Sensor

We decided to put one sensor per window and our basic assumption is that in houses we have one window per room. This means that:

$$N° \; of \; sensors \; per \; house = N° \; of \; windows \; per \; house \; = \; N° \; of \; rooms \; per \; house$$

Cost estimation starts from this point, in which we have:

$$N° \; of \; sensors \; needed \; per \; house = \; N° \; of \; sensors \; per \; room \cdot \; N° \; of \; rooms \; in \; one \; house = \\ = \; 1 \cdot \; N° \; of \; rooms \; in \; one \; house$$

$$N° \; of \; sensors \; needed \; per \; floor = \; N° \; of \; sensors \; per \; house \cdot \; N° \; of \; houses \; in \; one \; floor$$
$$N° \; of \; sensors \; needed = \; N° \; of \; sensors \; per \; floor \cdot \; N° \; of \; residential \; floors$$

Acquisition, installation and period costs were:

$$Sensors \; Acquisition \; Cost \; = \; N° \; Sensors \cdot \; Unitary \; Cost \; = \; N° \; Sensors \cdot \; 16€/unit$$
$$Discounted \; Sensors \; Acquisition \; Cost \; = \; Sensors \; Acquisition \; Cost \; \cdot \; (1 - Ec. Scale).$$
$$Sensors \; Installation \; Cost \; = \; 10\% \; \cdot \; Sensors \; Acquisition \; Cost$$
$$Sensors \; Period \; Cost \; = \; 3\% \; \cdot \; Sensors \; Acquisition \; Cost$$

With a final estimation of the investment of:

$$Total \; Initial \; Investment \; for \; Sensors \\ = Discounted \; Sensors \; Acquisition \; Cost \; + \; Sensors \; Installation \; Cost$$

AUTOMATED TRVS

Thermostatic Radiators Valves are programmable wireless digital devices that are screwed directly to the radiators, allowing the user to vary the flow of hot water according to the settings provided by the system or by the user. Furthermore, thanks to this type of valves it is not necessary to have temperature sensors in the individual rooms because the smart thermostatic valves use sensors that measure the heat of the environment in which they are located.

They allow the user to manage the heating system with extreme precision, optimizing its performance.

The control panel allows the user to save money, for example by heating only the bedrooms and decreasing the temperatures in the rest of the house, or by reducing the emission of heat during the day in unoccupied rooms. Using valves together with thermostats or the smartphone app, heating systems can be programmed based on daily habits, heating only when and where it is needed.

Figure 5.10: Netatmo Smart Valves

We choose as a reference Netatmo valves with a unitary price of 80 €.

To build an effective system one valve per radiator is needed. In our model we made the hypothesis of having one radiator that needs to be controlled per room. Therefore, the number of valves to install is proportionate to rooms.

$$N° \; of \; TRVs \; per \; house = N° \; of \; radiators \; per \; house \; = \; N° \; of \; rooms \; per \; house$$

Dimensioning formulas are:

$$Total \; n° \; of \; TRVs \; needed \; pe \; house = \; N° \; of \; TRVs \; per \; room \cdot \; N° \; of \; rooms \; in \; one \; house = \\ = \; 1 \cdot \; N° \; of \; rooms \; in \; one \; house$$

$$N° \; of \; TRVs \; needed \; per \; floor = \; N° \; of \; TRVs \; per \; house \cdot \; N° \; of \; houses \; in \; one \; floor$$

$$Total \; n° \; of \; TRVs = \; Total \; n° \; of \; TRVs \; per \; floor \cdot \; N° \; of \; residential \; floors$$

The three costs we always consider for making the model homogeneous change only considering the unitary price and period cost percentage:

$$Total \; TRVs \; Cost \; = \; N° \; TRVs \; * \; Unitary \; Cost \; = \; N° \; TRVs \; \cdot \; 80€/unit$$

$$Discounted \; Sensors \; Acquisition \; Cost \; = \; Total \; TRVs \; Cost \; \cdot \; (1 - Ec.Scale).$$

$$TRVs \; Installation \; Cost \; = \; 10\% \; \cdot \; TRVs \; Acquisition \; Cost$$

$$TRVs \; Period \; Cost \; = \; 1{,}5\% \; \cdot \; TRVs \; Acquisition \; Cost$$

The investment estimation is:

$$Total \; Initial \; Investment \; for \; TRVs \\ = \; Discounted \; TRVs \; Acquisition \; Cost \; + \; TRVs \; Installation \; Cost$$

SMART SOCKET & SMART SWITCH

We decided to show in the same paragraph how costs about those two items are calculated since the assumptions made are shared. Smart Sockets and switches are needed to make the lights and sockets manageable by routines, or a user interface that could be a smartphone. We decided to take as a reference items from Bticino and their market price is taken again from real catalogues.

Connected socket module
Connected to a power outlet, it allows the remote control of electrical devices and to control their consumption (instantaneous, daily, monthly). Price 35 €. Fig. 5.12.

Living Now Deviatore Connesso
It allows the user to control lights locally or remotely. It is installed like a traditional diverter and is compatible with all loads with a maximum power of 250 W. We considered a price of 30 €.
Fig. 5.11.

Figure 5.12: Connected Socket Module

Figure 5.11: Living Now Deviatore Connesso

To make the model less tied to single cases or contingencies, we decided to dimension these components by considering one socket and one switch per room. Therefore, their number is:

$$N°\ of\ Socket\ per\ house = N°\ of\ Switch\ per\ house\ =\ N°\ of\ rooms\ per\ house$$

We then estimate what are the quantities needed:

$$\begin{aligned} &Total\ n°\ of\ Sockets\ needed\ per\ house \\ &\quad =\ N°\ of\ Sockets\ per\ room \cdot\ N°\ of\ Sockets\ in\ one\ house = \\ &\quad =\ 1 *\ N°\ of\ rooms\ in\ one\ house \end{aligned}$$

$$Total\ n°\ of\ Sockets\ needed\ per\ floor =\ N°\ of\ Sockets\ per\ house \cdot N°\ of\ Sockets\ in\ one\ floor$$

$$Total\ n°\ of\ Sockets\ needed =\ Total\ n°\ of\ Sockets\ per\ floor \cdot\ N°\ of\ residential\ floors$$

The same calculation is done for Switches. What is changing is the estimation of costs, but only because unitary prices are not the same.
For Sockets we have:

$$Total\ Sockets\ Cost\ =\ N°\ Sockets\ \cdot\ Unitary\ Cost\ =\ N°\ Sockets\ \cdot\ 35€/unit$$

$$Discounted\ Sockets\ Acquisition\ Cost\ =\ Total\ Sockets\ Cost\ \cdot\ (1 - Ec.Scale).$$

$$Sockets\ Installation\ Cost\ =\ 10\%\ \cdot\ Sockets\ Acquisition\ Cost$$

$$Sockets\ Period\ Cost\ =\ 2\%\ \cdot\ Sockets\ Acquisition\ Cost$$

$$\begin{aligned} &Total\ Initial\ Investment\ for\ Sockets \\ &\quad =\ Discounted\ Sockets\ Acquisition\ Cost\ +\ Sockets\ Installation\ Cost \end{aligned}$$

For switches we have:

$$Total\ Switches\ Acquisition\ Cost\ =\ N°\ Switches\ \cdot\ Unitary\ Cost\ =\ N°\ Switches\ \cdot\ 30€/unit$$

$$Discounted\ Switches\ Acquisition\ Cost\ =\ Total\ Switches\ Cost\ \cdot\ (1 - Ec.Scale).$$

$$Switches\ Installation\ Cost\ =\ 10\%\ \cdot\ Switches\ Acquisition\ Cost$$
$$Switches\ Period\ Cost\ =\ 2\%\ \cdot\ Switches\ Acquisition\ Cost$$

$$Total\ Initial\ Investment\ for\ Switches$$
$$=\ Discounted\ Switches\ Acquisition\ Cost\ +\ Switches\ Installation\ Cost$$

SMART THERMOSTAT

This component allows the user to manage heating just from the fingertips: the user can easily set programs, intervene when he is away from home to adjust the thermostat and monitor consumptions. Thanks to the wi-fi connection it is equipped with, it can be programmed and controlled remotely.

Figure 5.13: Smart Thermostat

We chose Smarter2 with Netatmo as our reference because it is compatible with Netatmo smart thermostatic valves already described to set the desired temperature in each room.

Thermostats are a necessary and fundamental part of the smart home system but one per house is enough with a unitary price taken from the market of 180 €.

$$N°\ of\ Thermostats\ needed\ per\ floor = \ N°\ of\ Thermostats\ per\ house\ \cdot$$
$$N°\ of\ Houses\ in\ one\ floor$$
$$N°\ of\ Thermostats\ needed = \ N°\ of\ Thermostats\ per\ floor\ \cdot\ N°\ of\ residential\ floors$$

Cost calculation formulas for thermostats is:

$$Thermostats\ Acquisition\ Cost\ =\ N°\ Thermostats\ \cdot\ Unitary\ Cost$$
$$=\ N°\ Thrmostats \cdot 180\ €/unit$$
$$Discounted\ Thermostats\ Acquisition\ Cost$$
$$=\ Thermostats\ Acquisition\ Cost\ \cdot\ (1 - Ec.Scale).$$
$$Thermostats\ Installation\ Cost\ =\ 10\%\ \cdot\ Thermostats\ Acquisition\ Cost$$
$$Thermostats\ Period\ Cost\ =\ 4\%\ \cdot\ Thermostats\ Acquisition\ Cost$$

Final investment for this technology:

$$Total\ Initial\ Investment\ for\ Thermostats$$
$$=\ Discounted\ Thermostats\ Acquisition\ Cost$$
$$+\ Thermostats\ Installation\ Cost$$

GATEWAY ZIGBEE

To complete the system each home needs a gateway to manage all the radio communications between the devices in the house as well as the interaction with the internet and the cloud.
It has been chosen "Living Now Gateway" by Bticino, with a unitary cost of 115 €. Percentage period costs can be considered 3 %.
This Hub connects on one side to the main home network (Wi-Fi, meaning to the router) and on the other hand it connects to the peripherals through the Zigbee home automation protocol. According to the definition of gateway it should be installed one per house.

Figure 5.14: Zigbee Gateway

$$N° \; of \; Gateways \; needed \; per \; floor = N° \; of \; Gateways \; per \; house \cdot N° \; of \; Houses \; in \; one \; floor$$
$$N° \; of \; Gateways \; needed = N° \; of \; Gateways \; per \; floor \cdot N° \; of \; residential \; floors$$

$$Gateways \; Acquisition \; Cost = N° \; Gateways \cdot Unitary \; Cost = N° \; Gateways \cdot 115 \; €/unit$$
$$Discounted \; Gateways \; Acquisition \; Cost = Total \; Gateways \; Cost \cdot (1 - Ec.Scale).$$
$$Gateways \; Installation \; Cost = 10\% \cdot Gateways \; Acquisition \; Cost$$
$$Gateways \; Period \; Cost = 3\% \cdot Gateways \; Acquisition \; Cost$$

$$Total \; Initial \; Investment \; for \; Gateways = Discounted \; Gateways \; Acquisition \; Cost + Gateways \; Installation \; Cost$$

5.3 Benefits Calculation

According to the purpose of our model that wants to be general and cover a lot of different cases we do not calculate the benefits according to a single specific case, but rather we rely on pre-existing cases analysed in scientific papers to understand the benefits achievable. Our approach is simple: we calculate the actual consumption levels and then we estimate savings basing our reasoning on numerous paper outcomes of worldwide researchers.
This part addresses our way of reasoning and tries to define a likely outcome. We divide this in two paragraphs: one for the offices part and the second for the residential section of the model. The first part includes both Professional Offices and Open Space Office which share Lighting System benefits.
In each of the two parts benefits regarding lighting and benefits regarding HVAC/heating are calculated.

The model was developed to highlight the IoT related costs and benefits generated by building renovation projects for a smart building with respect to a case where no IoT solutions are installed.
Our goal is to combine multiple IoT-related technologies and strategies in the system to increase energy efficiency and improve lighting and heating performance without compromising on user satisfaction. Even if in this thesis we consider only economic benefits, potential benefits are even more than the simple consumption reduction. We can consider for instance, a decreased environmental impact, enhanced comfort standards or even new services enabled by IoT data.
We already talk about costs, now we want to show the formulas we intended to adopt to estimate benefits.

5.3.1 Offices Benefits Calculation

From a large quantity of paper analysed we can say that the potentialities of IoT energy savings technologies and techniques are far from being exploited. For instance, in Roth et al. (2005) the authors try to explain that sensors and controls continue to decline in cost and are relatively easy to install in building retrofit projects. With only these simple components the building automation system can reduce building energy consumption by 20–30% in small and medium commercial buildings if managed by a building management software.
In the following paragraphs we are going to estimate the potential benefit in Offices, but one important thing to underline is that there is much more than only energy savings.
We can say that consumer awareness of energy efficiency is a growing trend. Therefore, potential renters and buyers can base their decisions about leasing or buying buildings on energy efficiency and energy costs data or building energy performance. In order to strengthen the concept, we propose a survey carried out by Johnson Controls in 2016. The 2016 Energy Efficiency Indicator Survey queried more than 1.200 facility management executives on key drivers for investing in energy efficiency in their buildings. Two-thirds indicated that increasing their company brand reputation and attracting new tenants were substantial investment drivers. So, there is also a driver regarding the added value of Smart Building to leasing and sales and even the fact that owners of smart buildings can satisfy tenant expectations for flexible workspaces and autonomous control.
Moreover, the “Energy & Strategy Group” of “Politecnico di Milano” studied that the interest in the Smart Building concept was initially driven by environmental reasons, but now it is more about economical purposes. (Chiesa et al., 2020). They reported the estimates of the Global Real Estate Sustainability Benchmark (2020) that claims that the benefits deriving from redevelopment interventions in a Smart Building are quantified in:

- Increase in the value of the property between 2% and 17%
- Increase in the occupancy rate of spaces between 9% and 18%

- Increase in the value of rental contracts between 8% and 35%
- 30% operational & maintenance cost reduction

In the next pages we report our reasoning in order to understand what the benefits for a similar installation in terms of percentage on consumption values could be. At the end we consider 55% of savings for the lighting system and 30% for HVAC. The same reasoning is also valid for open space floors with 55% savings for lighting systems and 10% for HVAC.

Lighting System

In the benefits calculation of the lighting systems for offices we consider some contributions to the research environment. In Martirano et al. (2021) the authors measure savings of more than 70% with the adoption of LED modules coupled with advanced control systems. The advanced strategies considered were:

- Zoning: zoning of the environments to be illuminated in order to guarantee optimal levels of light performance taking into account the actual intended use.
- Occupancy: switch-on based on the actual presence of people inside the room (room occupancy) or in the work area considered (occupancy area).
- Metering: measurement of the energy commitments of the lighting system differentiated by room or building area.

The percentage savings obtained were high and even unbelievable for someone who does not really grasp the role of these technologies. It isn't the only paper that has obtained such values, Bannamas et al. (2016) has recorded a maximum of 68% savings when are applied to the base case the following functions together with luminance that can be dimmed to five levels:

- Occupancy Control
- Time Scheduling
- Daylight Control
- Task Control
- Variable Power shredding

The paper deals also with other cases and different strategies but, even in the simpler case only with movement sensors it can be obtained 12% of energy savings. One other important case for understanding how much saving can be reached with our setup is the Case 6 described in the paper, in which the base case is equipped with Daylight Control and dimmable LEDs to obtain a 45% electricity reduction.

From the paper Hughes et al. (2008) we can say that similar advantages also exist in Open Spaces offices.

It investigated the benefit of a system which has installed sensors and actuators to monitor lights as well as to adaptively modify lighting systems in accordance to individual occupants comfort. "*With a similar scenario, i.e., an open space office building, this adaptive lighting installation strategy when compared to static light control systems can achieve between 42 % and 69 % in terms of energy savings*" (Hughes et al., 2008).

Here we provide a table of the main references used for computing benefits of the lighting system with the related strategies implemented and the corresponding savings measured in real cases.

Paper	Percentage Savings		Strategies
	From	To	
Bannamas, S., *An Intelligent Lighting Energy Management System for Commercial and Residential Buildings*, 2016	45%	68%	Dimmable Lights + Occupancy Detection + Daylight Control
Jennings, J.D., et al., *Comparison of control options in private offices in an advanced lighting controls testbed*, 2000	46%		Occupancy Detection + Daylight Control
Nagy, Z., et al., *Occupant centered lighting control for comfort and energy efficient building operation*, 2015	38%	73%	Occupancy Detection + Daylight Control
Hughes, R.F., et al., *Substantial energy savings through adaptive lighting*, 2008	42%	69%	Adaptive lighting installation
Roisin, B., et al., *Lighting energy savings in offices using different control systems and their real consumption*, 2008	49%	63%	Occupancy Detection + Daylight Control
Tan, Y. K. et al., *Smart personal sensor network control for energy saving in dc grid powered led lighting system*, 2013	44%		Occupancy Detection + Daylight Control + Scheduling
Martirano, L., et al., *High efficiency lighting systems with advanced controls*, 2021	70%		Oversizing + Zoning + Occupancy Detection + Metering

Table 5.2: Lighting Percentage Savings

The strategy to be applied strictly depends on the user habits, therefore on the type of office we are referring to. Moreover, daylight control and possible savings are tied to the exposure of the building, how the different zones are placed inside the building. We do not want to propose the best possible solution for the building (with maximum percentages) because our model wants to be general, and these strategies depend on the contingencies. For these reasons we decided to calculate benefits as an average of all these real measured contributions, obtaining a value of 55%.
To transform this percentage into kWh saved and money saved we use the following formulas:

$$\begin{aligned} Electricity\ saved\ due\ to\ lighting\ (kWh) &= Energy\ Consumption\ due\ to\ lighting \cdot Percentage\ Savings \\ &= Energy\ Consumption\ due\ to\ lighting \cdot 55\% \end{aligned}$$

$$\begin{aligned} &Monetary\ Savings\ due\ to\ lighting\ (€) \\ &\quad = Energy\ Savings\ due\ to\ lighting\ (kWh) \cdot Electricity\ Costs\ (€/kWh) \end{aligned}$$

Heating System

Our setup is aimed at transforming the system into a BMS (Building Management System) that controls heating and cooling systems. It "Smartens" the HVAC system: in this modern configuration the systems not only sense the environmental conditions, but also control the single zone environmental settings. These controls include setting the setpoints for each zone (the temperature that the HVAC should meet) and the command state for each zone (whether the HVAC should be on or off). In order to obtain

tangible and consistent results a smart building must be able to access these controls in order to actuate the HVAC.
In the paper Weng et al. (2012), the authors set up HVAC control settings per zone based on if the room is occupied or not (having occupancy as an input from sensors) and then measure the savings obtained: "*in terms of electricity, our HVAC control scheme saved a significant 11.59%, despite only controlling one floor in a four-story building. We also note that the thermal load consumption was less than the baseline as well, saving 12.41% in thermal cooling loads and 9.59% in thermal heating loads. We estimate savings in excess of 30% if our system is deployed across the entire building*" (Weng et al., 2012).

Numerous publications have demonstrated that it is possible to leverage the occupancy information of a building to lower its energy consumption. For instance, in Sala (2016) the authors extensively deal with the problem, and they also cite Yang et al. (2016), that brings some percentage HVAC energy savings: "*around 30% energy savings could be achieved in HVAC cooling by using an occupancy controlled thermostat that switches the temperature set point to a higher threshold for the unoccupied zones*" (Sala et al., 2016).

Moreover, in 2011 the New Building Institute in America proposed a study analysing the results of existing buildings retrofit interventions obtaining average energy savings of 30% from the implementation of two or more energy efficiency measures.
Other contributions like Nguyen (2013) found a range of energy savings for smart heating systems of 10% - 42% (this study relies on simulations).

To calculate benefits related to the HVAC system we decide to take 30% as an average savings for our HVAC system in the Professional Office Part. Open Space Offices were treated in the same way but the considered saving factor was set up at 10 % as a very conservative value (the lowest boundary of the benefit ranges we found in the paper analysed) because of the space setting with little differences from traditional offices, where all the previous papers evaluate their solutions.

$$Energy\ saved\ due\ to\ HVAC\ (kWh) = Energy\ Consumption\ due\ to\ HVAC \cdot Percentage\ Savings$$

$$Monetary\ Savings\ due\ to\ HVAC\ (€) = Energy\ saved\ due\ to\ HVAC\ (kWh) \cdot Methane\ Gas\ Costs\ (€/kWh)$$

Contrary to the lighting system, the HVAC calculations for Professional Offices and Open Space Office varied because of the different savings percentage, as we just mentioned.

5.3.2 Benefits Calculation Smart Home

We have already stated about the differences between Residential and Offices. What should be underlined is that homes have a centralized heating system that exploits a vertical riser boiler. Having such a starting system the potentialities for introducing energy efficiency are high and also in terms of comfort the space for improvement is large. A simple intervention to improve the system is to act on the water flow control of the radiators, that is why we equipped them with automated thermostatic valves. Controlling the valves separately means controlling each radiator separately and therefore each room according to the occupants' needs.

In the following lines we want to address the economic benefits that are calculated as in the previous paragraphs, considering average savings coming from the existing literature, in a similar setup. The energetic and monetary savings in absolute terms are then calculated based on the actual consumption levels. Undoubtedly, each building achieves a different level of energy savings depending on its size and on the total number of stories and its exposure. Considering the single homes, top and ground floors have higher heating energy needs than the middle floors mostly because they face unconditioned zones like the outdoors. For these reasons we considered averages in order to not add too many details and specific contingencies on a wide-ranging model.

The approach adopted for the benefit calculation of smart homes is a bit different with respect to offices. We started from understanding the percentage benefits of applying a smart home installation in a retrofitting intervention and we analysed different papers. Then we tried to divide them into lighting and heating to apply the respective costs per kWh, like in offices.

In the first point of our approach, we look at Skvortsova (2019), which concludes with: "*The study revealed that the savings from the use of technology "smart home" in the house saves about 35%".* The paper estimates savings in an upgrading intervention of a 200 square meters house with a system of ABB i-Bus KNX. Data were recorded before and after the installation to calculate the savings. The paper is also useful to have a comparison of the costs for the smart home equipment which are about 2000 € and includes thermostats, motion sensors, window sensors and control sensors. The authors then provide also their definition of what should be a smart home: "*Smart Home is a single system, as if united into one common organism*" (Skvortsova, 2019).

Two important contributions were taken from Rehm (2018). In the paper it is reported the research study "SmartHome Rösrath", it is a field test that investigates the use of smart home technology to increase energy efficiency.
The first outcome considered is in the introduction where the authors, according to a review of the existing papers claims: "*According to different suppliers of Smart Home systems, energy savings of up to 40 % may be achieved (depending on the users´ profiles)"*(Rehm, 2018).
We also examined the first results of the study: "*energy shall be saved by better heating controls plus a higher awareness for the energy usage, which influences the prospective energy consumption – savings of up to 30% were noted"*(Rehm, 2018).

Not only benefits related to the entire smart home installation but also contributions regarding heating. According to Gluck et al. (2017), the adoption of a predictive strategy enabled by the smart thermostats and other smart home components can make savings of 10%-25% in comparison with a static strategy.

In calculating the benefits of the new heating setup, we estimate the savings considering some contributions to the research field of both smart thermostat's application and smart valves application.
Firstly, we investigated the declaration of the Smart Thermostats producer which are the ones better able to explain how much can be saved using their products.
As smart thermostats we consider:

1) Nest Learning Thermostat
   In the whitepaper *Energy Savings from the Nest Learning Thermostat: Energy Bill Analysis Results* from NEST labs of 2015 three different studies were conducted on how much energy could be saved by using Nest learning thermostats. The results of the studies were similar, showing equal to about 10%-12% of heating usage and electricity savings equal to about 15% of cooling usage in homes with central air conditioning.

2) Ecobee3 Smart Thermostat
   As reported in Năsulea et al. (2016), Ecobee users in the U.S. saved up to 23% their cooling and heating costs, these data are obtained from an internal analysis conducted in 2013.
3) Honeywell Wi-Fi smart thermostat
   The thermostat saves about 8% of energy use for home space heating and 17% of energy use for home space cooling during a year according to Honeywell website.

Not only whitepapers but also research papers were considered, for instance in Schäuble et al. (2020), it is investigated the impact of the implementation of these devices in residential buildings in Germany. A model is built and applied to two typical home types: single family house and apartment. For the average single-family house, the smart thermostat system is a cost-effective introduction which brings savings of at least 5.7% with respect to the base case. For the average apartment instead, a reduction in consumption is reached with savings of at least 7.7%.
Moreover, in the paper it is also reported an analysis of the existing literature which can be summed up in: "*in further field studies with sample sizes of between 66 and 653 houses, average savings of between 4.5% and 12.5% were measured"*(Schäuble et al., 2020).
Papers considered were not only related to Thermostats but also to Smart Valves. We have taken as our point of reference the paper Fabrizio et al. (2017), in which they try to investigate what could be the economic benefit of having installed smart valves in buildings located in different areas. "The installation of smart heating systems with TRVs leads to energy savings in all locations. In Helsinki, the maximum expected energy savings is around 7%, while in Madrid energy savings can go up to 18%". They also consider a comprehensive study of 2014 about the application of TRVs on multifamily buildings quite old (built between 1950 and 1970) in Torino. The savings registered from this field study ranges between 5% to 22% according to Monetti et al. (2015).
Given all the papers, whitepapers and reports analysed we came up with our considerations. Using averages we can say that with a smart home complete installation like the one we provide, savings ranges from 6% to 35% of the total energy consumption, even more in cases with great inefficiencies as a starting point. In order to calculate monetary savings, we have split the value into electricity savings and heating savings. We considered 15% as the final value of percentage benefits on the initial heating consumption values, computing the average between the contributions with a major weight to TRVs savings paper. Consequently, we consider 20% as the savings for what concerns lighting systems. A real example of this percentage can be found in Bannamas (2016) where savings considering an occupancy-based lighting system are about 19%-23%.

The following formulas are useful to calculate economical savings:

$$Energy\ saved\ due\ to\ Heating\ System\ (kWh) = Heating\ System\ Energy\ Consumption \cdot Percentage\ Savings$$

$$Energy\ saved\ due\ to\ Heating\ System\ (kWh) = Heating\ System\ Energy\ Consumption \cdot 15\ \%$$

$$Monetary\ Savings\ due\ to\ Heating\ System\ (€) = Energy\ saved\ due\ to\ Heating\ System\ \ (kWh) \cdot Methane\ Gas\ Costs\ (€/kWh)$$

$$Electricity\ saved\ due\ to\ Lighting\ System\ (kWh) = Energy\ Consumption\ due\ to\ Lighting\ System \cdot Percentage\ Savings$$

$$Electricity\ saved\ due\ to\ Lighting\ System\ (kWh) = Energy\ Consumption\ due\ to\ Lighting\ System \cdot 20\%$$

$$Monetary\ Savings\ due\ to\ Lighting\ System\ (€) = Energy\ Savings\ due\ to\ Lighting\ System\ (kWh) \cdot Electricity\ Costs\ (€/kWh)$$

5.3.3 Consumption Calculation

Having the percentage savings, what is missing is the values of energy consumption to quantify savings in energy and monetary terms.
As all the other parts in our model we divided the estimations into two main parts that correspond to HVAC/heating and lighting. To calculate those, even if we want to make our model general we should start from real consumption monitoring of lots of buildings on the Italian and European territory. We rely on average values, for our model, to not be tied to the single case and peculiarities. We exploit the results of different studies from accredited and authoritative resources, which we talk about in the next lines.

Offices Consumption

For what concerns offices we rely on the main reference when talking about energetic consumption in Italy that is ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile). ENEA has proposed a study in partnership with Assoimmobiliare with the goal of providing real estate operators with reference benchmarks to critically evaluate the consumption of office buildings in Italy. The study is based on the real consumption of 123 energy diagnoses of office buildings located throughout the country. What is fundamental for us are the kWh/m^2y of energy consumption for heating, cooling and lighting, therefore, we use their final results as our main starting point (ENEA, 2019). Some energy usages were not present in all the buildings (e.g. company canteens, server farms), therefore, it was needed to study them separately, maintaining the homogeneity of data analysed.
Instead, considering the energy usages presents in all the buildings, they have been organized according to the three main energy utilities:

- Heating, Cooling and Ventilation
- FEM devices (they group together a varied series of office appliances)
- Lighting

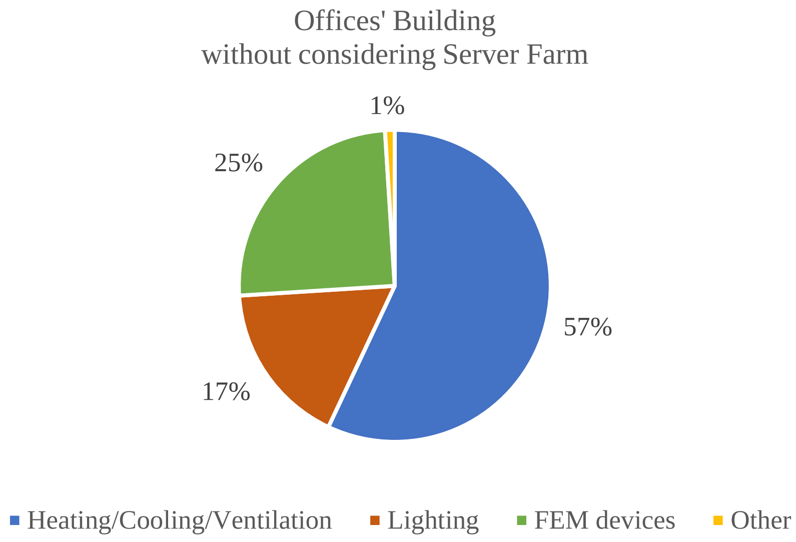


Figure 5.15: Percentage Energy Usage on the total in Offices (Source: ENEA)

They provide performance indexes, which are obtained by dividing consumptions by the declared surfaces.

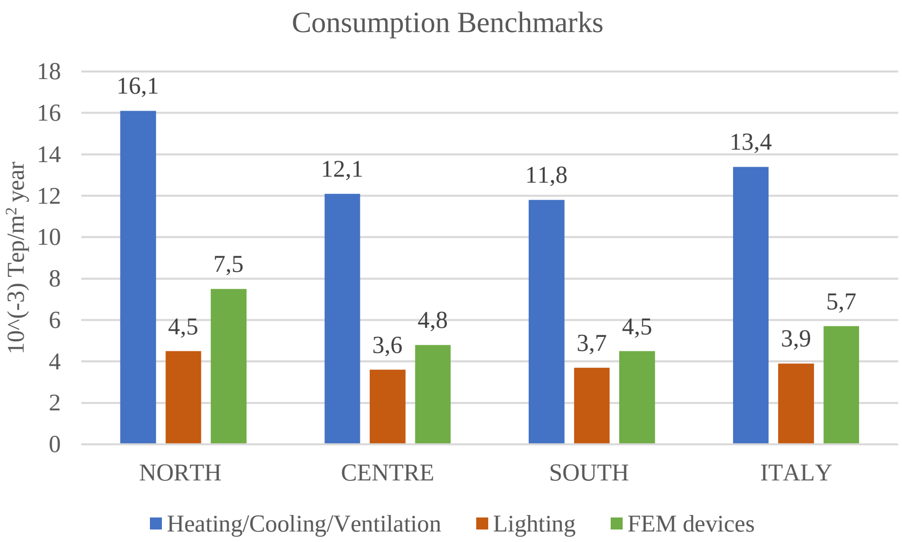


Figure 5.16: Energy Consumption in Offices according to the climatic region (Source: ENEA)

Indexes are given in 10^(-3) Tep/m^2 y which we should translate in kWh/m^2 y.
According to the conversion factor table provided by ENEA we are able to transform values in kWh.
We consider kWh/m^2 y = 10^(-3) Tep/m^2 y · 11,63 Tep/kWh

The values considered are:

Offices Consumption		
Type of Usage	**10^(-3) Tep/(m²y)**	**kWh/(m²y)**
Heating, Cooling and Ventilation	13,4	155,84
FEM Devices	5,7	66,29
Lighting	3,9	45,36

Table 5.3: Offices Energy Requirement per m² in Italy (Source: ENEA)

$$HVAC\ System\ Energy\ Consumption\ (kWh) = HVAC\ unitary\ consumption\ (kWh/(m2y)\ \cdot\ Offices\ floor\ space\ (m2)\ )$$

$$HVAC\ System\ Energy\ Consumption\ (kWh) = 155{,}84\ (kWh/(m2y)\ \cdot\ Offices\ floor\ space\ (m2)\ )$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = Lighting\ unitary\ consumption\ (kWh/(m2y) \cdot Offices\ \ floor\ space\ (m2)$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = 45{,}36\ (kWh/(m2y) \cdot Offices\ floor\ space\ (m2)$$

We considered the same consumption levels for both open space and professional types of offices.

Residential Consumption

We take as a reference the deliverable of BSRIA called: "*D2.1a Survey on the energy needs and architectural features of the EU building stock*" included in the project: "*Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems*". From this report we have taken the consumption values of residential buildings in Europe (EU-27), which considers an extensive research on the analysis of the consumption levels of EU-27 residential building stock. The data used are obtained by multiple sources from open-source literature combined with European level databases (Birchall et al., 2014). From this report we took this residential consumption summary table:

Residential Consumption	
Type of Usage	**kWh/(m²y)**
Heating	144
Cooling	50
Domestic Hot Water	21
Lightning	5

Table 5.4: Residential Energy Requirement per m² in Italy (Source: Birchall et al., 2014)

Thanks to the table, we are able to perform the calculation of the two main system we want to address in our model as:

$$Heating\ System\ Energy\ Consumption\ (kWh) = Heating\ unitary\ consumption\ (kWh/(m2y) \cdot Residential\ floor\ space\ (m2)\ )$$

$$Heating\ System\ Energy\ Consumption\ (kWh) = 144\ (kWh/(m2y) \cdot Residential\ floor\ space\ (m2)\ )$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = Lighting\ unitary\ consumption\ (kWh/(m2y) \cdot Residential\ floor\ space\ (m2)$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = 5\ (kWh/(m2y) \cdot Residential\ floor\ space\ (m2)$$

Chapter 6:
MODEL APPLICATION

The objective of this paragraph is to apply the model to a base case and compute the possible costs and benefits, with the calculation of a final payback time. The description of the building with its characteristics is the first step.

6.1 Building Description

We consider a building composed of 8 floors each of 500 m^2 of surface area, for a total area of 4000 m^2. The model is focused on multipurpose city buildings, in particular a building where IoT technologies have not been installed yet.
The floors have different usage destinations in particular:

- Ground and first floor: Open Space Offices
- Second and Third floor: Professional Offices
- Fourth, Fifth, Sixth and Seventh floor: Residential

Professional Offices floors are composed of multiple offices of different dimensions, in particular three different sizes according to the usage destination. We considered 8 offices of 15 m^2 that are used for managers, directors and single zones for business meetings, 2 bigger offices of 40 m^2, 2 conference rooms of 40 m^2 and a greater open office of 100 m^2 where all the desks for the employees are. Bath area extension is about 60 m^2 and it is composed of a 30 m^2 men's bathroom and a 30 m^2 women's bathroom. Inside each of them there are three WC zones and a wash basin area. To complete the floor there is also a 60 m^2 common area for relaxing, eating or taking a break.

Figure 6.1: Average Italian city building

For what concerns the Open Space Offices we consider in the first floors a large environment with no boundaries to divide the zones, which could also have separations, but the system is managed like one single zone. An example can be seen in the following images, thinking about the common working areas popular in tech companies.

Figure 6.2: Open Space Offices

The environment is considered as one single area of 440 m^2 with only the bath areas (equal to the one of professional offices floors) as separate zones.
The residential floor is also composed of different zones, which in this case are different sized apartments. We decided to consider in this part three dimensions: small, medium and big.

Type of Apartment	Surface m^2	N° of apartments per floor	N° of rooms per apartment
Small	85	2	6
Medium	120	1	8
Big	180	1	10
Stairs and Elevator	30	1	

Table 6.1: Residential floor structure

6.2 Cost Computation

The costs computation paragraph retraces the previous chapters in which formulas were explained and substitute into them the real numbers of our base case, to understand the total initial investment needed. This value together with period annual cost is used to estimate a payback time when also benefits are computed. As always, we divided the section into office and residential, considering in the first part both open space and professional offices. For what concerns the smart home part, we decided to make it more visual by introducing comparative tables to show clearly the differences between apartments type.
The most important thing to underline for the next paragraph is the estimation of the economies of scale in the acquisition costs. The percentage discount that providers usually make in case of big purchases. We consider 15% discount when huge orders are made, for instance in the case of LED lights and Sensors, while a lower percentage of 5% is considered for smaller batches, meaning in our case all the other components.

6.2.1 Offices

All the components installed in offices are described in the next lines, calculating their total costs after having defined the total quantity needed. Starting from the lighting system, we then analyse the HVAC requirement in the dedicated part.

LIGHTING SYSTEM

In the lighting system, the items included in the model are: ceiling LED Lights, Bathroom lights, DALI light sensors, Dimmer actuators and Venetian actuators.

CEILINGS LED LIGHTS

The estimation of the quantity of LED lights needed starts from the calculation of the required lumen which is equal to 1 lux/m2, as already stated the component we take as a reference has 4000 lumens with a unitary cost of around 100 €. The substitution of lights was necessary because we need dimmable lights to introduce daylight control strategies and reduce energy consumption.

$$Lumens\ for\ one\ Office\ =\ Lumens\ Required\ per\ m2\ \cdot\ Office\ Surface$$
$$=500\ lumen/\ m2\ \cdot Office\ Surface$$

$$N°\ LED\ lights\ in\ one\ Office = \frac{Lumens\ for\ one\ Office}{Lumen\ of\ one\ LED\ light} = \frac{Lumens\ for\ one\ Office}{4000\,\frac{lumen}{LED\ light}}$$

Type of Floor	Single Office m^2	Lumens for one Office	N° of LEDs in one Office
Professional Offices	15	7500	2
Professional Offices	40	20000	5
Professional Offices	100	50000	13
Professional Offices	60	30000	8
Open Space Office	440	220000	55

Table 6.2: Lumens and LED lights required in each office

We also considered in the table the Open Space entire floor which is the last row of the table because it can be considered as a unique huge environment.
We then came up with the number of ceiling LED lights needed in one office as:

$$N°\ LED\ lights\ per\ floor\ =\ N°\ LED\ lights\ in\ one\ Office\ \cdot\ N°\ Offices\ in\ the\ Floor$$

	Total N°LED lights per floor	N° of Floors
Professional Offices	57	2
Open Space Office	55	2

Table 6.3: LED Lights per floor

$$N°\ LED\ lights\ for\ all\ Offices\ =\ N°\ LED\ lights\ per\ floor\ \cdot\ N°\ floors\ in\ the\ building$$
$$N°\ LED\ lights\ for\ all\ Offices\ = 224\ LED\ Lights$$

Acquisition costs can be calculate as explained before considering 100 €/light as unitary costs

$$Acquisition\ Cost\ for\ LED\ Lights = \ Unitary\ LED\ Cost\ \cdot\ N°\ LED\ for\ the\ Building$$
$$= \ 100\ €/LED\ \cdot\ N°\ LED\ for\ the\ Building\ = \ 22400\ €$$

$$Discounted\ Acquisition\ Cost\ for\ LED\ Lights$$
$$= \ Acquisition\ Cost\ for\ LED\ Lights \cdot\ (1 - Ec. Scale)$$
$$= \ 22400\ €\ \cdot\ (1 - 15\%)\ = \ 19040\ €$$

To calculate the number of bath ceiling lights we should compute:

$$N°Baths\ LED\ Lights$$
$$= \ N°\ Bathrooms\ in\ one\ Floor\ \cdot\ N°\ Floors\ \cdot\ N°\ Subareas\ in\ Each\ Bathroom$$

Considering that each Bath Areas has 3 WC zones + 1 Wash basin we have 4 Subareas in each bathroom.

$$N°Baths\ LED\ Lights\ = \ 2\ \cdot\ 4\ \cdot\ 4\ = \ 32\ Bath\ LED\ lights$$

Acquisition costs are then calculated:

$$Acquisition\ Cost\ for\ Baths\ LED\ Lights = \ Unitary\ LED\ lights\ Cost\ \cdot\ N°Baths\ LED\ Lights$$
$$= \ 50\ €/LED\ \cdot\ 32\ Baths\ LED\ Lights\ = \ 1600€$$

$$Discounted\ Acquisition\ Cost\ for\ Baths\ LED\ Lights$$
$$= \ Acquisition\ Cost\ for\ Baths\ LED\ Lights \cdot\ (1 - Ec. Scale)$$
$$= 1600\ €\ \cdot\ (1 - 15\%)\ = \ 1360€$$

$$Total\ Acquisition\ Cost$$
$$= Acquisition\ Cost\ for\ Baths\ LED\ Lights\ + Acquisition\ Cost\ for\ LED\ Lights$$
$$= 1600\ €\ +\ 22400\ €\ = \ 24000€$$

$$Light\ Installation\ Cost\ = \ 20\%\ \cdot\ Total\ Acquisition\ Costs\ = \ 4800€$$
$$Light\ Period\ Cost\ = \ 2\%\ \cdot Total\ Acquisition\ Costs\ = \ 480\ €$$

$$Total\ initial\ Investment\ for\ Lights\ = Discounted\ Acquisition\ Cost\ for\ Baths\ LED\ Lights\ +$$
$$Discounted\ Acquisition\ Cost\ for\ Baths\ LED\ Lights\ + Light\ Installation\ Cost$$
$$= \ 19040\ €\ + 1360\ € + 4800\ € = 25200\ €$$

DALI LIGHT SENSORS

This sensor is useful to communicate with the DALI network and it represents an important part of the whole savings system. It is installed on the ceiling, and it covers the height of each story of the building of 3 meters with a diameter long enough to cover a square area of 8x8 meters. The number of sensors is defined by the following formula:

$$N° \; DALI \; Sensors \; in \; One \; Office = \frac{Office \; Area}{Area \; covered \; by \; one \; Sensor} =$$

Since the area covered is about a square of 64 m^2, one sensor is enough for the smaller offices like the 15 m^2 office and the 40 m^2 office. Considering the common areas that have a surface of 60 m^2 we decided to employ two sensors in order to also cover the areas with strange shapes.

For what concerns the Open Space Offices and the larger office of 100 m^2 other considerations should be made.

We consider that at maximum the 100 m^2 office could have a rectangular shape with sides of 5 m and 20 m therefore, with a ratio between the two sides of 1 to 4. With this kind of size, the needed sensors will be three, and they could cover the long side till 24 m. Over this measure we think that it is very difficult to find such a room because the short side will be less than 4 m.

A similar estimation is made for the entire open space floor. Here we have an area of 440 m^2 and if the floor has a square shape only 4 sensors will be needed. We should cover from particular shapes and therefore we consider the same sides ratio as before: 1 to 4. In this case the longer side will be approximately 42 m, and the shorter side will be 10,5 m. This is our worst case and we included in this scenario two lines of 5 sensors for a total of 10 sensors.

For the calculation of number of sensors per floor we have:

$$N° \; DALI \; Sensors \; in \; the \; Office \; Floor = N° \; DALI \; Sensors \; in \; One \; Office \cdot N° \; Offices \; in \; the \; Floor$$

$$N° \; DALI \; Sensors \; in \; the \; Floor \; for \; all \; Offices = N° \; DALI \; Sensors \; in \; One \; Office \cdot N° \; Offices \; in \; the \; Floor$$

After calculating the number of sensors for offices and common areas we can come up with a final number:

$$Total \; N° \; DALI \; Sensors \; per \; floor = (N° \; DALI \; Sensors \; in \; the \; Floor \; for \; all \; Offices + N° \; DALI \; Sensors \; in \; Common \; Areas \; in \; one \; Floor)$$

Here we have a table to sum up the results, considering that we do not install DALI sensors in baths.

Office type	100 m^2	40 m^2	15 m^2	60 m^2
Number of DALI sensors in one office	3	1	1	2
Number of Offices	1	4	8	1
Total number of DALI sensors for the type of office in one floor	3	4	8	2
Total number of DALI sensors in the office floor	**17**			

Table 6.4: DALI sensors computation

For the Open Space we have:

Open Space office	440 m^2
Total number of DALI sensors in the Open Space office	**10**

Table 6.5: N° of Multisensor in one Open Space Office

$$Total\ N°\ DALI\ Sensors = Total\ number\ of\ Multisensors\ in\ the\ Open\ Space\ office \cdot N°\ Open\ Space\ floors\ + $$
$$+Total\ number\ of\ Multisensors\ in\ the\ Professional\ Office \cdot N°\ Professional\ Offices\ \ floors\ = $$

$$Total\ N°\ DALI\ Sensors\ = 17\ sensors/floor \cdot 2\ floors + 10\ sensors/floor \cdot 2\ floors = 54\ Sensors$$

The three main type of costs are computed:

$$Acquisition\ Cost\ for\ DALI\ Sensors = Unitary\ Cost\ for\ DALI\ Sensors \cdot Total\ N°\ DALI\ Sensors$$

$$Acquisition\ Cost\ for\ DALI\ Sensors = 80€/Sensors \cdot 54\ Sensors = 4320\ €$$

$$Discounted\ Acquisition\ Cost\ DALI\ Sensors = Acquisition\ Cost\ DALI\ Sensors \cdot (1 - Ec.Scale)$$

$$Discounted\ Acquisition\ Cost\ DALI\ Sensors\ = 4320\ € \cdot (1 - 15\%) = 3672\ €$$

$$DALI\ Sensors\ Installation\ Cost = 20\% \cdot Acquisition\ Cost\ DALI\ Sensors$$

$$DALI\ Sensors\ Installation\ Cost = 20\% \cdot 4320\ € = 864\ €$$

$$Sensors\ Period\ Cost = 5\% \cdot Acquisition\ Cost\ DALI\ Sensors$$

$$Sensors\ Period\ Cost = 5\% \cdot 4320\ € = 216\ €$$

The initial investment required for this type of component is:

$$Initial\ Investment\ for\ DALI\ Sensors = Discounted\ Acquisition\ Cost\ DALI\ Sensors + DALI\ Sensors\ Installation\ Cost$$

$$Initial\ Investment\ for\ DALI\ Sensors\ = 3672\ € + 864\ € = 4536\ €$$

DIMMER ACTUATOR

In this case estimations are a bit more complex and as explained in the cost computation chapter, they depend on the following numbers:

- Max n° of input sensors per dimmer = 8
- Max n° of output lighting groups per dimmer = 8
- Max n° of lights connected = 64
- Unitary cost = 365 €
- Period cost Percentage = 3%

$$N°\ of\ Dimmer\ Actuators\ per\ floor\ (output) = RoundUp\left(\frac{Total\ n°\ of\ LED\ Lights\ per\ floor}{Max\ n°\ of\ LED\ Lights\ connected}\right)$$
$$= RoundUp\left(\frac{Total\ n°\ of\ LED\ Lights\ per\ floor}{64\ LED\ Lights/Dimmer}\right)$$

$$N°\ of\ Dimmer\ Actuators\ per\ floor\ (input)$$
$$= RoundUp\left(\frac{Total\ n°\ of\ Light\ Sensor\ per\ floor}{Max\ n°\ of\ input\ sensors\ per\ Dimmer}\right)$$
$$= RoundUp\left(\frac{Total\ n°\ of\ Light\ Sensor\ per\ floor}{8\ Light\ Sensor/Dimmer}\right)$$

$$N°\ of\ Dimmer\ Actuators\ per\ floor$$
$$= MAX\ (N°\ of\ Dimmer\ Actuators\ per\ floor\ (output);\ N°\ of\ Dimmer\ Actuators\ per\ floor\ (input))$$

Substituting the real numbers in the formulas we obtain the quantities that we show in this table:

	Total n° of sensors	**Total n° of LED lights**	**Minimum n° of Dimmer**	**RoundUp**
Open Space	10	55	1,25	2
Professional Offices	17	57	2,125	3

Table 6.6: N° of actuators computation

Considering all the floors dedicated to Offices we have:

$$N°\ of\ Dimmer\ Actuators = N°\ of\ Dimmer\ Actuators\ per\ floor \cdot N°\ of\ Floors$$

$$N°\ of\ Dimmer\ Actuators = 2\ actuator/floor \cdot 2\ floors + 3\ actuator/floor \cdot 2\ floors$$
$$= 10\ Dimmer\ Actuators$$

$$Acquisition\ Cost\ of\ Dimmer\ Actuators$$
$$= \ Unitary\ Dimmer\ Actuators\ Cost\ \cdot\ N°\ of\ Dimmer\ Actuators$$
$$=\ 365\ €/Dimmer\ *\ N°\ of\ Dimmer\ Actuators\ =\ 3650\ €$$

$$Discounted\ Acquisition\ Cost\ of\ Dimmer\ Actuators$$
$$=\ Acquisition\ Cost\ of\ Dimmer\ Actuators \cdot\ (1 - Ec. Scale)$$
$$=\ 3650\ €/Dimmer\ \cdot\ (1 - 5\%)\ =\ 3467{,}5\ €$$

$$Dimmer\ Actuators\ Installation\ Cost\ =\ 20\%\ \cdot\ Acquisition\ Cost\ of\ Dimmer\ Actuators$$
$$Dimmer\ Actuators\ Installation\ Cost\ =\ 20\%\ \cdot\ 3650\ €\ = 730\ €$$

$$Light\ Period\ Cost\ =\ 3\%\ \cdot\ Acquisition\ Cost\ of\ Dimmer\ Actuators$$
$$Light\ Period\ Cost\ =\ 3\%\ \cdot 3650\ €\ =\ 109{,}5\ €$$

Initial Investment can be found using this formula:

$$\begin{aligned} &Initial\ Investment\ for\ Dimmer\ Actuators \\ &\quad = Dimmer\ Actuators\ Installation\ Cost \\ &\quad + Discounted\ Acquisition\ Cost\ of\ Dimmer\ Actuators \end{aligned}$$
$$Initial\ Investment\ for\ Dimmer\ Actuators\ =\ 3467{,}5\ €\ + 730\ €\ = 4197{,}5\ €$$

VENETIAN ACTUATOR

In the estimation of the number of venetian actuators needed, we have to satisfy two constraints:

1) Connectable objects per one actuator = 249 Venetians
2) Max n° of groups to be controlled by one actuator = 4 Groups / Actuator

At the end it should be taken the maximum between these estimations.
For the first one the computation is relatively simple because can be done with this formula:

$$N°\ Venetians\ Actuators\ (Connectable\ Objects)\ = \frac{N°\ Venetians\ to\ Control}{Connectable\ Objects\ per\ one\ Actuator} =$$
$$= \frac{N°\ Venetians\ to\ Control}{249\ Devices/Actuator}$$

What is missing here is the number of windows in the floors, which are estimated like this:

$$Area\ of\ Windows\ for\ the\ Building\ =\ 1/8\ \cdot\ Building\ Surface$$
$$Area\ of\ Windows\ for\ the\ Building\ =\ 1/8\ \cdot\ 500 m2/floor\ \cdot 4\ office\ floors\ =\ 250\ m2$$

$$N°\ of\ Windows\ = \frac{Area\ of\ Windows\ for\ the\ Building}{Glass\ Area\ in\ one\ Window} =$$
$$= \frac{Area\ of\ Windows\ for\ the\ Building}{1{,}5\ m2} = \frac{250\ m2}{1{,}5\ m2} =\ 167\ windows$$

$$N°\ of\ Windows\ =\ N°\ Venetians\ to\ Control$$

$$N°\ Venetians\ Actuators\ (Connectable\ Objects)\ = \frac{167\ venetians}{249\ venetians/actuator} =\ 1$$

We made the hypothesis of having a square shape building with two different group of venetians per side of the building floor, consequently we have 8 groups of venetians groups per floor:

$$N°\ of\ Venetians\ Actuator\ (Groups) = RoundUp\ \left(\frac{Total\ n°\ of\ Venetians\ groups\ to\ control}{Max\ n°\ of\ Venetians\ groups\ controllable}\right)$$

$$= RoundUp\left(\frac{Total\ n° \ of\ Venetians\ groups\ to\ control}{4\ Groups/Actuator}\right)$$

$$= RoundUp\ (\frac{8\ Groups/floor\ *\ 4\ floor}{4\ Groups/Actuator})\ =\ 8\ Venetians\ Actuators$$

We have our final estimation for the number of Venetians Actuators needed that is:

$$N°\ of\ Venetians\ Actuators$$
$$= MAX\ (N°\ of\ Venetians\ Actuators\ (Connectable\ Objects);\ N°\ of\ Venetians\ Actuators\ (Groups))$$
$$N°\ of\ Venetians\ Actuators = 8$$

We can calculate the three types of costs needed for the final estimations:

$$Venetian\ Actuators\ Acquisition\ Cost\ =\ N°\ Venetians\ Actuators \cdot\ Unitary\ Cost\ =$$
$$= 8\ Actuators \cdot\ 352\ €/Actuator\ =\ 2816\ €$$

$$Discounted\ Venetian\ Actuators\ Acquisition\ Cost$$
$$=\ Venetian\ Actuators\ Acquisition\ Cost\ \cdot\ (1 - Ec.Scale)$$
$$Discounted\ Venetian\ Actuators\ Acquisition\ Cost\ =\ 2816\ €\ \cdot\ (1 - 5\%)\ =\ 2675{,}2\ €$$

$$Venetian\ Actuators\ Installation\ Cost\ =\ 20\%\ \cdot\ Venetian\ Actuators\ Acquisition\ Cost$$
$$Venetian\ Actuators\ Installation\ Cost\ =\ 20\%\ \cdot\ 2816\ €\ =\ 563{,}2\ €$$

$$Venetian\ Actuators\ Period\ Cost\ =\ 3\%\ \cdot\ Venetian\ Actuators\ Acquisition\ Cost$$
$$Venetian\ Actuators\ Period\ Cost\ =\ 3\%\ \cdot\ 2816\ €\ = 84{,}48\ €$$

For a total required initial investment of:

$$Initial\ Investment\ for\ Venetian\ Actuators$$
$$=\ Discounted\ Venetian\ Actuators\ Acquisition\ Cost$$
$$+\ Venetian\ Actuators\ Installation\ Cost.$$
$$Initial\ Investment\ for\ Venetian\ Actuators\ =\ 2675{,}2\ \ €\ +\ 281{,}6\ €\ \ =\ 3238{,}4\ €$$

WINDOW SENSORS

The quantity of window sensors to be installed is equal to the number of windows in order to exploit the benefits. We use the same calculation as before to estimate the windows. Down below formulas are reported.

$$Area\ of\ Windows\ for\ the\ Building\ =\ 1/8\ \cdot\ Building\ Surface$$
$$Area\ of\ Windows\ for\ the\ Building\ =\ 1/8\ \cdot\ 500m2/floor\ =\ 62{,}5\ m2/floor$$

$$N°\ of\ Windows\ =\ \frac{Area\ of\ Windows\ for\ the\ Building}{Glass\ Area\ in\ one\ Window}\ =$$
$$=\frac{Area\ of\ Windows\ for\ the\ Building}{1{,}5\ m2}\ =\ \frac{62{,}5\ m2}{1{,}5\ m2}\ =\ 42\ windows/floor$$
$$N°\ of\ Windows\ per\ floor =\ N°\ of\ Window\ Sensors\ per\ floor$$

$$N°\ of\ Window\ Sensors\ in\ the\ building =\ N°\ of\ Window\ Sensors\ in\ the\ floor\ \cdot N°\ floors$$
$$N°\ of\ Window\ Sensors\ in\ the\ building =\ 42\ sensors/floor\ *\ 4\ floors\ = 168\ sensors$$

The related costs are then computed:

$$Window\ Sensors\ Acquisition\ Cost\ =\ N°\ Window\ Sensors \cdot\ Unitary\ Cost\ =$$
$$= 168\ sensors \cdot\ 30\ €/unit\ = 5040\ €$$

$$Discounted\ Window\ Sensors\ Acquisition\ Cost$$
$$=\ Window\ Sensors\ Acquisition\ Cost\ \cdot\ (1 - Ec.Scale)$$
$$Discounted\ Window\ Sensors\ Acquisition\ Cost\ =\ 5040\ €\ \cdot\ (1 - 15\%)\ = 4284\ €$$

$$Window\ Sensors\ Installation\ Cost\ =\ 20\%\ \cdot\ Window\ Sensors\ Acquisition\ Cost$$
$$Window\ Sensors\ Installation\ Cost\ =\ 20\%\ \cdot\ 5040\ €\ =\ 1008\ €$$

$$Window\ Sensors\ Period\ Cost\ =\ 5\%\ \cdot\ Window\ Sensors\ Acquisition\ Cost$$
$$Window\ Sensors\ Period\ Cost\ =\ 5\%\ \cdot 5040\ =\ 252\ €$$

$$Initial\ Investment\ for\ Window\ Sensors$$
$$=\ Discounted\ Window\ Sensors\ Acquisition\ Cost$$
$$+\ Window\ Sensors\ Installation\ Cost.$$
$$Initial\ Investment\ for\ Venetian\ Actuators\ =\ 4284\ €\ +\ 1008\ €\ \ =\ 5292\ €$$

HVAC SYSTEM

The HVAC system is probably the most important one and the computation of costs related to it is very impacting on the overall investments and period costs. We reported below the application of the cost computation formulas for the IoT objects, needed to better control the HVAC systems.

MULTISENSOR

As stated in the cost computation we decided not to take a single reference here but rather a sort of market average because there were a lot of possibilities depending on the shape of the room to monitor. As a reference the price of 120 € was taken and we compute the quantities needed as in the case of the DALI sensor considering their covering as reference measure also for this type of sensor. Below the numbers:

Office type	100 m^2	40 m^2	15 m^2	60 m^2
Number of Multisensors in one office	3	1	1	2
Number of Offices	1	4	8	1
Total number of Multisensors for the type of office in one floor	3	4	8	2
Total number of Multisensors in the office floor	**17**			

Table 6.7: Multisensor computation

Open Space office	440 m^2
Total number of Multisensors in the Open Space office	**10**

Table 6.8: N° of Multisensor in one Open Space Office

Considering we have two floors of Open Space Offices and two floors of Professional Offices we have:

$$Total\ N°\ Multisensors\ = N°\ Multisensors\ in\ the\ Floor\ for\ all\ Offices \cdot N°\ Floors$$

$$Total\ N°\ Multisensors\ = 17\ units/floor\ \cdot 2\ floors\ +\ 10\ units\ /floor\ \cdot 2\ floors\ =\ 54\ units$$

After the dimensioning phase we can start calculating the costs:

$$Acquisition\ Cost\ for\ Multisensors\ =\ Unitary\ Cost\ for\ Multisensors\ \cdot\ Total\ N°\ Multisensors\ =\ 120€/unit\ \cdot\ 54\ €\ =\ 6480\ €$$

$$Discounted\ Acquisition\ Cost\ Multisensors\ =\ Acquisition\ Cost\ DALI\ Sensors\ \cdot\ (1-Ec.Scale)$$

$$Discounted\ Acquisition\ Cost\ Multisensors\ \ =\ 6480\ €\ \cdot\ (1-15\%)\ =\ 5508€$$

$$Multisensors\ Installation\ Cost\ =\ 20\%\ \cdot\ Acquisition\ Cost\ Multisensors$$

$$Multisensors\ Installation\ Cost\ =\ 20\%\ \cdot\ 6480€\ =\ 1296€$$

$$Multisensors\ Period\ Cost\ =\ 5\%\ \cdot\ Acquisition\ Cost\ Multisensors$$
$$Multisensors\ Period\ Cost\ =\ 5\%\ \cdot\ 6480€\ =\ 324€$$

The initial investment required for this type of component is finally calculated:

$$Initial\ Investment\ for\ Multisensors\ =\ Discounted\ Acquisition\ Cost\ Multisensors\ +\ Multisensors\ Installation\ Cost$$
$$Initial\ Investment\ for\ Multisensors\ =\ 5508€\ +\ 1296€\ = 6804\ €$$

HVAC ACTUATORS

The quantities of HVAC actuators, meaning the actuators for the fan coils is strictly dependent on the number of indoor units of the HVAC system. According to this statement the first thing to calculate is the number of indoor units. We started from the data of ENEA which provides power requirements for offices according to their dimensions.

m²	**kW HEATING**	**kW COOLING**
5	0,63	0,45
10	1,155	0,9
15	1,575	1,35
20	2,1	1,8
26	2,73	2,34
30	3,15	2,7
35	3,675	3,25
40	4,2	3,6
45	4,725	4,05
50	5,25	4,5

Table 6.9: ENEA Offices kW requirement per m²

Considering these values, we decided to calculate the requirement for our office types by making a proportion on the surface, obtaining:

	Office m²	**kW required for Heating**	**kW required for Cooling**
Professional Office	15	1,57	1,35
Professional Office	40	4,19	3,60
Professional Office	100	10,46	9,00
Open Space Office	440	46,04	39,61
Both	60	6,28	5,40

Table 6.10: Offices power requirement

In the table the offices of 60 m^2 are the common areas and the 440 m^2 office is the entire open space floor.

The next step is to estimate the number of indoor units based on the heating and cooling requirement. The indoor unit chosen as a reference is the 4-way cassette unit by Yanmar, it has 4 kW of maximum heating power and 3,6 kW in cooling power.

$$N° \ indoor \ units \ in \ one \ Office \ (Heating) = \frac{Heating \ kWh \ Required \ in \ one \ Office}{kWh \ Provided \ by \ the \ System} =$$

$$= \frac{Heating \ kWh \ Required \ in \ one \ Office}{4 \ kWh/Split}$$

$$N° \ indoor \ units \ in \ one \ Office \ (Cooling) = \frac{Cooling \ kWh \ Required \ in \ one \ Office}{kWh \ Provided \ by \ the \ System} =$$

$$= \frac{Cooling \ kWh \ Required \ in \ one \ Office}{3{,}6 \ kWh/Split}$$

$$N° \ indoor \ units \ in \ one \ Office = MAX(N° \ indoor \ units \ in \ one \ Office \ (Cooling); \ N° \ indoor \ units \ in \ one \ Office \ (Heating))$$

$$N° \ indoor \ units \ in \ Office \ floors = N° \ indoor \ units \ in \ one \ Office \cdot N° \ Offices \ in \ building$$

	Office m^2	kW required for Heating	kW required for Cooling	N° indoor units needed per office type
Professional Office	15	1,57	1,35	1
Professional Office	40	4,19	3,60	1
Professional Office	100	10,46	9,00	3
Open Space Office	440	46,04	39,61	12
Both	60	6,28	5,40	2

Table 6.11: N° of indoor units' computation

The number of indoor units in the bathrooms (60 m^2) is calculated as the common areas having the constraints of having at least one indoor unit in the male and one in the female bathroom. Therefore, the number of splits per bath area is 1, meaning 2 per floor.

$$Total \ N° \ of \ Splits \ per \ floor \ (Professional \ Offices) = N° \ indoor \ units \ (15 \ m2) \cdot N° \ offices \ (15 \ m2) + N° \ indoor \ units \ (40 \ m2) \cdot N° \ offices \ (15 \ m2) + N° \ indoor \ units \ (100m2) \cdot N° \ offices \ (100 \ m2) + N° \ indoor \ units \ (Common \ areas) \cdot N° \ Common \ areas + N° \ indoor \ units \ (bath \ area) \cdot N° \ bath \ area =$$

$$Total \ N° \ of \ Splits \ per \ floor \ (Professional \ Offices) = 1\frac{unit}{office} \cdot 8 \ offices + 1\frac{unit}{office} \cdot 4 \ offices + 3\frac{units}{office} \cdot 1 \ office + 2\frac{unit}{common \ area} \cdot 1 \ common \ areas + 2\frac{unit}{bath \ area} \cdot 1 \ bath \ area =$$

$$Total \ N° \ of \ Splits \ per \ floor \ (Professional \ Offices) = 19 \ unit/floor$$

$$Total\ N°\ of\ Splits\ per\ floor\ (Open\ Space\ Offices) = N°\ indoor\ units\ (440\ m2)\ + N°\ indoor\ units\ (bath\ area)\ \cdot N°\ bath\ area\ =$$

$$Total\ N°\ of\ Splits\ per\ floor\ (Open\ Space\ Offices) = 12\ units\ + 2\ unit/bath\ area\ \cdot 1\ bath\ areas\ =\ 14\ unit/floor$$

Having obtained the actual number of indoor units in the floors we can start the estimation for the actuators. The product acts as both controller and actuator and can be connected to a max number of 4 split per channel and a max number of 6 channels per actuator.
The formulas are as follows:

$$N°\ of\ channels\ needed\ in\ one\ Office\ = \frac{N°\ of\ indoor\ units\ in\ one\ office}{Max\ n°\ of\ units\ connected\ per\ channel} = \frac{N°\ of\ indoor\ units\ in\ one\ office}{4\ indoor\ units/channel}$$

OFFICE FLOOR	N° of offices	N° of indoor units per office	N° of channel needed in each office	Total n° of channel needed in the office floor
Number of offices of 100 m^2	1	3	1	1
Number of offices of 40 m^2	4	1	1	4
Number of offices of 15 m^2	8	1	1	8
Common Areas	1	2	1	1
Bathrooms	1	2	1	1

Table 6.12: Computation of the needed actuators' channels (one Professional Office floor)

OPEN SPACE OFFICE	N° of offices	N° of indoor units per office	N° of channel needed in each office	Total n° of channel needed in the office floor
Open Space	1	12	3	3
Bathrooms	1	2	1	1

Table 6.13: Computation of the needed actuators' channels (one Open Space Office floor)

$$Total\ n°\ of\ channels\ needed\ in\ one\ office\ floor = N°\ of\ channels\ needed\ in\ one\ Office\ \cdot\ N°\ of\ Offices$$

$$Total\ n°\ of\ actuators\ needed\ in\ one\ office\ floor = \frac{Total\ n°\ of\ channels\ needed\ in\ one\ office\ floor}{Max\ n°\ of\ channels\ per\ actuator} = \frac{Total\ n°\ of\ channels\ needed\ in\ one\ office\ floor}{6\ Channel/Actuator}$$

	Professional Office	Open Space Office
Total n° of channels	**15**	**4**
Total n° of actuators	**3**	**1**

Table 6.14: N° of actuators and actuators' channels per floor

$$Total\ n°\ of\ actuators\ needed = Total\ n°\ of\ actuators\ needed\ in\ one\ office\ floor \cdot N°\ floors$$

$$Total\ n°\ of\ actuators\ needed = 3\ Actuators/floor \cdot 2\ floors + 1\ Actuators/floor \cdot 2\ floors = 8\ Actuators$$

The investment necessary has been calculated according to the reference price of the ABB catalogue, we consider 400 € as market price for this controller/actuator.

$$Total\ Actuators\ Acquisition\ Cost = N°\ Actuators \cdot Unitary\ Cost = N°\ Actuators \cdot 400€/unit$$

$$Total\ Actuators\ Acquisition\ Cost = 8\ Actuators \cdot 400\ €/unit = 3200\ €$$

$$Discounted\ Actuators\ Acquisition\ Cost = Total\ Actuators\ Cost \cdot (1 - Ec.Scale)$$

$$Discounted\ Actuators\ Acquisition\ Cost = 3200\ € \cdot (1 - 5\%) = 3040\ €$$

$$Actuators\ Installation\ Cost = 20\% \cdot Actuators\ Acquisition\ Cost$$

$$Actuators\ Installation\ Cost = 20\% \cdot 3200\ € = 640€$$

$$Actuators\ Period\ Cost = 3\% \cdot Actuators\ Acquisition\ Cost$$

$$Actuators\ Period\ Cost = 3\% \cdot 3200\ € = 96\ €$$

$$Total\ Initial\ Investment\ for\ Actuators = Discounted\ Actuators\ Acquisition\ Cost + Actuators\ Installation\ Cost$$

$$Total\ Initial\ Investment\ for\ Actuators = 3040\ € + 640\ € = 3680€$$

THERMOSTATS

Formulas for thermostats are a bit quicker because it was decided to include one control point per each office, meaning that the number of thermostats was imposed equal to the number of offices. It has also been assumed to control the temperature of common areas and bathrooms from the central panel.

$$N° \, Thermostats = N° \, Offices$$

	Office type	N° of offices	N° of Thermostats
Professional Offices	100 m^2	1	1
Professional Offices	40 m^2	4	4
Professional Offices	15 m^2	8	8
Open Space Office	440 m^2	1	1

Table 6.15: N° of Thermostats per floor

The total number of thermostats per floor is:

$$N° \, of \, thermostats \, per \, floor \, (Professional \, Offices) = 1 \, unit + 4 \, units + 8 \, units = 13 \, Thermostats$$

$$N° \, of \, thermostats \, per \, floor \, (Open \, Space \, Offices) = 1 \, Thermostat$$

$$Total \, n° \, of \, thermostats = 13 \, units/floor \cdot 2 \, floors + 1 \, unit/floor \cdot 2 \, floors = 28 \, Thermostats$$

The costs for this component are then calculated:

$$Acquisition \, Cost \, for \, Thermostats = N° \, Thermostats \cdot Unitary \, Cost = 28 \, Thermostats \cdot 200€/unit = 5600 \, €$$

$$Discounted \, Acquisition \, Cost \, Thermostats = Acquisition \, Cost \, for \, Thermostats \cdot (1 - Ec. Scale)$$

$$Discounted \, Acquisition \, Cost \, Thermostats = 5600 \, € \cdot (1 - 5\%) = 5320 \, €$$

$$Thermostats \, Installation \, Cost = 20\% \cdot Acquisition \, Cost \, for \, Thermostats$$

$$Thermostats \, Installation \, Cost = 20\% \cdot 5600 \, € = 1120€$$

$$Thermostats \, Period \, Cost = 4\% \cdot Acquisition \, Cost \, for \, Thermostats$$

$$Thermostats \, Period \, Cost = 4\% \cdot 5600 \, € = 224 \, €$$

$$Total \, initial \, Investment \, for \, Thermostats = Discounted \, Thermostats \, Acquisition \, Cost + Thermostats \, Installation \, Cost$$

$$Total \, initial \, Investment \, for \, Thermostats = 5320 \, € + 1120€ = 6440€$$

BMS SOFTWARE

In the costs computation for offices what is missing is the software, with control panel and user interface.
The cost computation is related to the yearly cost of the software which is equal to 200 € per user. Considering one different user per floor we need 4 licenses. The software is used by the facility manager of the office which has the responsibility of setting parameters.

$$BMS\ Costs\ =\ N°\ of\ Offices\ Floors\ \cdot\ Unitary\ license\ costs$$
$$BMS\ Costs\ =\ 4\ floors\ \cdot\ 200\,€/floor\ =\ 800\,€/year$$

There is not an initial investment, but it is taken as a software as a service. Only an annual cost should be paid in order to exploit its functionalities.

6.2.2 Smart Home

The application of the model is divided into two parts, we already deal with the office one, the focus now is on the residential parts. The calculations were similar in terms of formulas with different ways of dimension pieces and different references. Moreover, we consider economies of scale as only one value that is 15% even if the quantities aren't high. This assumption has been done because a lot of the smart home components are taken from the same provider to build a coherent set of installations. As a consequence of this the bargaining power of the buyer has increased, which then he would be able to translate into a major discount effort by the provider.
All the components included in the smart home setup are summed up in the following table:

Components included in one Smart Home	Name of the piece	Cost per piece	Percentage Period Costs
Gateway Zigbee	Gateway Living Now BTIK4500C	115	3%
Presence e Motion sensor	Bticino	22	3%
Windows opening/closing Sensor	Door and Window Sensor	16	3%
Automated TRVs	Netatmo	80	1,50%
Smart Socket	Modulo per presa connesso	35	2%
Smart Thermostat	Bticino Smarther2 Netatmo	180	4%
Smart Switch	Living Now deviatore connesso	30	2%

Table 6.16: Smart Home components, unitary acquisition costs and percentage period costs

As already said some components are present as single pieces in houses while others should be quantified on the basis of the number of rooms. We define the number of Smart switches, Smart sockets and presence sensors as one per room in order to exploit the maximum benefits. For what concerns Smart Thermostats & the Zigbee Gateway we installed only one per apartment.
For the automated TRVs more considerations should be made. The number of valves strictly depends on the number of radiators, for simplicity we consider one radiator per room.

$$N°\ of\ rooms\ in\ an\ apartment\ =\ N°\ of\ radiators\ =\ N°\ of\ automated\ TRVs\ to\ be\ installed$$

For what concerns the number of window sensors, they have been installed per window. It has been considered one window per room.

$$N° \, of \, rooms \, in \, an \, apartment = N° \, of \, windows = N° \, of \, window \, sensors \, to \, be \, installed$$

For calculating costs, we use the following formulas and then insert the numbers of each component:

$$Total \ "Component" \ Cost = N° \, "Component" \cdot Unitary \, Cost$$

$$Discounted \, "Component" \, Acquisition \, Cost = Total \, "Component" \, Cost \cdot (1 - Ec.Scale).$$

$$"Component" \, Installation \, Cost = Percentage \, Installation \, costs \cdot "Component" \, Acquisition \, Cost$$

$$"Component" \, Period \, Cost = Percentage \, Period \, costs \cdot "Component" \, Acquisition \, Cost$$

The tables in the next part of the paragraph sums up all the costs and quantity for all the items in all the different types of apartments, we have:

Small Apartment (85 m^2): 6 rooms

Components included in one smart Home	**Number of pieces per small house**	**Total Acquisition Costs**	**Discounted Acquisition cost**	**Installation costs**	**Period costs**
Gateway Zigbee	1	115 €	97,75 €	11,5 €	3,45 €
Presence e Motion sensor	6	132 €	112,2 €	13,2 €	3,96 €
Windows opening/closing Sensor	6	96 €	81,6 €	9,6 €	2,88 €
Automated TRVs	6	480 €	408 €	48 €	7,2 €
Smart Socket	6	210 €	178,5 €	21 €	4,2 €
Smart Thermostat	1	180 €	153 €	18 €	7,2 €
Smart Switch	6	180 €	153 €	18 €	3,6 €
		Total Acquisition costs	**Discounted Acquisition Costs**	**Installation Costs**	**Period Costs**
		1393 €	**1184,05 €**	**139,3 €**	**32,49 €**

Table 6.17: Small Apartment costs calculation

Medium Apartment (120 m²): 8 rooms

Components included in one smart Home	Number of pieces per medium house	Total Acquisition Costs	Discounted acquisition cost	Installation costs	Period costs
Gateway Zigbee	1	115 €	97,75 €	11,5 €	3,45 €
Presence e Motion sensor	8	176 €	149,6 €	17,6 €	5,28 €
Windows opening/closing Sensor	8	128 €	108,8 €	12,8 €	3,84 €
Automated TRVs	8	640 €	544 €	64 €	9,6 €
Smart Socket	8	280 €	238 €	28 €	5,6 €
Smart Thermostat	1	180 €	153 €	18 €	7,2 €
Smart Switch	8	240 €	204 €	24 €	4,8 €
		Total acquisition costs	**Discounted Acquisition Costs**	**Installation Costs**	**Period Costs**
		1759 €	**1495,15 €**	**175,9 €**	**39,77 €**

Table 6.18: Medium apartment costs calculation

Big Apartment (180 m²): 10 rooms

Components included in one smart Home	Number of pieces per BIG house	Total Acquisition Costs	Discounted Acquisition Cost	Installation costs	Period costs
Gateway Zigbee	1	115 €	97,75 €	11,5 €	3,45 €
Presence e Motion sensor	10	220 €	187 €	22 €	6,6 €
Windows opening/closing Sensor	10	160 €	136 €	16 €	4,8 €
Automated TRVs	10	800 €	680 €	80 €	12 €
Smart Socket	10	350 €	297,5 €	35 €	7 €
Smart Thermostat	1	180 €	153 €	18 €	7,2 €
Smart Switch	10	300 €	255 €	30 €	6 €
		Total Acquisition Costs	**Discounted Acquisition Costs**	**Installation Costs**	**Period Costs**
		2125 €	**1806,25 €**	**212,5 €**	**47,05 €**

Table 6.19: Big apartment costs calculation

At the end we are able to estimate the initial investment and yearly period costs of the smart home components, considering that in one floor there are two small apartments, one medium and one big. As always, the initial investment is the sum of discounted acquisition costs and the installation costs.

$$\begin{aligned}&Initial\ Smart\ home\ investment\ per\ floor\\&\quad = Investment\ (small\ apart.) \cdot 2 + Investment\ (medium\ apart.)\\&\quad + Investment\ (big\ apart.)\end{aligned}$$

$$\begin{aligned}Initial\ Smart\ home\ investment\ per\ floor &= 1323{,}35\,€ \cdot 2 + 1671{,}05\,€ + 2018{,}75\,€\\&= 6336{,}5\,€\end{aligned}$$

$$Initial\ Smart\ home\ investment = Initial\ Smart\ home\ investment\ per\ floor \cdot N°\ of\ residential\ floors$$

$$Initial\ Smart\ home\ investment = 6336{,}5\ € \cdot 4 = 25346\ €$$

It is also important to have the total period costs per floor and by multiplying times the number of floors we can have the period cost for the residential part of the building.

$$Period\ cost\ per\ floor = Period\ cost\ (small\ apart.) \cdot 2 + Period\ cost\ (medium\ apart.) + Period\ cost\ (big\ apart.)$$

$$Period\ cost\ per\ floor = 32{,}49\ € \cdot 2 + 39{,}77\ € + 47{,}05\ € = 151{,}8\ €$$

$$Total\ Residential\ period\ costs = Period\ cost\ per\ floor \cdot N°\ of\ residential\ floors$$

$$Total\ Residential\ period\ costs = 151{,}8\ € \cdot 4 = 607{,}2\ €$$

6.3 Benefits Computation

In the following paragraphs it is described the application of the model to our case in terms of benefits or savings that could be enabled by IoT technologies.
We started by calculating the energy consumption and then by applying the percentage consumption reduction, we estimate the overall monetary and energetic savings.

6.3.1 Offices

As stated in the introduction the first item to be calculated is the office energy consumption in the AS-IS state. We exploit the table 5.3 presented in the paragraph 5.3.3.

Offices Consumption		
Type of Usage	**10^(-3) Tep/(m^{2}y)**	**kWh/(m^{2}y)**
Heating, Cooling and Ventilation	13,4	155,84
FEM Devices	3,9	45,36
Lighting	5,7	66,29

Table 6.20: Offices' kWh/m2 energy consumption

We take into consideration only the consumptions for lighting and HVAC systems. The office surface is about 4 floors of 500 m^2 each.

$$HVAC\ System\ Energy\ Consumption\ (kWh) = HVAC\ unitary\ consumption\ (kWh/(m2y) \cdot Offices\ floor\ space\ (m2)\ )$$

$$HVAC\ System\ Energy\ Consumption\ (kWh) = 155{,}84\ (kWh/(m2y) \cdot 4\ floors \cdot 500\ m2/floor = 311680\ kWh$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = Lighting\ unitary\ consumption\ (kWh/(m2y) \cdot Offices\ \ floor\ space\ (m2)$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = 45{,}36\ (kWh/(m2y) \cdot 4\ floors\ \cdot\ 500\ m2/floor\ = 90720\ kWh$$

Now we should divide the two professional office floors by the office floors because the percentage savings are different for the HVAC systems.

- Offices lighting savings = 55%
- HVAC savings (Professional Offices) = 30%
- HVAC savings (Open Space Offices) = 10%

Before entering into the table with the actual values, how we calculate unitary energy costs should be remarked.
We take data from the Eurostat website, which publishes all the statistics relating to the price of energy in the European Union. The value is composed of various elements related to the supply and demand situation, which varies with the change in the geopolitical situation, the national energy mix, diversification of imports, network costs, environmental protection costs, adverse weather conditions or levels of taxation and excise duties. From the tables they provide we consider the data of the last eight years computing the average.

Electricity Costs	€/kWh
Average (2013-2021)	0,2

Table 6.21: Unitary electricity cost (source: Eurostat website)

The same approach has been adopted for the calculation of the gas unitary price, performing our average function on the last twelve years. The only difference is that the unitary price is provided in €/Smc and should be translated into €/kWh. A standard cubic meter of methane gas (Smc) corresponds to 10.69 kWh according to multiple sources.

Methane Gas Cost	€/Smc	€/kWh
Average (2009-2021)	0,78	0,073

Table 6.22: Unitary methane gas cost (source: Eurostat website)

These values are used for both the office and residential monetary savings estimation.

Following the next formulas, we can come up with the energy saved as well as the monetary savings.

$$Energy\ saved\ due\ to\ Heating\ System\ (kWh) = Heating\ System\ Energy\ Consumption\ \cdot Percentage\ Savings$$

$$Monetary\ Savings\ due\ to\ Heating\ System\ (€) = Energy\ saved\ due\ to\ Heating\ System\ \ (kWh) \cdot Methane\ Gas\ Costs\ (€/kWh)$$

$$Electricity\ saved\ due\ to\ Lighting\ System\ (kWh) = Energy\ Consumption\ due\ to\ Lighting\ System \cdot Percentage\ Savings$$

$$Monetary\ Savings\ due\ to\ Lighting\ System\ (€) = Energy\ Savings\ due\ to\ Lighting\ System\ (kWh) \cdot Electricity\ Costs\ (€/kWh)$$

HVAC	Measure unit	Professional Offices	Open Space Offices
Total HVAC energy consumption	Kwh/y	155842	155842
HVAC percentage savings	%	30%	10%
Thermal energy consumption savings	**Kwh/y**	**46753**	**15584**
Monetary savings for HVAC	€/year	3411	1137

LIGHTING	Measure unit	Professional Offices	Open Space Offices
Total Electrical energy consumption	Kwh/year	45357	45357
Lighting percentage savings	%	55%	55%
KWH/y electrical energy saved for Lighting	**Kwh/year**	**24946**	**24946**
Monetary savings for lighting offices	€/year	4989	4989

Total monetary saving for offices	**€/year**	**8401**	**6126**

Table 6.23: Offices monetary savings calculation

Having the total monetary savings per each office we can now easily have the money saved by introducing IoT for the office part.

$$Total\ Monetary\ savings = Monetary\ savings\ (Prof.Off.) + Monetary\ savings\ (Open\ Space)$$

$$Total\ Monetary\ savings = 8401\,€/floor + 6126\,€/floor = 14527\,€$$

6.3.2 Smart Home

As for the office part we first have to estimate the consumption. The difference here is that in a smart home only the heating system is retrofitted while we do not include the cooling one. Therefore, from the table below we take only the heating and lighting values.

Residential Consumption	
Type of Usage	**kWh/(m^{2}y)**
Heating	144
Cooling	50
Domestic Hot Water	21
Lighting	5

Table 6.24: Residential kWh/m^2 energy consumption

Considering we have 4 floors of 470 m^2 each (30 m^2 are not touched by our interventions because are the stairs and elevator area), the computational formulas for savings are:

$$Heating\ System\ Energy\ Consumption\ (kWh) = Heating\ unitary\ consumption\ (kWh/(m2y) \cdot\ Residential\ floor\ space\ (m2)\ )$$

$$Heating\ System\ Energy\ Consumption\ (kWh) = 144\ (kWh/(m2y)\ \cdot\ 470\ m2/floor\ \cdot 4\ floors\ =\ 270720\ kWh/y$$

$$Energy\ Savings\ due\ to\ Heating\ System\ (€) = Heating\ System\ Energy\ Consumption\ (kWh) \cdot Percentage\ Savings\ Heating$$

$$Energy\ Savings\ due\ to\ Heating\ System\ (€) = 270720\ kWh/y\ \cdot 15\%\ = 40608\ kWh/y$$

$$Monetary\ Savings\ due\ to\ Heating\ System\ (€) = Energy\ saved\ due\ to\ Heating\ System\ \ (kWh) \cdot Methane\ Gas\ Costs\ (€/kWh)$$

$$Monetary\ Savings\ due\ to\ Heating\ System\ (€) = 40608\ kWh \cdot 0{,}073\ €/kWh\ = 2964{,}384\ €$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = Lighting\ unitary\ consumption\ (kWh/(m2y) \cdot Residential\ floor\ space\ (m2)$$

$$Energy\ Consumption\ due\ to\ Lighting\ System\ (kWh) = 5\ (kWh/(m2y) \cdot\ 470\ m2/floor\ \cdot 4\ floors\ =\ 9400\ kWh/y$$

$$Energy\ Savings\ due\ to\ Lighting\ System\ (€) = Lighting\ \ System\ Energy\ Consumption\ (kWh) \cdot Percentage\ Savings\ Lighting$$

$$Energy\ Savings\ due\ to\ Lighting\ System\ (€) = 9400\ kWh/y\ \cdot 20\%\ = 1880\ kWh/y$$

$$Monetary\ Savings\ due\ to\ Lighting\ System\ (€) = Energy\ Savings\ due\ to\ Lighting\ System\ (kWh) \cdot Electricity\ Costs\ (€/kWh)$$

$$Monetary\ Savings\ due\ to\ Lighting\ System\ (€) = 1880\ kWh/y \cdot 0{,}2\ €/kWh =\ 376\ €$$

HOME heating	**Measure unit**	**Values**
Average Consumption	Kwh/(m2*year)	144
Total consumption for heating	Kwh/(year)	270720
Methane Gas Costs	€/kWh	0,073
Total costs for heating	€	19753,19
Automated Thermostatic valves percentage savings	%	15,00%
Energy savings Heating for smart home	Kwh/(year)	40608
Monetary savings Heating for smart homes	**€/year**	**2962,98**

HOME electricity	**Measure unit**	**Values**
Average Consumption	Kwh/(m2*year)	5
Total consumption lighting system	Kwh/(year)	9400
Costs for electricity	€	0,2
Total costs for electricity	€/year	1880
Electricity savings	%	20,00%
Energy savings Lighting for smart home	Kwh/(year)	1880
Monetary savings Lighting for smart homes	**€/year**	**376**

Total monetary saving for residential floors	**€/year**	**3339**

Table 6.25: Residential monetary savings calculation

$$Total\ monetary\ savings\ for\ residentials = Monetary\ savings\ (Heating) + Monetary\ savings\ (Lighting)$$

$$Total\ monetary\ savings\ for\ residentials = 2962{,}98\ € + 376\ € = 3339\ €$$

6.4 Model Results

In this paragraph we are going to describe the final results of the model application to an 8-stories mixed building. The total costs computation for the components included is obtained by summing the values of initial investments and period costs. The following table shows a resume of the previous estimations.

		Initial Investment	Period Costs
OFFICES	Ceiling LED Lights	€ 25.200,00	€ 480,00
	DALI Lighting Sensors	€ 4.536,00	€ 216,00
	Dimmer Actuators	€ 4.197,50	€ 109,50
	Venetian Actuators	€ 3.238,40	€ 84,48
	Windows Sensors	€ 6.048,00	€ 252,00
	Multisensors	€ 6.804,00	€ 324,00
	Hvac Actuators	€ 3.680,00	€ 96,00
	Thermostats	€ 6.440,00	€ 224,00
	BMS software	€ 0	€ 800,00
	TOTAL	**€ 59.387,90**	**€ 2.585,98**

Table 6.26: Offices cost summary

		Initial Investment	Period costs
SMART HOME	Gateway Zigbee	€ 1.748,00	€ 55,20
	Presence/Motion Sensors	€ 2.508,00	€ 79,20
	Windows Sensors	€ 1.824,00	€ 57,60
	Automated TRVs	€ 9.120,00	€ 144,00
	Smart Socket	€ 3.990,00	€ 84,00
	Smart Thermostat	€ 2.736,00	€ 115,20
	Smart Switch	€ 3.420,00	€ 72,00
	TOTAL	**€ 25.346,00**	**€ 607,20**

Table 6.27: Smart Home cost summary

	Initial Investment	Period costs
TOTAL COSTS	**€ 84.733,90**	**€ 3.193,18**

Table 6.28: Cost Summary

The initial investment for the 8-stories building is 84.733,9 € with estimated running costs of 3.193,18 €.

The calculation of the total benefits obtainable by the application of our model to the 4000 m^2 building is taken from the previous paragraph. The sum between residential and offices savings is needed to have a complete overview:

$$Total\ monetary\ savings\ =\ Savings\ for\ residentials\ +\ Savings\ for\ offices\ =$$

$$Total\ monetary\ savings\ =\ 3339\ €\ +14527\ €\ =17866\ €$$

In the table below there is a spotlight of the main outcomes of the model which then are explained:

Building Type	Surface	Initial Investment	Period costs	Annual Benefits	Net Annual Benefits	Cost of capital	PBT
Mixed	4000 m2	€ 84733,9	€ 3193,18	€17.866	€14.672,82	2%	6,2

Table 6.29: Base case scenario model application

The payback time is the time in which the investment is repaid, expressed in years.

We calculate the payback time by actualizing the net annual benefit using inflation as cost of capital. We made the assumption of having all the acquisition and installation costs in the year 0 and then we sum the benefits and subtract the costs. The payback time is calculated starting from the table of the cumulative cash flows of the NPV.

The formula used for the NPV is the following:

$$NPV\ (20\ years) = Initial\ Investment + \sum_{0}^{19} \frac{Net\ Annual\ Benefit}{(1+k)\hat{}year}$$

We decided to take 20 years as a time range because the components taken from real market reference have all a declared lifespan between 15 and 20 years and then they should be substituted.

We use 2% as cost of capital after a reasoning that include different assumption:

- There aren't alternative investments for the building owner;
- The value of money is different nowadays and, in the future, and the difference is due to inflation. In order to have price stability inflation rates should be low but close to 2% according to the European Central Bank.

Starting from the previous formula we obtain interesting values, shown in the table:

	Actualized NCF	**Cumulative Actualized NCF**	**Payback time**
0	-84733,9	-84733,9	
1	€14.385,07	-€70.348,83	
2	€14.103,01	-€56.245,83	
3	€13.826,48	-€42.419,35	
4	€13.555,37	-€28.863,98	
5	€13.289,58	-€15.574,41	
6	€13.029,00	-€2.545,41	**6,20**
7	€12.773,53	€10.228,12	
8	€12.523,07	€22.751,18	
9	€12.277,52	€35.028,70	
10	€12.036,78	€47.065,48	
11	€11.800,76	€58.866,24	
12	€11.569,38	€70.435,62	
13	€11.342,53	€81.778,15	
14	€11.120,12	€92.898,27	
15	€10.902,08	€103.800,35	
16	€10.688,32	€114.488,67	
17	€10.478,74	€124.967,41	
18	€10.273,28	€135.240,69	
19	€10.071,84	€145.312,52	

Table 6.30: NPV values calculation (base case scenario)

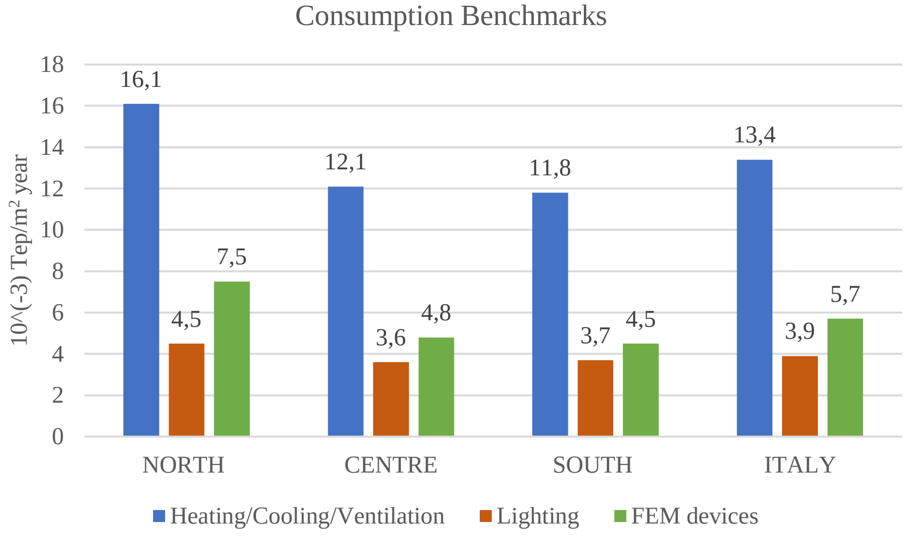
The 20 years NPV is 145312,52 €, the cumulated actualized NCF becomes positive in the fifth year. This suggests that the application of this type of installation is positive in the long term but also it can be repaid in short-medium terms. The combination of these outcomes gives a great help in terms of decision making for someone that is evaluating whether to invest or not.

6.5 Sensitivity Analysis

Sensitivity Analysis is a tool used to analyse how the different values of a set of variables affect another specific variable (in our case PBT) under certain specific conditions.
"*In a numerical (or otherwise) model, the Sensitivity Analysis (SA) is a method that measures how the impact of uncertainties of one or more input variables can lead to uncertainties on the output variables*" (Lam et al., 2020).
The analysis is useful to include in the model the variation of different variables and the results that can be obtained by having a bigger building, or a building with better energy performance. These variations are important to include in the overview a lot of different situations that could cover a good number of combinations, making the model adaptable. Understanding the trends of the values changing in the analysis, it is possible to understand when the investment is better performing and when it is not profitable to enter in it. Only the macro characteristics were changed and not the single mini cases, in the following lines we are going to describe the results of each of them. At the end we also provided tables with the combination of the variables' variation, understanding which combination is more suitable for this type of effort.
This analysis will be useful for all the building owners, including public administration, companies or individuals to better grasp the feasibility of their investments.
Starting from paragraph 6.5.1 we are going to describe the dimensions analysed. The variation of the building surface is the first one, introducing a smaller and a larger size to understand which one can drive better results. Then we focus more on consumption variation trying to understand what could be the impact of having a building in Northern Italy, Centre or South. Being the energy the main topic of the thesis, we dive into the analysis of the variation of the energetic starting class, and then the last variable we consider is the building typology (mixed building, only offices, only apartments).
As already stated, the combination of the sensitivity analysis results will become the most important outcome of the thesis.

6.5.1 Building Surface Variation & Climatic Region Variation

We decided to perform our first sensitivity analysis considering two variables simultaneously: the surface and the belonging climatic region. We consider the North, Centre and South of Italy and 2000, 4000 and 8000 m^2 of surface.
Starting from the climatic region it is very easy to calculate the variation of the PBT because it is impacted only by the savings given the different level of initial consumption in terms of heating, cooling and lighting requirements.
From the graph taken from the ENEA and Assoimmobiliare report already used in the consumption calculation of offices we can extrapolate the consumption data according to the three zones:



Graph 6.1: Energy Consumption in Offices according to the climatic region (Source: ENEA)

In table 6.31 it is reported the consumption of North, Centre and South Italy in kWh/m^2 considering the converting factor of: $kWh/m^2\,y = 10\text{^}(-3)\ Tep/m^2\,y \cdot 11{,}63\ Tep/kWh$.
Calculation explained in paragraph 5.3.3.

kWh / m^2	**NORTH**	**CENTRE**	**SOUTH**	**ITALY**
Heating, Ventilation and Cooling	187,24	140,72	137,23	155,84
Lighting	52,34	41,87	43,03	45,36
FEM	87,23	55,82	52,34	66,29
Other	3,30	2,41	2,35	2,70

Table 6.31: Office energy consumption kWh/m^2 according to the climatic region

From this table we are able to recompute the values of consumption first and savings second maintaining the same percentages explained in the benefit computation (paragraph 6.3.1).
Having understood how the benefits are impacted by the climatic states of the belonging region we focus on the surface variable.
Surface together with building type is the only variable that impacts both on the benefits and costs. Starting from the costs it is obvious that bigger is the building bigger are the costs because there is an increasing number of items to purchase and install. We made other considerations here; the discount percentage is increased by 5% per each component in the 8000 m^2 building and it is decreased by 5% in the 2000 m^2 building.

The economies of scale are inserted in this formula:

$$Discounted\ "Component"\ Acquisition\ Cost = "Component"\ Acquisition\ Cost \cdot (1 - Ec.Scale)$$

Here, has been provided a resume of the new economies of scale, considering as an assumption that discount will change by 5% increasing or decreasing the surface.

	Components	Ec. Scale
2000 m^2	**Components**	**Ec. Scale**
	Lights & Sensors	10%
	Other Offices components	0%
	Smart Home Devices	10%
4000 m^2	**Components**	**Ec. Scale**
	Lights & Sensors	15%
	Other Offices components	5%
	Smart Home Devices	15%
8000 m^2	**Components**	**Ec. Scale**
	Lights & Sensors	20%
	Other Offices components	10%
	Smart Home Devices	20%

Table 6.32: Economies of scale applied according to the building dimension

The surface does not only impact on the costs but also on benefits. The bigger the building the higher the consumption and as a consequence of this the higher the savings in absolute terms.
Considering the two variables varying simultaneously we can come up with the following numbers:

Surface	Climatic Zone	Initial Investments	Period costs	Annual Benefits	Net Annual Benefits	PBT
2000 m^2	Italy	€ 44.412	€1.614	€8.933	€7.319	6,54
2000 m^2	North Italy	€ 44.412	€1.614	€10.486	€8.872	5,33
2000 m^2	Centre Italy	€ 44.412	€1.614	€8.170	€6.556	7,35
2000 m^2	South Italy	€ 44.412	€1.614	€8.219	€6.605	7,30
4000 m^2	Italy	€ 84.734	€3.193	€17.866	€14.673	6,20
4000 m^2	North Italy	€ 84.734	€3.193	€20.972	€17.779	5,06
4000 m^2	Centre Italy	€ 84.734	€3.193	€16.341	€13.148	6,97
4000 m^2	South Italy	€ 84.734	€3.193	€16.438	€13.245	6,91
8000 m^2	Italy	€ 161.289	€6.315	€35.732	€29.417	5,87
8000 m^2	North Italy	€ 161.289	€6.315	€41.945	€35.630	4,79
8000 m^2	Centre Italy	€ 161.289	€6.315	€32.681	€26.366	6,59
8000 m^2	South Italy	€ 161.289	€6.315	€32.876	€26.561	6,54

Table 6.33: Model application results (variation of building dimension and climatic region)

To have a visual view of what we are talking about we can look at table 6.34 which provides a comparison between the values of PBT, our main indicator.

	2000 m^2	4000 m^2	8000 m^2
North Italy	5,33	5,06	4,79
Centre Italy	7,35	6,97	6,59
South Italy	7,30	6,91	6,54

Table 6.34: Payback times according to the variation of building dimension and climatic region

Results go from minimum in red to maximum in green. As already stated in the centre and south the consumption in terms of heating and HVAC is lower with respect to northern regions given the longer time of mild weather seasons. The values of energy consumption from centre and south are similar, and therefore, a similar payback time is resulted. In terms of building surface, we can see that a bigger building is able to recover faster from the investment made even. The better case is the 8000 m^2 because of the high bargaining power that a building owner could have that translates into higher economies of scale. The greener case is the north - 8000 m^2 which has a combination of high economies of scale and higher savings achievable given the starting high energy consumption and possible synergies. In the case of centre/south - 2000 m^2 we have a PBT which is 50% higher with respect to the best case, mainly because the costs for a smaller situation have a higher impact on PBT, and the lower consumption of the southern region leave less space for savings opportunities.

6.5.2 Energetic Class Variation

The energetic class applied to buildings is a scientific classification system that allows the evaluation of energy needs, it is calculated on the basis of various parameters in terms of structure and operation. Moreover, the energetic class variation strictly depends on the consumption levels of the building. Therefore, we consider the initial investment and period costs as in the base case. What is varying here is the consumption per square meter of surface. The costs do not vary at all because they depend on the type of building and on the surface which aren't changing here

To estimate the energy class of a building the professional takes into consideration a plurality of factors including the materials of the windows and walls, and the type of heating system used. In addition to these, also the primary energy requirement for winter heating: it is expressed in kWh / year per cubic meter of volume, or in kWh / year per square meter of useful surface.
The primary energy requirement for winter heating could be the data that can help even a non-professional to get an idea of the energy class of his home.

Energetic Class	MIN (kWh/m^{2}y)	MAX (kWh/m^{2}y)	Average (kWh/m^{2}y)
A	0	30	15
B	30	50	40
C	50	70	60
D	70	90	80
E	90	120	105
F	120	160	140
G	160	200	180

Table 6.35: Heating consumption kWh/m^2 per energetic class

It should be computed where the base case is placed inside this table. One thing to remark is that the values of consumption we take are derived from Italian averages.
In the case of apartments, the consumption per square meter is 144 kWh/m^{2}y while for offices we have 155,84 kWh/m^{2}y. Considering we have the same surface for both the parts we can make an average between the two values:

$$\begin{aligned} &Average\ building\ consumption \\ &\quad = (Consumption\ Offices\ (kWh/m2y) \\ &\quad + \ Consumption\ Apartments\ (kWh/m2y))\ /\ 2 \end{aligned}$$

$$Average\ building\ consumption\ =\ 149{,}92\ kWh/m2y$$

Being a value near to 150 kWh we are almost in the middle of class F. The next step is to consider the percentage variation in consumption for the classes in correspondence of class F (the base case situation). Then unitary heating consumption (kWh/m^{2}y) will be adjusted considering this percentage increase/decrease.

Energetic Class	Average heating consumption (kWh/m^{2}y)	Percentage Variation Class “X” to F
A	15	11%
B	40	29%
C	60	43%
D	80	57%
E	105	75%
F	140	100%
G	180	129%

Table 6.36: Energy consumption percentage variation according to the energetic class

For instance, considering apartments heating the formulas for the computation of unitary consumption in the different classes are:

$$Unitary\ Consumption\ (Class\ E) = Average\ Unitary\ Consumption * Percentage\ Variation\ (E - F)$$

$$Unitary\ Consumption\ (Class\ E) = 144\ kWh/m2y * 75\% = 108\ kWh/m2y$$

With this new value we repeat the calculation for offices and each class to obtain the values to substitute in the consumption calculation formulas. The same method explained in the previous chapters is then applied.

For what concerns the consumption of electricity for lighting, it does not change according to the class.

Energetic Class	Initial Investments	Period costs	Annual Benefits	Net Annual Benefits	PBT
A	€ 84.734	€3.193	€11.159	€7.966	12,08
B	€ 84.734	€3.193	€12.501	€9.308	10,15
C	€ 84.734	€3.193	€13.574	€10.381	9,00
D	€ 84.734	€3.193	€14.647	€11.454	8,09
E	€ 84.734	€3.193	€15.988	€12.795	7,18
F	€ 84.734	€3.193	€17.866	€14.673	6,20
G	€ 84.734	€3.193	€20.012	€16.819	5,37

Table 6.37: Model application results (Variation of the energetic class)

As can be seen by table 6.37 the PBT increases if the energetic performance of the building improves. PBT goes from almost 10 years to 4,5 years of the G class, this result isn't surprising since to the lowest classes corresponds to higher energy wastes that can be saved thanks to our installations. In paragraph 6.5.4 it is described the variation of the PBT according to the combination of all the variables.

6.5.3 Type of Building Variation

The usual table we use to sum up results (table 6.38) has very different outcomes between the lines, considering the building type variation.

Type of Building	Initial Investments	Period costs	Annual Benefits	Net Annual Benefits	PBT
MIXED	€ 84.733	€ 3.193	€17.866	€ 14.673	6,20
OFFICES	€ 141.894	€ 5.992	€ 33.602	€ 27.610	5,48
APARTMENTS	€ 50.692	€ 1.214	€6.678	€ 5.464	10,37

Table 6.38: Model application results (type of building variation)

Starting from the costs we can see that the initial investment is the almost the double in case of an “Office building” with respect to “Mixed building”, the period costs follow the same trend. Office’s building is the one with the higher costs given the quantity of components included and their installation costs.
The initial investment for “Mixed” is 67% higher than the one for “Apartments”, but in this case running costs are 163% higher. This difference is caused by the fact that in the apartments we do not need dimmable LED lights which carry a high cost of maintenance.

The real difference between all the cases is about the benefits.
Considering only the lighting system the differences are wide because the possibilities of savings in the office are higher. In homes the electricity is a major source of costs, but only a small part is related to the lightning usage which is our main focus (we do not consider appliances that generate a considerable level of consumption). In case of offices, lights are switched on for the total working hours and an energy consumption strategy can cause major monetary savings. Moreover, the heating costs are different given the different working hours of each system. Here a strategy that considers occupancy can generate more benefits than what can be made in houses.
For all these reasons we can see an increasing trend in the annual benefits from apartments to mixed to offices buildings.
At the end the PBT is low in case of a mixed building, even lower in the case of only offices and a bit high in the apartments building, the results do not discourage the investment, but a deeper analysis should be made to understand better the variable composition to obtain the best return on the investment.

6.5.4 Comprehensive Sensitivity Analysis

At the end we want to provide an analysis that tries to consider all the aspects of our model combining them. We made comprehensive tables that consider each situation and possible variation of the characteristics already described. Three blocks of tables for the different types of building are made of two dimensions: the Surface on the columns and the Energetic Class combined with the Climatic Region on the rows. Inside the cells there is the payback time expressed in years, they are highlighted in colours from green to red meaning from the best PBT to the worst. These tables are aimed at giving a visual expression of the results to have an immediate way to understand the feasibility of the investment.

The tables down below include the Italian averages values for the cell, ITALY A for instance means that the payback time is referred to the average Italian value of PBT for Energy Class A buildings. Later on, we will also discuss the single climatic zones.

For the comparison we consider our starting point, namely the mixed building. We can see how the values of “Mixed” and “Offices” are very similar even if a difference of 1 or 2 years can always be registered. Considering only offices the costs will be much higher but at the same it is the place where bigger savings can be made, for both the cases bigger surfaces are better but good results can be achieved also in smaller buildings. The real and important difference arises when comparing “Mixed” and “Offices” with the residential part, here we can see how only in low energy performance building the investment is profitable. We consider that only if the PBT is lower than 20 years the investment can be made because after that some components started to be substituted. From class G to class E we have positive payback time, while from class C there are high PBTs. Class D is at the boundary suggesting that maybe other most profitable investments can be found, Class E instead suggests that an investor can enter into such a project if he considers as a priority not only economic savings but also the related environmental savings (e.g. emission reduction).

	2000 m^2	4000 m^2	8000 m^2
ITALY A	**12,81**	**12,08**	**11,37**
ITALY B	**10,74**	**10,15**	**9,57**
ITALY C	**9,52**	**9,00**	**8,50**
ITALY D	**8,54**	**8,09**	**7,64**
ITALY E	**7,57**	**7,18**	**6,79**
ITALY F	**6,54**	**6,20**	**5,87**
ITALY G	**5,65**	**5,37**	**5,08**

Table 6.39: Payback time results Italy average (Mixed Building)

	2000 m^2	4000 m^2	8000 m^2
ITALY A	**10,79**	**10,27**	**9,75**
ITALY B	**9,18**	**8,74**	**8,30**
ITALY C	**8,20**	**7,81**	**7,42**
ITALY D	**7,41**	**7,06**	**6,71**
ITALY E	**6,61**	**6,30**	**5,99**
ITALY F	**5,75**	**5,48**	**5,21**
ITALY G	**5,00**	**4,77**	**4,54**

Table 6.40: Payback time results Italy average (Only Offices Building)

	2000 m^2	4000 m^2	8000 m^2
ITALY A	**> 30**	**> 30**	**> 30**
ITALY B	**> 30**	**> 30**	**> 30**
ITALY C	**> 30**	**> 30**	**29,92**
ITALY D	**23,67**	**21,50**	**19,53**
ITALY E	**16,09**	**14,84**	**13,66**
ITALY F	**11,14**	**10,37**	**9,63**
ITALY G	**8,25**	**7,72**	**7,20**

Table 6.41: Payback time results Italy average (Residential Building)

We can now move onto the table considering also the belonging climatic region (North, Centre, South). Singles tables show the trend of the Italian values with the first two building types very similar and the third totally different.
As can be seen North tables are always better, for "Offices" it is almost totally green with a value for North-G-8000 very low. PBT values for "Mixed" and "Offices" are always profitable even if there is a steady decrease in values from North to Centre and South.
Higher PBT values means that the investment requires more time to recover, in the first two building types we can find the highest values in Class A as expected. In this row the required time in South and Centre probably suggests that alternative investments should be made, because consumption levels are already low.
Talking about residential we can see how the best performing classes do not justify the investment, while the lowest push it through the model results. We can understand that in North also class D buildings permit the investment while it is off limits for Centre D and South D.
In any table provided the difference between the values are notable because from the lowest to the highest the values always more than double.

	2000 m^2	4000 m^2	8000 m^2		2000 m^2	4000 m^2	8000 m^2		2000 m^2	4000 m^2	8000 m^2
NORTH A	**10,23**	**9,68**	**9,13**	CENTRE A	**14,65**	**13,79**	**12,96**	SOUTH A	**14,08**	**13,26**	**12,47**
NORTH B	**8,64**	**8,18**	**7,73**	CENTRE B	**12,22**	**11,53**	**10,86**	SOUTH B	**11,86**	**11,20**	**10,55**
NORTH C	**7,69**	**7,28**	**6,88**	CENTRE C	**10,79**	**10,19**	**9,61**	SOUTH C	**10,54**	**9,96**	**9,40**
NORTH D	**6,92**	**6,56**	**6,21**	CENTRE D	**9,66**	**9,14**	**8,62**	SOUTH D	**9,49**	**8,97**	**8,47**
NORTH E	**6,15**	**5,84**	**5,53**	CENTRE E	**8,54**	**8,09**	**7,64**	SOUTH E	**8,43**	**7,98**	**7,54**
NORTH F	**5,33**	**5,06**	**4,79**	CENTRE F	**7,35**	**6,97**	**6,59**	SOUTH F	**7,30**	**6,91**	**6,54**
NORTH G	**4,62**	**4,39**	**4,16**	CENTRE G	**6,35**	**6,02**	**5,70**	SOUTH G	**6,32**	**6,00**	**5,68**

Table 6.42: Payback time results (Mixed Building)

	2000 m^2	4000 m^2	8000 m^2		2000 m^2	4000 m^2	8000 m^2		2000 m^2	4000 m^2	8000 m^2
NORTH A	**8,69**	**8,27**	**7,86**	CENTRE A	**12,28**	**11,68**	**11,07**	SOUTH A	**11,82**	**11,23**	**10,66**
NORTH B	**7,42**	**7,07**	**6,72**	CENTRE B	**10,40**	**9,89**	**9,39**	SOUTH B	**10,10**	**9,61**	**9,13**
NORTH C	**6,65**	**6,34**	**6,03**	CENTRE C	**9,27**	**8,82**	**8,38**	SOUTH C	**9,05**	**8,62**	**8,19**
NORTH D	**6,02**	**5,74**	**5,46**	CENTRE D	**8,36**	**7,96**	**7,56**	SOUTH D	**8,20**	**7,81**	**7,42**
NORTH E	**5,39**	**5,14**	**4,89**	CENTRE E	**7,44**	**7,09**	**6,74**	SOUTH E	**7,34**	**6,99**	**6,65**
NORTH F	**4,70**	**4,48**	**4,27**	CENTRE F	**6,45**	**6,15**	**5,85**	SOUTH F	**6,40**	**6,10**	**5,80**
NORTH G	**4,10**	**3,91**	**3,72**	CENTRE G	**5,60**	**5,34**	**5,08**	SOUTH G	**5,58**	**5,32**	**5,06**

Table 6.43: Payback time results (Only Offices)

	2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²		2000 m²	4000 m²	8000 m²
NORTH A	**> 30**	**> 30**	**> 30**	CENTRE A	**> 30**	**> 30**	**> 30**	SOUTH A	**> 30**	**> 30**	**> 30**
NORTH B	**> 30**	**> 30**	**> 30**	CENTRE B	**> 30**	**> 30**	**> 30**	SOUTH B	**> 30**	**> 30**	**> 30**
NORTH C	**26,24**	**23,72**	**21,44**	CENTRE C	**> 30**	**> 30**	**> 30**	SOUTH C	**> 30**	**> 30**	**> 30**
NORTH D	**17,47**	**16,06**	**14,75**	CENTRE D	**28,63**	**25,76**	**23,19**	SOUTH D	**29,55**	**26,53**	**23,84**
NORTH E	**12,34**	**11,46**	**10,62**	CENTRE E	**18,88**	**17,31**	**15,86**	SOUTH E	**19,43**	**17,80**	**16,29**
NORTH F	**8,76**	**8,19**	**7,64**	CENTRE F	**12,82**	**11,90**	**11,01**	SOUTH F	**13,18**	**12,22**	**11,31**
NORTH G	**6,58**	**6,18**	**5,78**	CENTRE G	**9,39**	**8,77**	**8,17**	SOUTH G	**9,65**	**9,00**	**8,38**

Table 6.44: Payback time results (Only Residential)

6.6 Investment Analysis

In the previous paragraphs was demonstrated the sustainability of the investment in the base case of an average city building, and then the analysis has been concentrated on the single variables that could vary to understand how the investment will be affected. One thing to remake is that the size of the investment is not negligible and, therefore, it should be investigated deeper what are the parts to prioritize. The two typologies of offices are equipped with components that could be reconciled to the lighting system and HVAC system which is why we consider, in the following paragraph, these investments separated to better understand the numbers.
The analysis is based on the assumption that these systems are independent realities that can be separately installed in the building. The results are different with respect to the model, since the perspective is not the same: in the model, it was assumed to install together the systems, exploiting synergies and scale to reduce the investment required. This difference is quantified in the tables below and derives from the unitary costs of the devices needed in each system.
Houses not only have been divided according to the type of system, but also considering the single house in order to isolate the economies of scale and give suggestions also to private owners who want to make such an intervention in their properties.

6.6.1 Offices Investment Analysis

In order to understand what are the costs related to the single system, components are categorized according to their belonging system, some components are useful for both the systems as can be seen in the table 6.45. To make the analysis even more specific we consider only one floor of both the types, to really being able to compare the systems and the environments.

	PROFESSIONAL		**OPEN SPACE**		
	Initial Investment	**Period Costs**	**Initial Investment**	**Period Costs**	**System**
Ceiling LED Lights	€ 6.405,00	€ 122,00	€ 6.195,00	€ 118,00	Lighting
DALI Lighting Sensors	€ 1.428,00	€ 68,00	€ 840,00	€ 40,00	Lighting
Dimmer Actuators	€ 1.259,25	€ 32,85	€ 839,50	€ 21,90	Lighting
Venetian Actuators	€ 809,60	€ 21,12	€ 809,60	€ 21,12	Lighting
Windows Sensors	€ 1.323,00	€ 63,00	€ 1.323,00	€ 63,00	HVAC
Multisensors	€ 2.142,00	€ 102,00	€ 1.260,00	€ 60,00	Both
Hvac Actuators	€ 1.380,00	€ 36,00	€ 460,00	€ 12,00	HVAC
Thermostats	€ 2.990,00	€ 104,00	€ 230,00	€ 8,00	HVAC
BMS software	€ 0	€ 200,00	€ 0	€ 200,00	Both

Table 6.45: Components belonging systems

Costs can be easily calculated by summing up single values and then, also benefits are obtained dividing between the two systems. In the next paragraphs we perform the analysis for a single floor in the two types of offices for the different systems.

At the end the payback time is calculated using the same approach as before (starting from the NPV calculation).

Professional Office

	Savings	Investments	Period costs	Payback Time
Professional offices HVAC	€ 1.705,50	€ 8.355,00	€ 505,00	6,960
Professional Offices lighting	€ 2.494,50	€ 13.083,80	€ 545,97	6,715

Table 6.46: Investment values according to the single system installation (Professional Offices)

In the analysis of the investment for a single floor it is clear that a lot of economies of scale obtained in the base case of the entire building cannot be achieved.
Looking at the values of Payback time for professional offices it is clear that the two values are almost equal, meaning that it is hard to say which one is best. Moreover, the values for HVAC systems strictly depend on the variation of the characteristics already analysed in the sensitivity analysis, a change in those will make the PBT totally different, making the prioritization wrong. For instance, a building placed in northern Italy with a lower energetic class is able to achieve higher HVAC savings.

The two systems are equally impacting on the floor, but the differences start arising if the two are implemented together and for an entire building. This would cause a reduction in PBT of about 20% from 6,9y to 5,48y (PBT of a building with only offices - 4000 m^2 - Energetic class F).

We make the hypothesis to prioritize the investment about lighting since in our model is the one to which are associated the major benefits due to ceiling lights change. The savings achievable through the lighting strategies enabled by the IoT are higher comparing the two systems. With dimmable LEDs a significant reduction in the time lights are switched on and a reduction in their intensity can be achieved, that correspond to monetary savings. Considering the base case HVAC savings are lower even if consistent.

Starting from the lighting investment we have:

Year	Actualized NCF	Cumulative actualized NCF	Payback time
0	-€ 13.083,80	-€ 13.083,80	
1	€ 1.948,53	-€ 11.135,27	
2	€ 1.948,53	-€ 9.186,74	
3	€ 1.948,53	-€ 7.238,21	
4	€ 1.948,53	-€ 5.289,68	
5	€ 1.948,53	-€ 3.341,15	
6	€ 1.948,53	-€ 1.392,62	**6,715**
7	€ 1.948,53	€ 555,91	
8	€ 1.948,53	€ 2.504,44	
9	€ 1.948,53	€ 4.452,97	
10	€ 1.948,53	€ 6.401,50	
11	€ 1.948,53	€ 8.350,03	
12	€ 1.948,53	€ 10.298,56	
13	€ 1.948,53	€ 12.247,09	
14	€ 1.948,53	€ 14.195,62	
15	€ 1.948,53	€ 16.144,15	
16	€ 1.948,53	€ 18.092,68	
17	€ 1.948,53	€ 20.041,21	
18	€ 1.948,53	€ 21.989,74	
19	€ 1.948,53	€ 23.938,27	

Table 6.47: NPV calculation office floor lighting system

It is also useful to understand what could be the impact of installing the IoT components to control HVAC. We can obtain a lower PBT compared to the case in which we perform the investment since the beginning, because sensors can be shared between the systems. It is important to highlight that even though after year 7 the first system employed produces savings, it is not possible to use these resources to repay the investment for the HVAC system, since they are two different investments and must be separately evaluated.

Year	Actualized NCF	Cumulative actualized NCF	Payback time
0	-€ 6.009,00	-€ 6.009,00	
1	€ 1.502,50	-€ 4.506,50	
2	€ 1.502,50	-€ 3.004,00	
3	€ 1.502,50	-€ 1.501,50	**4,00**
4	€ 1.502,50	€ 1,00	
5	€ 1.502,50	€ 1.503,50	
6	€ 1.502,50	€ 3.006,00	
7	€ 1.502,50	€ 4.508,50	
8	€ 1.502,50	€ 6.011,00	
9	€ 1.502,50	€ 7.513,50	
10	€ 1.502,50	€ 9.016,00	
11	€ 1.502,50	€ 10.518,50	
12	€ 1.502,50	€ 12.021,00	
13	€ 1.502,50	€ 13.523,50	
14	€ 1.502,50	€ 15.026,00	
15	€ 1.502,50	€ 16.528,50	
16	€ 1.502,50	€ 18.031,00	
17	€ 1.502,50	€ 19.533,50	
18	€ 1.502,50	€ 21.036,00	
19	€ 1.502,50	€ 22.538,50	

Table 6.48: NPV calculation office floor HVAC system

Looking at the numbers it is clear how the HVAC system investment is very profitable also after the first one of the lighting system. This result will enlarge the possibilities for an investor which is able to enter in one of the two projects and then after having tested the actual results can enter in the second, and repay the investment in a few years. It is obvious that the two combined will repay in less time than the sum of the two, but it is important to underline that it will take only about 7 years to repay the first project and then the investor will be able to enter the second without having to put in place huge one-shot monetary efforts.

Open Space Office

The analysis of the investment in the Open Space offices introduces some differences with regards to the previous one. The table 6.49 reports the values of the single systems as before.

	Savings	Investments	Period costs	Payback Time
Open Space Offices HVAC	€ 568,50	€ 3.549,00	€ 343,00	15,738
Open Space Offices lighting	€ 2.494,50	€ 10.805,80	€ 461,02	5,314

Table 6.49: Investment values according to the single system installation (Open Space Offices)

The payback time of the only-HVAC solution is sensibly higher than separated offices because the system should be run together in a huge area, and therefore, possibilities for savings are lower, obtaining 15,738 y of PBT.

On the contrary a better result is registered in the case of the lighting system, which has higher potential for consumption reduction given the possibilities to act on groups of LEDs separately.

The first investment to carry out is the lighting one that can be repaid in 5,314 years following the same computation of the previous paragraph. If the HVAC system is carried out after the first project than we have the following numbers:

	Savings	Investments	Period costs	Payback Time
Open space Offices HVAC (Complementary investment)	€ 568,50	€ 2169,00	€ 83,00	4,467

Table 6.50: Complementary HVAC investment values (Open Space Offices)

It is clear that having already sustained costs related to the shared components, the system is now more affordable if compared to the case in which this investment was prioritized. Also in this case splitting the investment into two according to the system will reduce the total amount, and distributing it on a larger time horizon will require lower economic outlays.

One last thing to highlight is that the values considered are calculated isolating the economies of scale deriving from large acquisition batches that would decrease the overall costs. This investment analysis is performed on a single floor to have an idea of the single part of the investment that should be performed and make it independent from the building dimension. Considering a whole building with the whole system some synergies and scale will arise.

6.6.2 Smart Home

In the case of a Smart Home, an analysis is not needed to claim that the heating system has the protagonist role in the system, so it is obvious that the first investment to consider in this case is the one related to installation of IoT components for managing this system. We have analysed values of PBT related to one floor which can be found in the table 6.51.

	Payback Time
Home Heating	7,141
Home Lighting	>20

Table 6.51: Payback time according to the single system investment in smart home

We decided to focus our attention on the possibilities of making the investment in the case of private house owners who decide to implement these technologies in one single home. We consider the usual three types of homes: small size, medium and big.

Starting from the 120 m^2 house, which in our case is the medium apartment, we have repeated the estimations to get rid of the economies of scale.
Costs and benefits are as follows:

Components included in one smart Home	Number of pieces per medium house	Acquisition Costs	Installation costs	Period costs
Gateway Zigbee	1	€ 115,00	€ 11,50	€ 3,45
Presence e Motion sensor	8	€ 176,00	€ 17,60	€ 5,28
Windows opening/closing Sensor	8	€ 128,00	€ 12,80	€ 3,84
Automated TRVs	8	€ 640,00	€ 64,00	€ 9,60
Smart Socket	8	€ 280,00	€ 28,00	€ 5,60
Smart Thermostat	1	€ 180,00	€ 18,00	€ 7,20
Smart Switch	8	€ 240,00	€ 24,00	€ 4,80
		Total Acquisition costs	Installation Costs	Period Costs
		€ 1.759,00	€ 175,90	€ 39,77

Table 6.52: Single 120 m^2 apartment costs computation

	HEATING	LIGHTING
Unitary Consumption (kWh/m2y)	144	5
Surface (m2)	120	120
Total Consumption (kWh/y)	17280	600
Percentage Savings (%)	15%	20%
Energy Savings (kWh/y)	2592	120
Unitary Energy Costs (€/kWh)	€ 0,073	€ 0,200
Monetary Savings (€/y)	€ 189,22	€ 24,00

Table 6.53: Single 120 m^2 apartment benefits computation

Repeating these estimations for every type of apartments we can obtain the following numbers:

Type of Apartment	Surface (m2)	Initial Investment	PBT
Small	85	€ 1.532,30	12,93
Medium	120	€ 1.934,90	11,16
Big	180	€ 2.337,50	8,57

Table 6.54: Investment for single apartments summary (dimension variation)

We highlighted only those results that are really important for a house-owner who is evaluating the investment, meaning the initial effort and the time for the investment to be repaid. What is useful here is to understand if the numbers can be seen in real installations. For instance, in Skvortsova (2019) the authors provide an estimation of the benefits that can be achieved installing a complete "Smart Home" system of ABB i-Bus KNX, which costs starts from 2000 €. They propose their model basing the calculation on a house of 200 m^2 in Russia and thanks to the reduction in consumption they achieved payback time in 11 years. This result is similar to ours even if it relies on totally different calculations and they also affirm that the system is profitable if applied with awareness of what are its capabilities.

Our smart home system is considered efficient, but its payback is not immediate. We should consider that the purpose of a system like that is not to gain money but rather to reduce consumption, reduce bills and reduce emissions. For a house owner it is important to repay the investment and be conscious to save some energy, the total NPV takes a back seat. It is only important to reach PBT below 20 years because then probably the user should change components.

Chapter 7: CONCLUSIONS

The major goal of this work is to develop an analysis of the Smart Building environment, focusing the attention on the application of IoT components to energy management purposes.
Energy efficiency is probably one of the top trends worldwide: companies, institutions and international governments are struggling with it in every sector. The earth is at its last call and interventions to avoid climate change should be taken. Only with a systemic approach involving all the countries something impactful can be done. To avoid the global warming catastrophe EU has committed to reach carbon neutrality by 2050 involving two main strategies: on one hand is the exploitation of renewable energy sources, the so called "Green Revolution"; on the other hand, consumption reduction is fundamental as well as energy usage optimization, improved control strategies and energy conservation.

As already stated, IoT would be an enabler for reaching higher efficiency in traditional systems. If Smart Objects are employed in a communicating network it is possible to enable an optimization of energy usage on a large scale, considering the sum of small single systems as a whole.
Smart energy management is not possible without IoT devices, equipped with sensors that record interactions with the outside world and exchange this data with other devices or end users.

To investigate the topic from a scientific literature perspective the starting point was a Literature Review analysing 97 Papers in the field of Smart Building, IoT and Energy Management. The scientific literature was complemented by whitepapers coming from components companies (i.e. Schneider Electric, ABB, BTicino) but also from consultancy companies (e.g. McKinsey) that are supporting their clients in this as complex as crucial topic. Demographic results were clear, almost the total of the researches (97%) were coming from Asia, Europe and America, while the most investigated technologies were HVAC (46 papers out of 97), Lighting system (38 papers out of 97), BMS and Control Schema (64 papers out of 97) and Appliances (40 papers out of 97).

Thanks to the analysis performed during the whole thesis, it is possible to answer the Research Questions previously formulated:

RQ1. What is the current Smart Building state of the art?
Answered through the following split:
RQ1.1 What is the application scenario and the technological frontier?
From the literature review emerged that topics related to Building Management System and HVAC system are the most discussed, meaning that the sector is concentrating mainly on them.
Looking at the most innovative solution the analysis has been concentrated on a sample of 11 Smart Building examples (single successful projects were analysed to understand the main direction of the market) and a range of 307 startups within the Smart Building field. Results show a dominance of investments and number of startups from North-America (41%) and Europe (38%), but with North America startups receiving almost 3 time the fundings amount of European ones. The most prolific European countries are France, Germany and the UK, while the most tackle topic is related to Energy Optimization Technologies with almost 40% of the whole sample falling into this category.

RQ1.2 What are the current data valorisation strategies implemented in Smart Building?

The startup analysis is useful to investigate what strategies do the most important newcomers implement to extract value from IoT. The approaches found were mainly about "Process Optimization" according to the classification of Tumino et al. (2012). The main strategies were about the optimization of energy usage inside the building systems declined in different solutions according to the company. Predictive maintenance is also a popular data valorisation strategy in the process optimization category. Approaches related to the "Customisation of product/service" were also found. Startups like WeMaintain use data obtained from IoT to provide a customised service in the field of lift predictive maintenance. Most of the startups will exploit a software business model meaning they provide services based on software functionalities.

RQ2. Which are the IoT-enabled benefits and costs of the IoT solutions for energy management in Smart Buildings?

The Literature Review recognizes a gap in the knowledge about the estimation of costs and benefits related to solutions for energy management in Smart Building that have both residential, office and multiple technologies installed. Right after this, the decision to develop a quantitative model which evaluates costs and benefits of the IoT components to make the building smarter was made.

The model can be useful during the decision-making process in order to have a global view of the investment.

The model considers a "mixed" building in which there are three types of different floors. The first type is the Open Space Office in which the main characteristic is to be considered as one single environment, with bathrooms as separated zones. Professional Offices is considered as the same space but divided into single offices of different measures. As already said the third part is the residential one. Different technologies are installed according to the commercial/residential division, but they have the same objective of improving the energy performance of the building. Lighting system and HVAC/Heating system have been considered.

The model was then applied to a hypothetical Italian city building of 4000 m^2, with four floors dedicated to offices and four to apartments. The total investment required for IoT objects for their installation is about 6,2y, with the related benefits estimated from average percentage values and average consumption values in €17.866. Savings calculated are related to the control methods derived from the use of the IoT components for the lighting system and the HVAC. Benefits and period costs of € 3.193,18 are combined to obtain Net Annual Benefits, which is the value of net savings that permits the repayment of the investment. NPV of 84.733,9 € was calculated over 20y and the time needed to repay the investment was calculated in 6,2y.

Moreover, interventions of energy efficiency would attract new tenants, and companies started looking at the sustainability of the buildings they are in. There is also a driver regarding the added value of Smart Building to leasing and sales, as an example the fact that owners of smart buildings can satisfy tenant expectations for flexible workspaces and autonomous control.

After having concluded that the investment is positive in the base case scenario, then it has been investigated how the PBT will vary according to changes in the main macro-variables.

The investment is more convenient for bigger buildings placed in colder climates, and it can be said after the sensitivity analysis based on the variation of building dimension and climatic region. Average values of Italian buildings have been considered, then the consumption values according to the belonging climatic region were computed. As already stated, for the higher heating levels of consumption of Northern Italy it is possible to reach higher savings, which translate into 5,06y of PBT. In Centre and South Italy values of PBT are similar because the starting consumption levels are similar.

The variation of building dimension influences the number of components to be installed in each building. The increasing requirement for components increases the bargaining power of the buyer and make him obtain higher economies of scale. This results in a major discount which translates into lower costs per m^2. This is the main reason why in bigger buildings PBT diminished and the contrary in smaller ones.

After that, it has been analysed the main characteristic of building when talking of energy management: its energetic class. Buildings are classified from class A to G, with G class meaning that they have very bad energetic performances. Using the value of consumption typical of class F in which the base case building is placed, the consumption unitary values have been estimated according to a proportion with class F.
At the end it results that in A, B and C classes the PBT increases a lot, due to the starting level of energy conservation standards. The class G is the best one in terms of repayment with 5,37y of PBT. The difference between A and G is about 125% (6,71 years).

The building typology is the last variable considered to understand how it will affect the results. It is important to note the differences between “Only Offices”, “Only Residential” and the base case which is a “Mixed” Building. The higher savings can be achieved in an office setup with a PBT of 5,48y, it is even better than the Mixed configuration because higher synergies can be achieved. Moreover, the residential part of the model is able to achieve lower savings having lower starting consumption values with respect to offices. The residential part achieves 10,37y of PBT.

The goal of the model is to provide insights and suggestions for an investor that decides to enter in this type of investment. This is why a comprehensive analysis that takes into account the variation of the characteristics simultaneously has been made.
The outcome is straightforward: the best results can be achieved in North Italy with big class G buildings only dedicated to offices with a PBT of 3,72y.
The values of “Mixed” and “Offices”, considering the variation of climatic region and building dimension, are very similar even if a difference of 1 or 2 years can always be registered, having the same variables starting situation. In these cases, the investment is always profitable even if there is a steady decrease in values from North to Centre and South.

One of the main assumptions is that if the PBT is lower than 20 years the investment can be made because after that some components started to be substituted. From class G to class E there is a positive payback time, while from class C there are higher PBTs. Class D is at the boundary suggesting that maybe other more profitable investments can be found.
Talking about residential, the North-class D buildings permit the investment while it is off limits for Centre-class D and South-class D. For each building type the difference between the best and the worst configuration is more than 100%.

One thing to remember is that the investment is not negligible, thus it is important to study more what sections to prioritize. The study is based on the premise that these systems are different realities that may be put in the building independently. The HVAC and lighting systems have been split, considering each floor type as separated. The components were allocated according to the reference system.

Looking at the values of Payback time for professional offices for each separated system, it is clear that the values of Lighting and HVAC investments are almost equal, meaning that it is hard to say which one is the best.

The two systems are equally impacting on the single floor, but the differences start arising if the two are implemented together and for an entire building. This would cause a reduction in PBT of about 20% from 6,9y to 5,48y, meaning that applying them together has a certain impact.

Considering instead the Open Space Office floor it can be stated that the lighting system is the one to prioritize with PBT of 15,74y with respect to 5,31y of HVAC.
Performing the HVAC intervention after having repaid the first one has a positive impact resulting in a payback time for the single system of 4,7y.

Also, in this case splitting the investment into two according to the system will distribute the total amount on a larger time horizon and will require lower economic outlays. Once the investor repays the first investment it enters in the second.

It is important to highlight that even after the seventh years the first system employed produces savings. It is not possible to use these resources to repay the investment for the HVAC system, since they are two different investments and must be separately evaluated.

In the Smart Home configuration, the investment for heating should be the one to prioritize because savings are much higher than for the lighting, the second system benefits are more about the comfort of inhabitants. A single homeowner with a 120 m^2 apartment can reach 11,16y of PBT with an investment of € 1.935. This last analysis suggests that also a single house owner could have positive returns on an investment to introduce this IoT configuration.

The usefulness of the model is to provide insights and suggestions as well as a first estimation of an IoT energy efficient retrofit intervention on an existing building. Technologies to implement have been defined starting from real standards and existing components.
The information gathered about benefits are taken from the literature, therefore, a certain margin of error should be considered, given that the application in the single case could have a range of savings that vary a lot. This information subsequently used in the model is not as strong as the background of technicians, who can choose the most appropriate technologies and better scale the systems according to the unique building.
Results are in line with the expectation with PBT generally positive. The benefits achieved are not high in absolute terms because there are not strong masonry works, but only installations of sensors and actuators. The approximation in costs and benefits with respect to the values of an actual Smart Building implementation project is, of course, one limit.
The thesis initial topics are about smart building and energy efficiency which have been investigated in the Literature Review even if this work only analyses a sample of all the publications on the topic. In doing so, the completeness of the analysis has been maximized subject to the constraint of time availability.
The same has been done for startups considering only those registered on Crunchbase, which is the reference site for startups but does not include all the existing ones.
Further development of the research could include not only energy efficiency but also estimation of comfort and wealth that these types of installations provide. A more comprehensive study can be done in this way or considering technologies not only related to energy efficiency but to other functionalities of the Smart Building, like security and safety.
Given the rate of adoption of IoT, the development of the market and the size of investments startups are receiving, there is no doubt about the fast evolution of those technologies. Thus, an update of the model will be needed to adjust it for new technologies and the evolution of existing ones.

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APPENDIX A: Communication Protocols

Considering the architecture to create a "Network of things" in the IoT paradigm Smart Objects must have a communication capability to make edge units interact with remote applications and enable all the functions. According to the Tumino et al. (2012) a lot of technologies exists each with their own characteristics, the following paragraph is developed to propose a general overview:

- RFID (Radio frequency identification): it is a technology which uses electromagnetic fields to automatically identify and track tags attached to objects. It is possible to distinguish among two typologies of RFID:
    - Passive RFID: it is the first and simplest technology used for IoT. Thanks to a tag that is able to store information electronically. The tag is usually composed of an antenna to transfer data and a chip, that in case of passive RFID is powerless and it is being activated through a reader.
      The role of the reader is that of a device which reads information included in the tag RFId and transfers signal to the antenna, waiting for the answer. It also interacts with the management system to exchange information.
    - Active RFID: The main difference with the passive one is the presence of a battery whose main functionality is to enable independent operations even without the input of the reader device. Moreover, it can be read from higher distances.

- PAN (Personal Area Network): it is a standard for personal communication in short range networks. It ranges from a few centimeters to a few meters. In this classification are considered Bluetooth low energy, ANT and NFC, all used for consumer applications with narrow communication bands.
    - Bluetooth: it represents an important short-range IoT communications protocol/technology, the latest version is 5.2 that also includes LE Power control features. This makes it possible to manage the transmission of power between two connected devices both running Bluetooth version 5.2.
        - Bluetooth Low-Energy: it is a standard for data transmission in Wireless Personal Area Network (WPAN). Compared to Classic Bluetooth, Bluetooth Low-Energy is intended to provide considerably reduced power consumption and cost while maintaining a similar communication range.
    - ANT: it is a proprietary, but open access, wireless sensor network. ANT establishes a wireless communication protocol that enables communication by defining standard rules for data representation, signalling, error detection and, most important, co-existence. It is conceptually similar to BLE, but it is more oriented towards sensors usage.
    - NFC (Near field communication): it is a technology that allows to transfer information by bringing two equipped devices in close range of each other, communication among nearby devices (few centimeters). One NFC-enabled device can operate in different ways: emulation (enables devices to act like smart cards, allowing users to perform transactions), reader (enables devices to read information stored), peer-to-peer (enables two devices to communicate with each other and exchange information).

  These technologies are used a lot and integrated with mobile devices such as smartphones and tablets.

- WiFi: WiFi connectivity is one of the most popular IoT communication protocols allowing wireless access to broadband connection within LANs.
  There is a wide existing infrastructure and WiFi is able to handle high quantities of data and transfer them fast. However, they have high energy consumption and, because of that there are limitations in the full applicability in the IoT sector.

- Wireless Bus includes all the communication standards like Wireless M-Bus, KNX and X10 that represent the no-wired solution of the field bus architecture widespread in industrial work. Wireless Meter Bus, for instance, is an open standard developed for power efficient smart metering applications and it is quickly spreading in Europe for electricity, water, gas and heat metering. A Wireless M-Bus network (WM-Bus) is based on a star topology network and supports point to point connections.

- Low Power Mesh Network: it is a type of network composed by low-power nodes characterized by a mesh architecture. Mesh networks offer a high degree of reliability and LPMN technologies are optimized for low energy consumption, which makes them really interesting for developing the IoT paradigm. Even if there are some standards like WHart, Z-Wave and the most famous ZigBee, lots of actors are working on the standardization of the protocols.

- Cellular Networks: these protocols/technologies include the traditional mobile communication technologies such as GPRS, LTE (4G) and the recent 5G. They have high energy consumption, but they can cover long distances with the respect to the other technologies presented. The application is limited to cases in which it is possible to supply power to the nodes and it is usually used in combination with other methods to communicate with the control centre.

- Power Line Communication (PLC): it is a communication method that exploits powerline transmission systems to carry both coded data and electric power on existing power lines. With the same technology there are protocols for the residential field and for the medium and high power network.