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Business model innovation for the energy management of building networks in smart cities

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Abstract: In recent years, buildings have been equipped with building and automation control systems (BACS) that provide a reliable active energy efficiency measure for reducing energy consumption. Given the need for both evidence and practical applications in this field, this study presents some detailed scenario analyses for evaluating the economic convenience of BACS interventions within a network of buildings, in a smart city context. To this end, a simulator was developed capable of modelling and quantifying the main technical-economic variables to examine potential impacts of several 'building network management' scenario types, according to different scales and application areas. The simulator was tested through the results obtained in the smart village project carried out by ENEA in Italy. Our findings allow to assess the convenience of an investment in automation, control and monitoring systems by varying the complexity of the installed automation network, to determine the optimal solution from a technical-economic point of view.

Keywords: smart cities; business model innovation; digital transformation; impact evaluation; energy efficiency; smart buildings; construction industry; sustainable innovation.

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1 Introduction

World energy consumption has become a major concern to both scientific and political communities. At a European level, research and innovation (R&I) policy has shown a strategic turn over the past years. Technology foresight is increasingly oriented towards socio-economic aspects, interdependencies, innovation systems and its transitions. These new priorities are set within a general context characterised by the need for a broader understanding of innovation for societal demands, reflected in concepts such as green economy (Gibbs and O'Neill, 2015), social innovation (Shier and Handy, 2015), and in the 2030 United Nations Agenda for Sustainable Development (SDGs – Sustainable Development Goals). Therefore, technologies and knowledge, actors and organisations, user needs and demand, as well as institutional and policy frameworks are elements that need to co-evolve for any innovation systems scenario to unfold (Weber and Schaper-Rinkel, 2017). One of the most promoted measures, highly supported from the administration side, is the design of energy-efficient buildings. Indeed, according to existing studies, energy consumption in buildings represents a 40% rate of the worldwide energy, of which more than a half is used by heating, ventilation and air conditioning (HVAC) systems (Álvarez et al., 2013; Moroşan et al., 2010; Pérez-Lombard et al., 2008).

The rapid evolution of energy production and consumption models brought by the strong integration of technological innovations has led to a disruptive wave of progress. Europe is at the forefront in the challenge of containing the climate change by promoting a profound transformation of energy systems, investing in the use of innovative tools for an efficient energy management and its production from renewable sources. Indeed, in the main urban centres live three quarters of the total European population which consumes about 70% of the overall energy produced.

The growing interest in energy savings and efficiency in the construction industry is also leading to an increase in the demand for innovative information and communication technologies (ICTs) and automation systems in buildings. Employing efficient building techniques may lead to long-term economic, social and environmental benefits. In addition, the technological breakthroughs in efficient constructions not only must be addressed at saving energy, but also at achieving thermal comfort for the occupants. To reduce the energy consumption while maintaining an optimal well-being for the occupants, energy-efficient buildings incorporate both active and passive measures (Álvarez et al., 2013). A recent analysis (Navigant Consulting, 2016) predicts that in the next few years smart building management systems (BMS) – also known as building automation and control systems (BACSs), or with the terms building control systems, building automation systems, and building energy management systems (BEMS) – will become even more popular, quadrupling their presence and rising their market value towards a billion dollars by 2020.

In this scenario, the holistic smart city approach has stimulated the development of new paradigms that have joined the more established ones of energy efficiency and sustainable development (Copenhagen Capacity, 2014). What differentiates the 'smart city' approach from the past is the inclusion, in a single framework, of many aspects that before were considered only separately: energy; water; mobility; buildings; and government. Indeed, the concept of smart cities is emerging in multiple continents, based on the deployment of internet of things (IoT) applications on a city-wide scale such as intelligent transportation systems (e.g., smart mobility, vehicular automation, and traffic control); smart grids; enhanced street lighting management; traffic light management; waste management; smart services; environmental monitoring (e.g., sensors on city vehicles to monitor environmental parameters); water management; public safety and surveillance (Minoli et al., 2017). The city is therefore thought as a set of interconnected networks (i.e., the transport network, the electricity grid, the building network, the network of social relations, the public lighting, water and waste networks) (Ippolito, 2018). The integration of these networks in a coordinated design is the innovation that makes possible new services unthinkable until the last decade and opens up possibilities for the progressive transformation of the city. The next evolution of the smart city model is the application of these concepts in a more confined physical space, namely, to building environments. Indeed, nearly all the applications for smart cities have comparable applicability to building networks management (Minoli et al., 2017). The application of these innovative processes and tools to the buildings creates the concept of smart buildings, recently defined by Buckman et al. (2014) as "buildings which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at its core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction".

On this topic, Papantoniou et al. (2015) recently published a study that analyses a building optimisation and control (BOC) algorithm implemented in the existing BEMS of the Saint George Hospital in Chania, Greece, able to achieve an estimated annual energy saving of almost 36%.

Moreover, predictive control techniques to obtain high thermal comfort levels by optimising the use of an HVAC system have been studied by Álvarez et al. (2013). The authors in their work aimed to maximise the thermal comfort of the occupants located in different rooms of a building, taking into account the limited availability of energy, the room features and the energy demand in each room. The optimisation problem was hard-to-solve given the large number of considered rooms. Therefore, to do so, the authors proposed a Lagrangian dual strategy that allows to solve several optimisation problems in parallel, one for each room, and obtain positive results in terms of maintaining the thermal comfort in all the rooms (Álvarez et al., 2013).

Furthermore, Yang and Wang (2012) proposed a study to address one of the major issues for energy and comfort management in building automation: the conflict between the users' comfort and the total energy consumption. To this end, in this paper the authors proposed a multi-agent-based control framework for smart building applications in commercial buildings, in which the energy consumption and the overall comfort level are considered as two control objectives in the system (Yang and Wang, 2012). More recently, some relevant papers analysed the topic of lighting strategies in office buildings according to the areas of lighting control in a multi-user open office context (Lashina et al., 2019); experimental and simulation approaches to examine the impact of lighting control systems on lighting energy use in private offices (Gilani and O'Brien, 2018); and indoor lighting simulation tools to optimise the use of lighting systems in buildings (Baloch et al., 2018).

European regulations for new building have an explicit orientation toward low-emission and energy-efficient designs. However, the optimal design of buildings should consider multiple, and usually competitive, objectives such as energy consumption optimisation, financial costs reduction and decrease of environmental impacts (Fesanghary et al., 2012). Based on these objectives and considering the lack of literature focused on the management of a network of smart buildings, the research presented in this paper pursues the main purpose of developing a convenient instrument of analysis – a simulation tool – useful to determine quantitatively, from both technical and economic perspectives, the viability and convenience of possible interventions on a system of smart buildings including monitoring, diagnostics and control functions. Insights will allow to identify the necessary actions to be taken for a future large-scale intervention.

To achieve the abovementioned research objective (i.e., simulate a complete model of energy management of smart building networks, aimed at saving energy in a cost-efficient manner), a simulator was developed capable of modelling and quantifying the main technical-economic variables in order to examine possible impacts of different 'building network management' scenario types. The simulator was designed by taking into account the results obtained during the 'smart village' experimental project carried out by ENEA in Italy: it was designed for the tertiary sector, and particularly to provide results applicable to a network of buildings that can be referred to both offices and schools.

This paper is structured as follows: Section 2 describes the antecedents as well as the methodology used for the development of the proposed simulation tool. In Section 3, the different possible scenarios of building networks are presented in detail in order to evaluate and discuss their convenience. Finally, conclusions, limitations and future research paths are presented in Section 4.

2 Methods

The building network management approach seeks to develop an innovative system for the optimal management of a network of buildings, based on the application of advanced methodologies and technologies (Romano, 2016). The aim is the reduction of energy consumption of a network of buildings as well as the interaction with energy services suppliers, both thermal and electrical, in order to have an active control on energy demand. The first step is to equip the network of buildings with sensors, implementation systems, data transmission systems and an ICT infrastructure for data collection and processing (Di Pietra et al., 2015). This enabling infrastructure dialogues with a network analysis and optimisation system, the network intelligence system (NIS). The latter was implemented in Italy by ENEA and allows the network modelling, the profiling of utilities, the diagnostics on each building within the network, the comparison between their relative performances, the management strategies of each building and their optimisation (Annunziato et al., 2013). First of all, this system allows to process the acquired data to carry out a remote diagnostics in order to identify and notify eventual breakdowns, faults, system inefficiencies or wrong behaviour of people. Subsequently, the NIS is responsible for the optimisation of consumption and the application of energy-on-demand strategies, in connection with the data acquisition and implementation systems – the BEMSs. Such a structured system is thus able to optimise the BEMS set points (i.e., switch-on/switch-off times, partialisations, temperatures of the heat exchange systems, and set points of the rooms and the thermal power plant) for the control of the final users on the basis of a series of targets such as comfort, energy saving, energy expenditure, etc. To achieve these results, it is necessary the use of innovative and distributed sensors, smart agents, which acquire data that can be integrated with that from other types of devices for diagnostic and control activities (Annunziato et al., 2013).

The innovativeness of this approach lies in its concept, designed as a network of buildings: the goal is not the achievement of the energy efficiency of an individual building, but of a network of them thanks to intelligent automated and centralised diagnostics and optimisation systems that lead to considerable energy and economic savings in the face of low investment costs (ENEA-GSE, 2017). Indeed, it is not necessary to make structural interventions or replacements of components. Moreover, the real time monitoring and knowledge of the current state of the buildings allows to develop predictive models which, based on historical data, climatic conditions and real occupancy of buildings (i.e., presence of personnel), are able to forecast the expected consumption of the single building: in this way new scenarios are opened up for the achievement of energy efficiency. For instance the active demand, based on the dynamic modulation of the energy supply according to the demand, that becomes an active part of the system as it is made flexible and adaptable (Clerici Maestosi et al., 2015). To obtain this result, specific algorithms are developed for the optimisation of the set points of the BEMS installed (Vincenzi, 2016): in this way the energy demand for air conditioning, lighting and driving force is controlled and optimised dynamically, minimising discomfort for users. At the same time, it is necessary to define a strategy that is a business model, to promote the integration of the different components that make a building efficient and effective. The smart building is the model that best represents this concept of integration, by providing it in the form of a real interaction based on information protocols that allow the control and management of the result through a smart interconnection and communication among the elements that constitute the building-facility system (Confindustria, 2013). As an example, it is possible to consider the following 'efficiency improvement in office buildings' business case. Assuming efficiency measures on a micro sample equal to 728,000 square meters supported by an adequate incentive system, and a time span of 30 years, it would result in the following environmental externalities (see Table 1).

Table 1 Efficiency improvement in office buildings

Action	*Measure*	*Saving*
Reduction of primary energy consumption	Tep	432,734
Economic valorisation of the reduction of primary energy consumption	Mln €	296
Avoided CO_2	Ton CO_2	970,530
Economic valorisation of avoided CO_2	Mln €	16.0

At the national level (macro level), in the time frame 2014–2020 and according to the best available technology (BAT) scenario of this business case, with an adequate incentive system and assuming the annual redevelopment of 2,240,000 square metres on the entire area for office use surveyed by the Territory Agency – 570,000 real estate units, for an indicative area of 56 million square metres – the following results could be obtained (see Table 2).

Table 2 Efficiency improvement in office buildings at the national level 2020

Action	*Measure*	*Saving*
Reduction of primary energy consumption	Tep	1,242,723
Economic valorisation of the reduction of primary energy consumption	Mln €	850
Avoided CO2	Ton CO2	2,787,163.1
Economic valorisation of avoided CO2	Mln €	46.0

The environmental impact of a national energy redevelopment program for office buildings, considering a time span of 30 years, would be more significant as indicated in Table 3.

Table 3 Efficiency improvement in office buildings over 30 years

Action	*Measure*	*Saving*
Reduction of primary energy consumption	Tep	1,331,489
Economic valorisation of the reduction of primary energy consumption	Mln €	911
Avoided CO_2	Ton CO_2	2,986,215,3
Economic valorisation of avoided CO_2	Mln €	49.3

In order to demonstrate the cost-effectiveness of investing in a smart building network management through technologically advanced tools, innovative and automated systems and cutting-edge methodologies, a simulator based on an Excel platform was created. The objective is to simulate a complete model of energy management of smart building networks, aimed at saving energy by designing systems with monitoring, diagnostics and control functions, which can be replicated at low costs (Unione Europea, 2014). The user, who will enter the inputs in the simulator, will be able to observe the dynamics of a network of buildings with similar characteristics. Currently, the simulator is limited to the fact that the network of buildings needs to present identical characteristics for all; however, it is possible to obtain more detailed results by treating each building separately and then entering inputs related to the individual buildings into the simulator. Furthermore, this simulation tool has been designed for the tertiary sector and provides results on a network of buildings that can be referred to both offices and schools. The choice between offices and schools involves different logical systems. For example, for schools there are different logics regarding electrical equipment (Romano, 2016). The simulator is developed based on the following five Excel sheets:

1 Input sheet: reference is made to the following items: structural characteristics of buildings; working hours; electronic equipment used; system that you choose to install. The entries are grouped into the following categories:
   - building reference
   - installation

- work times
- equipment and technologies
- heating
- cooling.

2 Costs sheet: this sheet shows all the costs that will be part of the CAPEX, i.e., the invested capital, and the OPEX, that is the operating or management capital (these are the costs that will be incurred in all the years considered). The main cost items are:

- Sensors costs.
- Installation costs: both those referring to the installation of sensors (i.e., design, installation and testing costs, audit, diagnostic calibration and optimisation calibration), and those of the network (depending on the type and functionality of the monitoring/diagnostics software and the installation of the NIS).
- Operating costs: consider cloud hosting costs and those of the software licenses.

3 Consumption and savings sheet: this sheet shows the consumption and the related bill costs, before obtaining any energy savings; furthermore, it reports the savings deriving from the different logics adopted, which are the following:

- Energy on demand logics: they consist in supplying the energy you need at the time and place where it is required. This leads to significant energy savings because it makes services more efficient and significantly reduces waste. It also allows for savings due to the renegotiation of contracts with electricity or heat energy suppliers.
- Optimisation logics: they consist in determining consumption optimisation rules (for instance night-time shutdown or absence of personnel, preventive maintenance, etc.).

The following are the categories of energy consumption, for which the relative cost savings can be calculated:

- lights
- electronic devices
- maintenance
- heating
- cooling.

4 Economic analysis sheet: this sheet includes a series of calculations, economic indicators and cash flow analysis. In detail, the main results of the previous sheets are reported (which depend on the levels of monitoring and control) and other data are also taken into consideration such as energy costs, their respective rates of increase and the discount rate.

5 Summary sheet: this sheet shows the (printable) summary of the main inputs, providing the technical and economic analysis that results from the user's preferences.

In conclusion, after entering the inputs related to their buildings, users will immediately have a clear and complete picture of the network trend as well as of the optimal management strategy, evaluating the economic results obtained by selecting different implementation scenarios of monitoring and control systems. It should be noted that, as the complexity of the network increases, there is a corresponding increase in the appropriateness of the investment deriving from the logic adopted on the network costs, which increase or decrease depending on the variation of both the sites and the number of buildings as well as the number of sensors installed. Therefore, as the size of the building network increases, costs are reduced until a threshold is reached at which the savings settle.

3 Results and discussion

In order to analyse the economic development of a network of buildings and to evaluate the effect of increasing the complexity of the network on the convenience of the investment, a comparison among various scenarios has been carried out. Particularly, different scenarios are compared ranging from one building and gradually growing with a network consisting of 2, 5, 10, 20, 50, 100, 500, 1,000, up to 10,000 buildings. The characteristics of the network of buildings, technologies and systems adopted have been set as equal for all the scenarios. The parameters included in the comparison take as a reference model a series of smart building interventions carried out by ENEA, and particularly the ‘F40’ building model (which is a highly representative office building). This building, which is part of the experimental smart village project at the ENEA Casaccia’s centre in Italy, has emerged as an important subject of study for several years in order to validate, on a real case, the development of methodologies oriented to the integrated management of a network of buildings. These studies were then also applied to a network of nine buildings, always within the smart village project. More in detail, the type of building taken into consideration concerns the tertiary sector and specifically the public sector offices. Moreover, for all the buildings, the same inputs have been set as the ones considered in the model.

Concerning the system chosen, it allows the monitoring at a level of detail of the area and the control at a level of detail of the single room. Therefore, it is a matter of installing innovative technologies, with an average life of 15 years, which give the possibility of obtaining energy savings allowing control with a very high level of intervention, thanks to the installation of sensors up to the rooms/offices. In addition, the network system adopted is based on hosting in the cloud. The main features are as follows:

- type of buildings: offices
- type of sector: public
- monitoring: zone level + control: room level
- system: hosting in cloud
- average life: 15 years.

Table 4 Different scenarios and related indicators

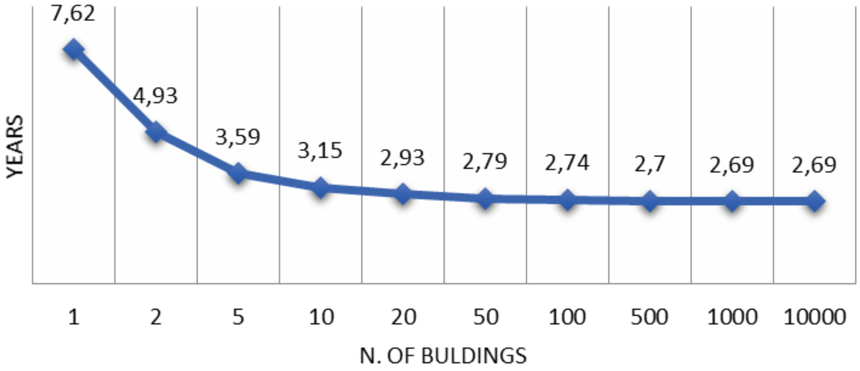
No. buildings	*Investment (€)*	*Total savings (€)*	*Total costs (€)*	*Net profit (€)*	*Net profit discounted (€)*	*PBP (years)*	*NPV (€)*	*IRR*	*ROI*
1	192,018	922,591	585,324	337,267	317,877	7.7	317,877	13%	166%
2	329,035	1,845,182	823,632	1,021,550	973,634	4.11	973,634	21%	296%
5	720,088	4,612,954	1,344,148	3,268,806	3,129,855	3.7	3,129,855	30%	435%
10	1,359,720	9,225,908	2,076,145	7,149,763	6,855,227	3.2	6,855,277	34%	504%
20	2,632,493	18,451,815	3,449,154	15,002,661	14,394,310	2.11	14,394,310	34%	547%
50	6,444,699	46,129,538	7,447,059	38,682,480	37,129,084	2.10	37,129,084	38%	576%
100	1,279,656	92,259,077	14,035,699	78,223,378	75,092,647	2.9	75,092,647	39%	587%
500	63,603,630	461,295,384	66,400,467	394,894,918	379,134,856	2.8	379,134,856	39%	596%
1,000	127,112,440	922,590,768	131,727,867	790,862,901	759,312,172	2.8	759,312,172	40%	597%
10,000	1,270,269,994	9,225,907,685	1,306,355,424	7,919,552,261	7,603,729,939	2.8	7,603,729,939	40%	599%

Thanks to the abovementioned simulator, it is possible to estimate the trend of the discounted cash flow and therefore easily verify the return on investment (ROI), which is considered at the break-even point (i.e., the point where revenues equal costs) (Mella and Navaroni, 2015). By comparing the various scenarios (see Table 4) there is a real convenience already starting from investing in this type of management of a single building, but it emerges even more as the number of buildings gradually grows up. Indeed, there is a considerable advantage in managing a network of buildings with a number of ten and more.

It can also be noted that, starting from a network of 500 buildings the payback period (PBP) begins to stabilise in two years and eight months, which is the same value for a network of 1,000 and 10,000 buildings, even if in these last two cases the model shows net present value (NPV) and ROI which continue to grow progressively.

The evidence presented so far can also be seen in Figure 1, which shows the trend of the PBP based on the number of buildings, and therefore in all the scenarios considered. The chart analysis shows how the PBP decreases as the number of buildings increases, since the return time of the investment decreases as the network grows.

Figure 1 PBP trend according to the different scenarios considered (see online version for colours)



Through an in-depth analysis of Table 4 this trend can be further confirmed. In fact, as the number of buildings increases, the investment increases, but also savings and costs. The latter, however, shows a less than proportional increase, demonstrating that there is a convenience in investing in a larger network due to the network effects that progressively lead to the proportional reduction of costs.

4 Conclusions

In the last decade there has been an undoubtedly rising interest in the field of intelligent and smart built environments from design and construction to management, operational and governance perspectives. These recent developments, observed at both academic and professional levels, can be classified into city, neighbourhood and building scales. In this context, understanding what is really meant by the word smart is crucially important, especially through practical cases and simulations (Ghaffarianhoseini et al., 2018). BEMSs are essential for any strategy to reduce energy consumption and maintenance costs, and are designed to provide complete control of the building's technological systems (Efficienza Energetica, 2017). Modern smart management systems can determine whether to start a process to optimise the heating or cooling of a building, ensuring the operation of the system only for the strictly necessary time, with huge savings on energy consumption (i.e., the *active demand*). The present study provides a methodology to identify the best scenario to invest in for the reduction of energy consumption, and focuses on public sector buildings, and particularly on the office and school sectors (Rete Irene – Riqualificazione Energetica, 2017). The main objective was to develop an empirical methodology of investigation that allowed to determine quantitatively, from both technical and economic viewpoints, the validity of possible interventions on the building/plant system, in order to identify the necessary actions to be taken to find the fund needed for a large-scale intervention (Deloitte Development LLC, 2018). The simulator developed allowed to obtain interesting results in modelling and quantifying the most important technical-economic variables in order to examine the economics of different intervention scenarios of the 'building network management' type for several scales and different application areas. In conclusion, it should be noted that this study must be considered as an exploratory approach to the problem stated, to which further developments, verifications and additions will have to follow. Therefore, the results that are exposed constitute an evaluation of the magnitude of the problem of interest and the potentialities that its solution can put in place. The generalisability and extension of these insights to wider scales is plausible but needs to rely on a larger set of buildings (at least 20–30, instead of the nine considered in the experimental project) so that they can be considered reliable and stable. Finally, other sectors, types of buildings and applications can be taken into account, and the simulation tool expanded with more indicators.

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