Rethinking Buildings Design, Construction and Management Through Sustainable Technologies and Digitization

Alessandro Carbonari, Elisa Di Giuseppe, Marco D'Orazio, Alberto Giretti, Massimo Lemma, Placido Munafò, Berardo Naticchia, Enrico Quagliarini, Francesca Stazi and Massimo Vaccarini

Abstract A technological development not threatening natural and human life is one of the core concepts of sustainability. In the construction sector, which is worldwide responsible of a huge consumption of energy and natural resources, thus strongly impacting on climate change, sustainability requires a prompt transition towards eco-friendly, smart and resilient buildings. However, despite the current Forth Industrial Revolution, where many sectors have been able to transform themselves improving productivity while lowering the environmental impact, construction is still suffering

A. Carbonari · E. Di Giuseppe (✉) · M. D'Orazio · A. Giretti · M. Lemma · P. Munafò · B. Naticchia · E. Quagliarini · M. Vaccarini
Department of Civil and Building Engineering and Architecture, Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy
e-mail: e.digiuseppe@univpm.it

A. Carbonari
e-mail: alessandro.carbonari@univpm.it

M. D'Orazio
e-mail: m.dorazio@univpm.it

A. Giretti
e-mail: a.giretti@univpm.it

M. Lemma
e-mail: m.lemma@univpm.it

P. Munafò
e-mail: p.munafo@univpm.it

B. Naticchia
e-mail: b.naticchia@univpm.it

E. Quagliarini
e-mail: e.quagliarini@univpm.it

M. Vaccarini
e-mail: m.vaccarini@univpm.it

F. Stazi
Department of Materials, Environmental Sciences and Urban Planning, Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy
e-mail: f.stazi@univpm.it

S. Longhi et al. (eds.), *The First Outstanding 50 Years of "Università Politecnica delle Marche"*, https://doi.org/10.1007/978-3-030-32762-0_20

from several intrinsic backwardness. A new approach is required. Sustainable product innovation and process digitalization are established roadmaps to reinventing construction throughout the whole building life-cycle: conception and design, planning and execution, operation and maintenance, end-of-life, reuse and recycling. This paper goes back over the major research results achieved by Construction division of the Department of Civil and Building Engineering and Architecture of Università Politecnica delle Marche in this context. It also outlines the emerging challenges and future directions of the research in this long-established sector.

1 Introduction

Construction industry is one of the largest sectors of the world economy. Every year, there is about $10 trillion in construction-related spending globally, equivalent to 13% of GDP, and the sector employs 7% of the world's working population. Furthermore, the buildings in which we live or work, which create our energy, materials and goods, and on which we travel, have an impact well beyond their own operational boundaries, including the natural environment and the social life. It is estimated that the building sector consumes about 40% of primary energy contributing to 23% CO_2 emission of the global economics activity [6], so a prompt transition towards sustainable buildings is urgent and vital. However, despite its enormous environmental and economic impact, the construction sector is not evolving at the right pace. Both high performance buildings and efficient construction processes are still on the horizon of the research perspective. The construction techniques of the inhabited areas have remained almost unchanged for centuries, even with variations linked to the different geographical and climatic contexts in the world. Only in the first decades of the twentieth century, with an ever-increasing use of reinforced concrete and the strong industrial drive of the post-war period, the way of living inside the buildings has been rethought and more performance has been required to building components, especially in the field of energy efficiency and sustainability.

On the other side, the construction process has suffered for decades from remarkably poor productivity and high environmental impact compared to other sectors. Concerning productivity, construction has evolved at a glacial pace with respect to manufacturing, where lean principles and aggressive automation have been transformative. Indeed, global labour-productivity growth in construction has averaged only 1% a year over the past two decades (it was flat in most advanced economies). Contrasted with growth of 2.8% in the world economy and 3.6% in manufacturing, this clearly indicates that the construction sector is underperforming [3]. Causes of this situation are manifold, however a common fundamental factor is that the construction industry has not yet embraced the new digital technologies that are needed to manage the complexity imposed by the globalization of the markets. Thus, large projects across asset classes still typically take 20% longer to finish than scheduled and are up to 80% over budget. A parallel trend to industry 4.0 is expected to invest the construction sector, generally known as Construction 4.0, implementing a significant growth phase through the adoption on a large scale of information and automation technologies.

In this paper these challenging issues are investigated, as they are driving the research at the Construction division of the Department of Civil and Building Engineering and Architecture (DICEA) of Università Politecnica delle Marche.

Section 2 reports the main results obtained by the Architectural Engineering group (AE) of DICEA in the development and optimisation of innovative, durable and sustainable technological solutions for existing and new buildings. Section 3 will investigate the enormous potential that the digitization of the construction process has in terms product quality, workers' safety and increase of productivity, as it is outlined by the research that is being carried out by the Design and Construction Management group (DCM) of DICEA. Main conclusions are drawn in Sect. 4.

2 High Performance Components, Advanced Assessment Tools and Occupant Behaviour-Based Building Design and Operation

Today, the building designer comes up against the need to choose among several design solutions and construction technologies, having to assess their performance according to multiple, somehow conflicting points of view, also considering current construction codes and standards. This process is even more complicated for existing and historic buildings, subjected to further architectural, social, cultural constraints, with high energy consumptions and safety issues. Furthermore, buildings are places where people live, work, enjoy, so the mutual interactions among occupants and built environment should be properly considered to improve the design and operations of buildings based on end-user needs, requirements, safety and preferences. DICEA AE group has been dealing with research in these topics for years, especially aiming to:

- the development of innovative, durable and sustainable materials and technological solutions for new and existing buildings and for cultural heritage;
- the development of advanced optimization and assessment tools for building performance, especially focusing on sustainability, energy, CO_2 emissions and costs;
- the development of smart and cognitive building components, based on embedded specific sensors-actuators, able to adapt their configuration to users' needs, in terms of environmental conditions and safety.

The following sub-sections presents the main research findings related to these topics and outlines future research perspectives, aimed to make future buildings and components, through their intelligent and "cognitive" features, able to more and more adapt and respond to the users' needs in terms of comfort and safety, by also considering economic and environmental issues in the building life-cycle.

2.1 Durability and Sustainability in Built Environment: Towards Highly Performing Building Components and Assessment Tools

One of the first research area of the AE group focused on existing buildings and cultural heritage, aiming to rediscover the technical know-how of the past in order to better safeguard both the material vehicles and the constructive systems that characterize the historical architecture. These studies concerned, for instance: wooden structures (floors and trusses), finishing elements (plasters), decorative elements of façades (Renaissance cornices, frames for window linings). Special attention was given to earth constructions in Marche Region and to the architecture of early decades of the 20th century [22].

In the last decades, in response to the first energy crises and with the emerging awareness of the environmental impact of the construction sector, energy efficient and sustainable components have been proposed and applied to new and existing buildings to reduce the energy consumption and the consequent environmental impact. AE group contributed to this research field, by developing and/or optimising innovative, durable and sustainable technological solutions. Investigations were conducted through integrated methodologies including laboratory tests, on site monitoring of real buildings, experimental campaigns on test rooms and numerical evaluations. The main outcomes in this field concerned the building envelope, including the development and optimization of external opaque components, transparent surfaces, internal finishing materials and load bearing preassembled units.

As regards the *opaque components*, several numerical and experimental studies, both on-field and on test rooms, were focused on the comparison of different type of components in order to identify the most efficient solutions according to several points of view (e.g. energy efficiency, mitigation of urban heat island (UHI), optimization of indoor comfort, costs reduction), especially considering the Mediterranean climatic context. Studies included passive solar systems, ventilated facades and insulated envelopes, as in [1]. Prototypes for facades with different typologies of layers and external claddings were experimented and patented (Italian Patent no. 0001407018).

Special attention was paid to building roofs, as a significant amount of the heat exchanged between building and internal and external environment is via the roof. In [20], Di Giuseppe et al. carried out experimental and numerical activities in order to extensively characterize the optical properties of roofing materials and investigate their impact, also coupled with above sheathing ventilation, on the thermal performance of a roof under warm-temperate climate. In [17], ventilated, green and cool roofs have been compared under real climatic conditions.

The impact of the introduction of specific requirements on highly insulated envelope for energy efficient buildings in Mediterranean climate has been investigated in detail, considering the potential negative effects in terms of indoor summer overheating and biofouling of internal and external facades [16], in order to actively contribute to a review of the current legislative framework.

The *transparent surfaces* of the building envelope have been largely investigated through experimental comparative studies on several glass smart coatings and frame materials, also evaluating the potential of integrating nanotechnologies [30]. Moreover, different external shadings were experimentally compared, the consequent thermal and visual comfort analysed, and the best solutions identified. A new profile for glazed wall facades to reduce the visual impact of the external frame was also developed [33] and patented (European Patent WO2015/071882A1). Researches carried out on the interaction of building occupants with windows, led to the development of an automatized system for windows opening/closing according to real users' preferences, by tuning a behavioural algorithm on experimental data.

Several studies of AE group also focused on *building internal envelope finishing and components,* aiming to improve the thermal and hygrometric performance. Stazi focused on the identification of the optimal levels of thermal inertia to achieve occupants' comfort and energy saving and proposed new limits for envelope dynamic thermal parameters, to guide the design of future building envelopes [29]. Studies have been carried out on different internal finishing systems, also including phase change materials. New components aiming at the improvement of the Indoor Air Quality have been developed, e.g. a dynamic insulation systems integrating thermal and filtration functions, and an active device for indoor humidity control based on moisture buffering materials [18].

As regards *the loadbearing envelope components*, studies have been carried out on the development of integrated energy-structural solutions using new materials such as composite profiles, nanofoamed insulations, seismic dissipating rubbers, cross-laminated timber panels. The materials and assembled components were tested to identify durable and energy efficient solutions with improved seismic performance.

Furthermore, during recent years, the development and application of further new materials and technologies has been investigated, aiming to reach a technological and construction simplification compared to the existing products. These are, e.g. structural glass, structural adhesives, ceramics. A new constructive/structural principle, based on tensegrial structures, has been patented (Italian Patent no. 0001426973). Alderucci et al. have tested the mechanical performances of structural joints with several possible applications (for example pultruded/pultruded, glass/pultruded, glass/aluminium, pultruded/steel, glass/glass, etc.) made with different structural adhesives typologies in environmental conditions [2]. Further invented technologies are being patented, including a collaborating deck with structural adhesives and a strut for curtain walls. In collaboration with small and medium enterprises, the industrial production processes of some of these technologies have also started.

Given the growing need of proper decision-support tools for buildings design and operation, addressing all the complex set of environmental and economic issues, AE group research is recently geared toward the development of advanced assessment methodologies and softwares. An assessment tool has been developed, combining parametric building energy simulation and life cycle cost calculation, to provide designers an efficient mean of comparing the affordability of energy efficiency measures. Stochastic approaches to Life Cycle Assessment (LCA) and Costing (LCC)

Fig. 1 Exemplary page of the software tool developed by AE group for the probability-based LCA/LCC of building renovation measures

of building renovation were proposed [19], in order to overcome the limits of traditional "deterministic" methods based on notable simplifications and hypothesis that may affect results' reliability. A specific building renovation LCA and LCC software, based on these methodologies, has been developed during the framework of the Horizon 2020 project RIBuild[1] (Fig. 1). These works demonstrate the potential of probability-based building assessment in providing robust and realistic results.

2.2 *Safety and Energy in Built Environment: Towards a (Human) "Behavioural Designed" Approach*

The design of architectural spaces generally follows a "schematic" and "deterministic" approach. The architect generally believes that space configurations could be enough for inducing occupants to behave as he imagines. This approach seems to exclude behavioural aspects: real-world environments demonstrate how theoretical solutions scarcely comply with users' attitudes, desires' and, above all, behaviours inside buildings. People behaviour is indeed recognized as one of the key factor for the buildings energy assessment. People actions have a strong influence on the indoor environment both in a passive and active way. The former is related to users as sources of heat, vapour and CO_2, the latter concerns the interaction between people and building systems and devices (windows, heating equipments, etc.), not necessarily coherent with the energy reduction needs and caused by the perceived quality of the internal environment at each moment of the day [31].

---

[1] www.ribuild.eu.

The underestimation of the importance of the human component in the simulation environment led in the past to significant discrepancies between real and simulated building performances. Most of simulation softwares adopt yet simple deterministic rules to model behavioural features. These tools, neglecting the stochastic character of people behaviour and possible interactions between different users, are barely able to reproduce the actual patterns of occupancy and the interactions with the building devices. Unfortunately, this approach is still the most diffused, although some signs of progress have been achieved in last years.

Following the necessity of a shift in the research paradigm from the optimization of the components to the optimization of the interactions among people and components, AE group directed its efforts towards the experimental recognition of typical behavioural patterns and the development of simulation tools able to predict human-building interactions. Experimental activities have been performed to recognize typical behavioural patterns related to offices, dwellings, schools and other building types [23]. Surveys were performed using dedicated sensor networks to monitor environmental variables, and to determine the presence of people and their interactions with windows, plants and appliances. Then data-driven behavioural models have been developed to predict users' interactions with building devices [32]. The behavioural framework has been coupled with a simulation engine through a co-simulation approach which allowed the data exchange during the simulation runtime (Fig. 2). The research is addressed to extend to different building typos and climates developed behavioural models.

Human behaviour issues are relevant especially in emergency conditions (e.g.: evacuation and post-disaster phases) and are noticed at both building and urban scale. In fact, in case of disaster, the individuals' safety depends on interactions between buildings vulnerability, related to post-event damages and environmental conditions, human reaction to hazardous situations. As demonstrated by the recent research at the AE group, such interferences are critical in case of different man made (fire, terrorist acts) and natural (flooding, earthquake) emergencies, because of built environment features like: intrinsic hazard (presence of fire sources; positioning in earthquake or floods hazard-prone areas); intrinsic built elements vulnerability and

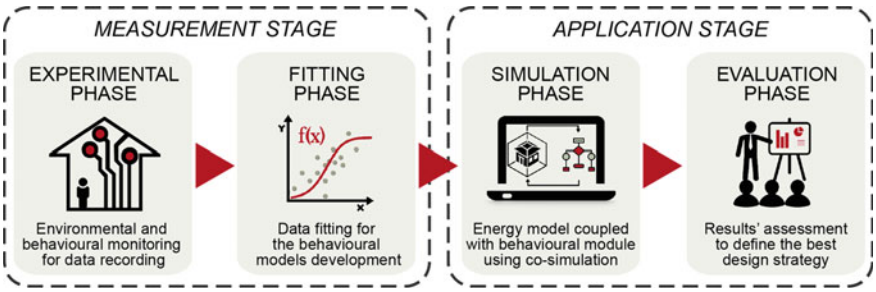

Fig. 2 Schematic illustration of the methodology developed by AE group for the experimental recognition of typical occupant behaviour patterns and their application in energy simulation softwares

correlation with event-induced damages (materials fire vulnerabilities; seismic vulnerability; structural vulnerability to floods); spatial layout, especially in complex spaces like urban ones, historical scenarios and public buildings, which can also have hinder safety to specific individuals' categories (disabled, elderly); possible individuals' low familiarity with the layout (visitors, tourists); high hosted people's density that introduces crowding safety stressors; organization of emergency management to cope with disaster by supporting the population evacuation (i.e.: evacuation plan; monitoring, alarm systems, wayfinding facilities). AE group work focuses on a "behavioural design" (BD) approach for increasing people's safety in architectural spaces [4]. BD is aimed at adapting architectural spaces depending on human behaviours. Defining how individuals behave in emergency conditions provides essential elements for safety assessment evaluation and risk-reduction strategies proposals. Evacuees-evacuees, evacuees-environment and evacuees-emergency management system interactions can be highlighted during the assessment and design phase, thus focused interventions and evacuation planning strategies can be proposed. Hence, methodology phases include:

1. *Understanding behaviours*: experiments/real world events analysis (mainly focused on human motion) both qualitative (behavioural), quantitative (motion quantities) and perception (i.e. brain activities) data are collected in relation to specific disasters conditions (fire, flood, earthquake);
2. *Developing evacuation simulation model*: models and simulators are defined and validated against experimental results [12] by integrating disaster-induced architectural spaces modifications due to disaster;
3. *Analysing emergency processes*: simulators are used to represent specific emergency conditions [4], and risk indexes are considered to include human factor in overall analysis [4, 27, 28], as: evaluation on the number of injured people/fatalities due to the disaster; probabilistic assessment of used evacuation paths in terms of evacuees' flows/densities; estimation of assembly areas use and possibility of "spontaneous" gathering areas; calculation of overall evacuation times.
4. *Proposing safety solutions*: they are based on retrieved critical behaviours and the impact is verified by simulator or drills [5]. Solutions include management strategies for rescuers, Internet-of-Thing based solutions which can directly help evacuees by using personal devices and intelligent evacuation signs.

Results show how emergency patterns could be retrieved to allow safety designers to propose a scheme for evacuation modelling and risk-mitigation strategies depending on the peculiar disaster reactions, especially for motion quantities. Using similar design methods based on effective human behaviours could lead to high level of sustainability for tomorrow architectural spaces, by: proposing interventions within the built layout where they are effectively needed by occupants; activating the response of building components only when they are needed by occupants; supplying information to occupants in the clearest way, and in each environment condition.

3 Construction 4.0—Productivity and Sustainability in the Digital Construction Industry of the Second Millennium

Having access to accurate information on time and in place is pivotal for construction management to tackle the remarkably poor productivity suffered for decades. The latest development of Digital Information and Communication Technologies provide the background to implement new revolutionary construction methodologies that will ensure the design is built and delivered in accordance with quality requirements, on time and within budget. The digitization of design and construction processes will drive the near future development of the construction sector. Digitization is about knowledge and value encountering connected systems and processes at every level of the operational chain. It is about working with ICT tools and processes that empower managers, filed engineers and workers by untangling the projects' values, allowing in-depth analysis of real situations, shortening reaction time to unforeseen events, and in general connecting the abstract understanding of the project with the contingency and the variability of the real domain. Four research lines have been identified at the DCM group of DICEA for the implementation of the digital construction vision, which are based on the envisage of a planning process grounded on lean design and construction principles:

- *Lean Building Design*—The biggest impact on productivity would come from institutionalizing value management and engineering throughout the building life cycle, from design to construction and operation. Strong and clear value chains propagating through the project development will reshape the relationships and interactions between owners and contractors. Constructability, sustainability and resilience will thus become major drivers of the design process, operationalizing along new dimensions the long-established efficiency end economy objectives.
- *Building Intelligence*—New constructions and refurbishment projects can achieve significant improvements in terms energy efficiency and sustainability by lowering the use of materials with high energy footprints, through the adoption of advanced intelligent technologies aimed at optimising the overall building behaviour in existing conditions.
- *Real-Time Construction Management*—Substantial improvements in construction efficiency can be achieved by means of real-time management supported by pervasive sensing and on-site site intelligence. Capturing information in real time, while the site and the whole process is in operation provides readily available data that improve the construction process in several areas, namely finance, quality and progress monitoring. Improved site information management would enhance progress measurement, equipment and material tracking, safety planning and productivity tracking. The new management approach will be supported by ubiquitous computing, on-demand access to a shared pool of configurable computing resources (e.g. networks, servers, applications, devices, data) that can be quickly accessed and discharged with minimal service provider interactions. Platforms such as 5D BIM would establish transparency in design, costing, and progress

visualization. On-site productivity can be boosted by implementing a cloud-based control tower that rapidly assembles accurate data in near real time, which supports advanced analytics to improve on-site monitoring of materials, labour and equipment productivity. Once working places can be connected, off-site fabrication can be encouraged by developing new lightweight materials and construction methodologies, which facilitates the adoption of advanced automated equipment and tools (bricklaying and tiling robots), which can accelerate on-site execution.

- *Operation and Maintenance*—Information management during the building operation phase represents one of the most critical aspect in the management of facilities. The retrieval of specific data during the lifecycle of buildings in fact represents a high cost for all the stakeholders involved in this field. The digitalization of the Architecture, Engineering and Construction industry is a great opportunity to improve this process, by providing geo-located and timely information pervasive sensing and through augmented reality technologies.

In the following sections, some of the main results achieved so far by the DCM group for the above topics are summarized, providing reference to the main papers.

3.1 Real-Time Construction Management

Construction projects are significantly affected by the level of awareness about the project status. Information has inherent value for real-time or near real time decision making in construction management. Good resource procurement and allocation, project risk mitigation and safety assurance can be effectively assessed if a relevant and timely information flow is provided to the decision makers. In this field a proper ICT technology development is necessary to interface the construction site dynamics and harshness. The following results show that current technology let one trace the construction site workflow in such a way that safety and productivity can be significantly improved.

In [9] an advanced system for the real time tracking of workers' paths in construction sites, aimed at preventing workers' hazardous situations, has been investigated. This research was part of a wider ongoing research concerning the development of a new generation of advanced construction management systems, allowing for real-time monitoring and coordination of tasks, automatic health and safety management, on-site delivering of technical information, capture of as-built documentation. Exploiting the high accuracy provided by the ultra wideband (UWB) system responsible for position tracking, the proposed solution can trace movement patterns of workers and induce likely paths. The system constantly monitors hazardous areas accesses, using its path prediction capability, in fact performing virtual fencing. In [14] the strength and weakness of UWB position tracking technology, and its completion with Zigbee technology, applied to building construction environments have been further investigated. UWB position tracking has demonstrated to be completely reliable in real world construction sites up until the completion of structural frames, providing support for real time management and health & safety tasks. The UWB indoor tracking capabilities in boundary installations fade considerably when envelopes and partition walls are raised. In these cases, optimized UWB design with increased number of receiver or hybrid design merging UWB with *ZigBee* based zoning systems are both possible. In the first case the tracking resolution of the UWB system is maintained at the expense of an increased number of receivers, rising significantly the equipment and installation costs. Anyway, it is often the case that UWB boundary installation cannot suit indoor tracking in some spaces whatever number of receivers is used. In that frequent case hybrid mode position tracking design can provide support for high level management tasks. In general, hybrid mode position tracking in construction sites is still an open research issue. More specifically the open issues concern the sensor fusion approach and the relation between the tracking accuracy and the level of support of high-level management tasks. Sensor fusion can be as simple as switching between systems in case of tracking failure, or much more complex as merging information at data processing level, developing hybrid TOA-SS algorithms. How optimized performance can be achieved in hybrid frameworks through careful layout design of hybrid sensor systems is a second point that requires investigation and on-site testing. In this chapter we have shown how boundary UWB set-ups can be complemented by *ZigBee* zoning systems deployed in the inner indoor spaces. Nevertheless, in these cases some redundancy can be used to increment reliability of the UWB tracking and the robustness of the overall solution. To what extent this can be done is still a research topic. Finally, the localized lower resolution provided by the *ZigBee* zoning system may potentially downgrade the support to the high-level management tasks. This depends both on the resolution and on the specific lay-out of the tracking solution with respect to the spatial arrangement of the working activities. Naticchia et al. [25] and Carbonari et al. [10] survey the feasibility of a cable less real-time monitoring system to provide prompt support for inspectors in charge of health and safety management on construction sites. The system was tested in the specific application of monitoring interference between teams working on large construction sites. The system accounts for a wireless and untethered tracking technology and a local server running a software tool for handling collected data, real-time site state visualization and remote interaction with safety inspectors. The low-level tracking technology is a ZigBee-based easily deployable and reconfigurable technology. In this paper the system is found to be able to cover large fields while keeping its non-invasive features, thanks to the implementation of a novel low-power approach. This paper shows the degree of support inspectors can get from the system: it is able to alert in the occurrence of interference and to log any unexpected behaviour.

Giretti et al. [13] provide further development of real-time monitoring technology by investigating the application of intelligent probabilistic models to real-time estimation of construction progress, which operate based on a continuous data flow collected by monitoring networks deployed on-site. Several authors listed the advantages that would be provided by the availability of such models, like project performance and quality control, timely onsite inspections, better control of health and safety prescriptions against job injuries and fatalities. The findings reported in this paper represent a feasibility study and preliminary examples of Bayesian Networks, which can infer the work progress attained at every step, starting from real-time tracks of the construction site activities. Activity tracks are represented as a set of state variables representing workers' effort, equipment and materials usage rates and other knowledge about the context. As estimations are always related to dynamic processes, Dynamic Object-Oriented Bayesian Networks have been used to develop a set of first order Hidden Markov Models. Hence, the models are arranged as a sequence of time steps, where each time step propagates evidences collected by the site monitoring sensor network along the time line. The actual cumulative progress is computed as a function of the progress achieved in each time step. Models representing several typical tasks (external piping, on-site cast of reinforced concrete floor slab, walls erection, ceiling installation) for a real case of a construction site have been developed. Their structure has been designed as part of a general monitoring framework, covering all the phases from design to execution, where BIM design, monitoring systems, methodological process innovations, intelligent inferences and advanced visualization are combined. The networks have been developed and validated through data collected from a real case, and they have been shown to be able to infer work progress, the accuracy of which depends on the resolution and quality of the collected data.

3.2 Digital Frameworks for Real Estate and Facility Management

Building operation is the phase of the entire building life cycle which produces the highest costs. However, to date little attention has been paid to its optimal management. ICT can provide significant advances in this field. The digital approach to real estate and facility management relies on a juxtaposition of emerging ICTs which are all grounded on the BIM technology. Then cloud systems for distributed data management, artificial intelligence for decision support, and mixed reality for on-site operation support, provide the background for advanced facility management solutions.

The efficiency issue in facility management surveying is discussed in [7]. Surveying of large real estate management is an expensive activity that affects strategic management, providing data for key performance indicators, and the operation & maintenance, through the assessment of the status of systems' components. The paper proposes a system that performs multicriteria probabilistic assessment of key performance indicators related to accessibility, energy efficiency and acoustic comfort with reduced time and costs. This is made possible using Bayesian Networks models that are able to incorporate different level of certainty about data, thus providing a graded and smoothed outcome of the assessment process with respect to the available information. The research discussed in [8] is analogously concerned with the management of large building stocks, where available information is often incomplete and the process of information updating is expensive and time consuming. Many public administrations, developing BIM models of their stock to mitigate the lack of information issue, are encountering severe problems in making the modelling process sustainable, due to the high cost of surveying and information filling. The paper presents a decision support tool, aimed at can help prioritizing refurbishment actions on large building assets, based of probabilistic models, that mitigate the information lack by quantifying the uncertainty level of approximate assessment. The system supports multi-criteria decision by means of Bayesian Networks models instantiated automatically from BIM models. Key Performance Indicators corresponding to different requirements are compared through multi-criteria analysis, each building is assigned an overall score and a ranking is created. Naticchia et al. [24] aim to provide advanced support for the operation and maintenance phase during building life-cycle. This study focuses on the combined use of three key technologies, the BIM for data management, cloud-based management of the information flows and onsite operation support through mixed reality.

3.3 Intelligent Control of Building Systems

The construction 4.0 revolution cannot but affect the building itself. Intelligent buildings are the natural technological evolution of traditional passive buildings. The pervasive layout of sensor and communication networks makes possible intelligent control, optimised performance and advanced interactions with the occupants. So, intelligent building modelling and controlling, and occupants' behavioural models are key research themes in this area. Casals et al. [11] and Vaccarini et al. [34] reports about the intelligent energy control of a metro station in Barcelona, developed within the SEAM4US FP7 EU project. The predictive energy control was implemented by means of a stochastic model of the energy behaviour of the metro station. High rate of energy saving was achieved by dynamically adapting the various fan speeds to the environmental indoor and outdoor conditions measured to an extended sensor network. Predictions were provided by a stochastic model of the station whose parameters were induced from measured data. This kind of models can be extended to house environment once behavioural models of the occupants are developed. Jones et al. [21] investigate about the possibility of predicting home occupants' behaviour concerning windows operation from environmental data. Finally, the same models used for control can be adopted in performance contracting. Intelligent buildings are more reliable in providing established level of performance. Thus, both Principi et al. [26] and Giretti et al. [15] investigate minimum information modelling methodologies suited to provided rapid and reliable assessment of energy consumption and robust forecasting.

4 Conclusions

Even if construction industry is one of the largest sectors of the world economy, it is suffering for decades from poor modernisation, thus maintaining huge energy and environmental impacts. The recognized road to innovation in this sector is based on technology development and digitization, in order to reach higher levels of sustainability and resiliency facing the actual climate challenges. The paper discussed the major research results achieved by the Construction division of the Department of Civil and Building Engineering and Architecture (Università Politecnica delle Marche), concerning optimised innovative, durable and sustainable technological solutions for building design, construction and management. From the outlined framework, the following key research directions emerged:

- the development of building technologies able to integrate, in a logic of constructive simplification, multiple aspects and functions, as energy efficiency, seismic resistance and high durability, reducing environmental impacts, costs and construction time;
- the development of "cognitive" building technologies able to adapt and respond to the users' needs, involving several performance domains (e.g. energy, comfort, safety, durability);
- the development of effective building design and management tools, able to address in an efficient way all the complex set of design, performance, environmental and economic issues;
- the development of a real-time construction management approach, supported by pervasive sensing and on-site site intelligence;
- the development of digitization of design and construction processes, in order to optimize these processes.

Addressing all these challenges is the actual contribution of the Construction division of DICEA for a more sustainable and resilient Construction 4.0.

References

1. Alderucci T, Patrono L, Rametta P, Munafo P (2018) The effectiveness of an internet of things-aware smart ventilated insulation system. Therm Sci 22:909–919. https://doi.org/10.2298/TSCI170906024A
2. Alderucci T, Terlizzi V, Urso S, Borsellino C, Munafò P (2018) Experimental study of the adhesive glass-steel joint behavior in a tensegrity floor. Int J Adhes Adhes 85:293–302. https://doi.org/10.1016/J.IJADHADH.2018.04.017
3. Barbosa F, Woetzel J, Mischke J, Ribeirinho MJ, Sridhar M, Parsons M, Bertram N, Brown S (2017) Reinventing construction: a route to higher productivity
4. Bernardini G, D'Orazio M, Quagliarini E (2016) Towards a "behavioural design" approach for seismic risk reduction strategies of buildings and their environment. Saf Sci 86:273–294. https://doi.org/10.1016/j.ssci.2016.03.010
5. Bernardini G, Postacchini M, Quagliarini E, D'Orazio M, Brocchini M (2019) Flooding pedestrians' evacuation in historical urban scenario: a tool for risk assessment including human

behaviors. In: Aguilar R, Torrealva D, Moreira S, Pando MA, Ramos LF (eds) RILEM bookseries, 1st edn. Springer, Cham, Cham, pp 1152–1161

6. Buyle M, Braet J, Audenaert A (2013) Life cycle assessment in the construction sector: a review. Renew Sustain Energy Rev 26:379–388. https://doi.org/10.1016/j.rser.2013.05.001
7. Carbonari A, Corneli A, Di Giuda G, Ridolfi L, Villa V (2018) BIM-based decision support system for the mangement of large building stocks. In: 35th International symposium on automation and robotics in construction (ISARC 2018). Berlin, Germany, pp 348–355
8. Carbonari A, Giretti A, Corneli A, Villa V, Di Giuda GM (2017) Decision support tool for multi-criteria analyses of the quality of large building stock. In: 34th international symposium on automation and robotics in construction and mining (ISARC 2017). Taipei, Taiwan, pp 22–29
9. Carbonari A, Giretti A, Naticchia B (2011) A proactive system for real-time safety management in construction sites. In: Automation in construction. Elsevier, pp 686–698
10. Carbonari A, Giretti A, Naticchia B (2014) Automation solutions supporting real-time safety and work progress management in construction. In: International scientific conference on construction technology and management (CTM 2014), pp 98–104
11. Casals M, Gangolells M, Forcada N, Macarulla M, Giretti A, Vaccarini M (2016) SEAM4US: an intelligent energy management system for underground stations. Appl Energy 166:150–164. https://doi.org/10.1016/j.apenergy.2016.01.029
12. D'Orazio M, Quagliarini E, Bernardini G, Spalazzi L (2014) EPES—Earthquake pedestrians' evacuation simulator: a tool for predicting earthquake pedestrians' evacuation in urban outdoor scenarios. Int J Disaster Risk Reduct 10:153–177. https://doi.org/10.1016/j.ijdrr.2014.08.002
13. Giretti A, Carbonari A, Novembri G, Robuffo F (2012) Full paper: estimation of job-site work progress through on-site monitoring. In: ISARC 2012 proceeding of the international symposium for automation and robotics in construction. https://doi.org/10.4017/gt.2012.11.02.348.704
14. Giretti A, Carbonari A, Vaccarini M (2012) Ultra wide band positioning systems for advanced construction site management. In: New approach of indoor and outdoor localization systems. InTech, pp 89–113
15. Giretti A, Vaccarini M, Casals M, Macarulla M, Fuertes A, Jones RV (2018) Reduced-order modeling for energy performance contracting. Energy Build 167:216–230. https://doi.org/10.1016/j.enbuild.2018.02.049
16. Di Giuseppe E (2013) Nearly zero energy buildings and proliferation of microorganisms. Springer International Publishing, Cham
17. Di Giuseppe E, D'Orazio M (2014) Assessment of the effectiveness of cool and green roofs for the mitigation of the Heat Island effect and for the improvement of thermal comfort in Nearly Zero Energy Building
18. Di Giuseppe E, D'Orazio M (2014) Moisture buffering "active" devices for indoor humidity control: preliminary experimental evaluations. Energy Procedia 62:42–51. https://doi.org/10.1016/j.egypro.2014.12.365
19. Di Giuseppe E, Iannaccone M, Telloni M, D'Orazio M, Di Perna C (2017) Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: methodology and application example. Energy Build 144:416–432. https://doi.org/10.1016/j.enbuild.2017.03.055
20. Di Giuseppe E, Sabbatini S, Cozzolino N, Stipa P, D'Orazio M (2018) Optical properties of traditional clay tiles for ventilated roofs and implication on roof thermal performance. J Build Phys
21. Jones RV, Fuertes A, Gregori E, Giretti A (2017) Stochastic behavioural models of occupants' main bedroom window operation for UK residential buildings. Build Environ 118:144–158. https://doi.org/10.1016/j.buildenv.2017.03.033
22. Munafò P, Tassi C (2009) L'edificio ex G.I.L. di Macerata. Florence (Italy)
23. Naspi F, Arnesano M, Zampetti L, Stazi F, Revel GM, D'Orazio M (2018) Experimental study on occupants interaction with windows and lights in mediterranean offices during the non-heating season. Build Environ 127:221–238. https://doi.org/10.1016/j.buildenv.2017.11.009

24. Naticchia B, Corneli A, Carbonari A, Bonci A, Pirani M (2018) Mixed reality approach for the management of building maintenance and operation. In: 35th international symposium on automation and robotics in construction (ISARC 2018), pp 191–198
25. Naticchia B, Vaccarini M, Carbonari A (2013) A monitoring system for real-time interference control on large construction sites. Autom Constr 29:148–160. https://doi.org/10.1016/j.autcon.2012.09.016
26. Principi P, Roberto F, Carbonari A, Lemma M (2016) Evaluation of energy conservation opportunities through energy performance contracting: a case study in Italy. Energy Build 128:886–899. https://doi.org/10.1016/j.enbuild.2016.06.068
27. Quagliarini E, Bernardini G, Santarelli S, Lucesoli M (2018) Evacuation paths in historic city centres: a holistic methodology for assessing their seismic risk. Int J Disaster Risk Reduct 31:698–710. https://doi.org/10.1016/j.ijdrr.2018.07.010
28. Santarelli S, Bernardini G, Quagliarini E, D'Orazio M (2018) New indices for the existing city-centers streets network reliability and availability assessment in earthquake emergency. Int J Archit Herit 12:153–168. https://doi.org/10.1080/15583058.2017.1328543
29. Stazi F (2017) Thermal inertia in energy efficient building envelopes. Elsevier
30. Stazi F, Giampaoli M, Tittarelli F, Di Perna C, Munafò P (2016) Durability of different glass coatings in humid and saline environments, ageing impact on heat-light transmission and thermal comfort. Build Environ 105:210–224. https://doi.org/10.1016/j.buildenv.2016.05.029
31. Stazi F, Naspi F, D'Orazio M (2017a) A literature review on driving factors and contextual events influencing occupants' behaviours in buildings. Build Environ 118:40–66
32. Stazi F, Naspi F, D'Orazio M (2017b) Modelling window status in school classrooms. Results from a case study in Italy. Build Environ 111:24–32. https://doi.org/10.1016/j.buildenv.2016.10.013
33. Terlizzi V, Alderucci T, Munafò P (2017) An innovative window with an invisible frame: from the applied research to the industrial production. Tema Technol Eng Mater Archit 3:61–71. https://doi.org/10.17410/tema.v3i2.142
34. Vaccarini M, Giretti A, Tolve LC, Casals M (2016) Model predictive energy control of ventilation for underground stations. Energy Build 116:326–340. https://doi.org/10.1016/j.enbuild.2016.01.020