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# Building Automation and Control Systems and performance optimization: A framework for analysis

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ABSTRACT

The pressing global environmental issues are fostering a rapid change in the energy and sustainability policies for the built environment. New paradigms are emerging, such as "Nearly Zero Energy Building" (nZEB), and resource efficiency is progressively becoming a crucial topic in the building sector, implying an appropriate consideration of performance over the whole life cycle. However, empirical evidences show how, very often, the gap between the predicted (design phase) and measured (operation phase) performance is very large, due to errors committed during all the phases of building life cycle. This performance gap determines a problem of credibility in the building industry and, more in general, in sustainability oriented practices. Therefore, design and operation practices should evolve in order to be able to cope with performance uncertainty determined, for example, by evolution of climate conditions, variability of behavioural patterns and performance degradation of technological components.

For these reasons, a framework for the analysis of the potential of Building Automation and Control Systems for performance optimization is proposed. This framework aims to highlight, in particular, the possibility of establishing an effective methodological continuity among building performance simulation, control and data analytics, not immediately recognizable in current practices. Further, it aims to envision the possibility of creating a unified methodological approach, which could guarantee multiple feed-backs from measured data, useful for the evolution, first of all, of design and operation practices but also, more in general, of the whole value chain of the building sector.

## 1. Introduction

The reduction of the environmental impact determined by building technologies and services is fundamental for global sustainability today. In fact, residential and commercial buildings account at present for more than the 30% of the primary energy consumption at the global level [1] and for approximately the 40% of total primary energy in the EU [2] and in the US [3]. The energy demand related to heating, cooling and ventilation is often the predominant part, although the incidence of the energy use for appliances and lighting should not be underestimated, in particular in commercial buildings and, in some cases, even in residential ones [4,5].

In response to the issues of energy efficiency and renewable energy production, a new building paradigm has been conceived, that of "Nearly Zero Energy Building" or "nZEB" [6–12]. At the EU level, important initiatives are ongoing in the building sector with respect to sustainability assessment [13], energy efficiency of products and practices [14] and energy policy [15], up to the more general concept of resource efficiency [16], which implies an appropriate consideration of performance over the whole building life cycle. The nZEB paradigm embraces both new and refurbished buildings, in order to promote a radical renovation of the built environment.

Deep renovation strategies represent a fundamental chance of sustainable development [17] for the building sector and can act in synergy with the emerging economic and production paradigms, respectively circular economy [18] and Industry 4.0 [19]. This potential synergy constitutes an issue both from a regulatory [20,21] and a market point of view [22].

Several different regulatory definitions have been developed in EU countries [23]. In general, Nearly Zero Energy Buildings should combine very low energy demand with a relevant quota of onsite renewable energy production and should be able to reduce, as much as possible, the mismatch between demand and production [24–28]. Design choices in nZEBs should be optimal from the techno-economic point of view [29–33], considering clearly not only the initial investment cost, but also the energy-related running costs, in a life cycle cost accounting perspective [34]. There is however and increasing concern regarding the mismatch between simulated and measured energy

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performance [35]. This issue is generally addressed with the term "performance gap" [36]. Fundamentally, this gap can be determined by design phase errors, construction phase errors, commissioning and operation phase errors. These errors can directly reflect on energy performance and, consequently, on running costs and on global cost optimality. Therefore, this gap can create relevant problems in the case of deep retrofit practices, because of the constraints in terms of return of investments [22], or when Energy Performance Contracting (EPC) [37,38] is present for building services. In order to maintain the impact of these errors with acceptable and quantifiable performance ranges, adequate indicators and benchmarking strategies should be applied during building life cycle [39] and across the whole value chain of the sector [16,18]. The analysis of the measured performance represents the starting point for reducing the gap; therefore, applications aimed at monitoring energy and information flows [40,41] are essential. Building Automation and Control Systems (BACS), considering their Technical Building Management (TBM) capabilities [42], are essentially enabling platforms for the development in this direction. In fact, a good energy and environmental design, by itself, cannot guarantee appropriate performance levels during the whole life cycle without proper commissioning and technical management [24,43]. While monitoring strategies are mostly aimed at anomaly detection [44–46], other fundamental insights can be learned from data, by employing inverse modeling techniques [40,47,48] and calibrated energy simulation models [49–54], which can inform the design process (e.g. by comparing measured data with initial assumptions). Indeed, a unified methodological approach could possibly guarantee multiple feed-backs useful for the evolution, first of all, of design practices but also, more in general, of the whole value chain of the building sector.

However, up to recent years, control of energy performance in buildings has received less attention than in other application fields, like aerospace, petro-chemical, electronics or automotive [55], despite the fact that buildings waste a large amount of energy due to poor control performance and have, consequently, a large energy saving potential by improving it [55,56]. Finally, advanced control systems will be crucial to facilitate the integration of buildings within "intelligent" energy infrastructures [57–59] (e.g. the Smart Grid), in particular with respect to operational flexibility [60] and optimal dispatch of onsite resources (generation, storage, exchange with the grid, etc.) [61–69]. For these reasons, the paper addresses the most relevant issues of BACS for performance optimization. A more general overview about these topics can be found in [70,71].

## 2. Building Automation and Control Systems: motivation for research

As introduced before, the scope of the research presented is providing a general framework for the analysis of the potential of Building Automation and Control Systems (BACS) for performance optimization. Generally, buildings that are equipped with BACS and Technical Building Management (TBM) are addressed with the term "intelligent" or "smart" [72,73]. Although these terms are rather generic, we can state that the intelligence of a building resides in its ability to provide building services (thermal comfort, indoor air quality, lighting, etc.) while maximizing efficiency and cost savings and minimizing environmental impact [73–75]. More precise definitions related to building automation are present in literature [42]. Particularly relevant are the definition of Building Automation and Control (BAC), BACS and TBM. BAC are products, software, and engineering services for automatic control, monitoring and optimization, human intervention and management to achieve energy-efficient, economic and safe operation of buildings services equipment. BACS comprise all products and engineering services related to BAC and a term used alternatively to BACS is Building Management System (BMS). TBM involves all the processes and services related to operation and management of buildings and technical systems. TBM represents a part of Facility Management [76]. TBM involves not only the presence of automation and control systems but also their effective integration in operation [56]. All these definitions clarify the multidisciplinary role of automation and control, involving hardware and software. A survey about terminology related to automation and control in buildings can be found in [56].

The functions in BACS belong generally to the following main areas:

1. heating, ventilation and air conditioning systems (HVAC);
2. domestic hot water (DHW)
3. lighting system control;
4. shading systems control;
5. energy conversion and storage (heating and cooling);
6. onsite power generation;
7. monitoring and data acquisition;
8. communications and security management.

As made clear in the previous definition, BACS are aimed at energy-efficient building operation and, therefore, control and energy management functions are partially overlapping. As a consequence, BACS are also indicated as Energy Management and Control Systems (EMCS) [77].

Wang in [78] outlines an evolution pathway of these systems through the following steps:

1. *Dedicated Systems* (1980–85, all subsystems characterized by individual functions);
2. *Integrated Multifunction Systems* (1985–90, the individual subsystems were grouped into functional areas);
3. *Building Level Integrated Systems* (1990–95, first phase of integration at the building level of automation, BAS, and communication, ICS);
4. *Computer Integrated Building* (1995–2002, exploiting the capabilities of network technologies);
5. *Enterprise Network Integrated System* (ENIS) (after 2002, the integration is carried out at a higher level to connect even more buildings).

This evolution pathway determined an increasing level of integration among components, devices, systems and services, as summarized in Fig. 1.

At present, the digital revolution, which contributed to a major change in our behaviour and started to reshape the way we approach our "physical" objects, is bringing in a new concept, the "Internet of

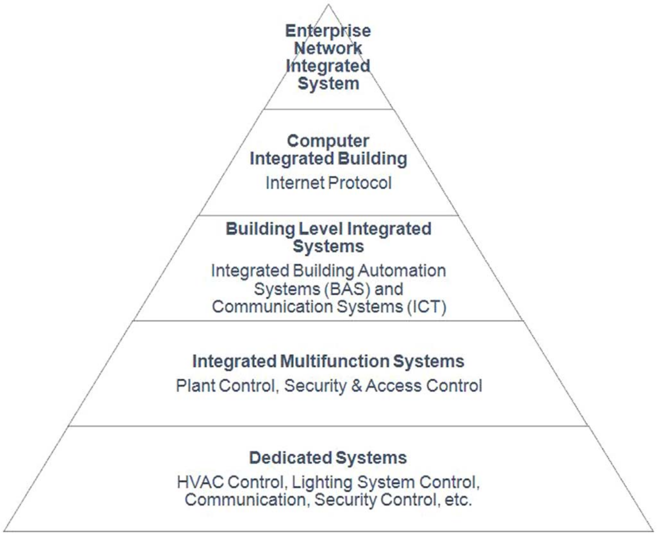

**Fig. 1.** Evolution pathway of Building Automation and Control Systems.