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PhD Yearbook | 2023

Chair:
Prof. Marco Scaioni

DOCTORAL PROGRAM IN ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING

Vision

The Doctoral Program in Architecture, Built Environment and Construction Engineering (ABC) started in 2012 from the evolution of five older programs, active since the institution of the Italian Dottorato di Ricerca (PhD) in 1988. The aim of the ABC-PhD Program is to become a national reference point for training researchers and experts in the following fields:

- the sustainable transformation and management of the Built Environment, holistically viewed as an environmental, economic, cultural and social ecosystem, as well as time and space series of Architectures and cultural landscapes;
- the Engineering of buildings and components, structures and infrastructures, materials and service systems those architectures and landscapes are part of;
- the organization of the Industrial Systems that design, realize, manage and transform them and the Public Administration System that defines the rules for taking care of their value as social assets.

Program organization

The Program pursues the following ten pillars:

1) Selection through a transparent open process.
2) Candidates as independent, mentored and monitored, researchers.
3) Training plans tailored on Candidate's research topic and needs.
4) Training activities based on research practice.
5) Research practice hinged on the framework of Department activities.
6) Transparent tracking of Candidates' scientific production.
7) Systematic assessment and open and supportive peer review of Candidates' advancements.
8) Candidates as hot spots of international research institutions.
9) Systematic valorization of PhD holders and their products among stakeholders.
10) Candidates as active part of the Program's Quality Management System.

The award of ABC-PhD title requires that Candidates, under the control of their Supervisors:

- plan and carry out a three year, full-time, research activity
- plan, attend and pass, with positive evaluation, a complementary series of Doctoral Courses, to complete her/his skills as researchers
- develop a PhD thesis and defend it, in a Final Exam session certifying its original advancements on a specific topic

For what concerns courseware, ABC-PhD Program boasts a wide (more than 20 titles/yr), diverse, educational assortment on cutting edge, specialized, research topics. It is an open list of courses that changes, year after year, following Candidates' needs as well as the opportunities offered by the Department. This list is further enriched with the transferrable skills courses offered by the PhD School and may be integrated by the offer of all the university Doctoral Programs.

Academic, industrial and social collaborations

Each Candidate is mentored by one main Supervisor and inherits Supervisor's Scientific Sector as reference. Due to the multidisciplinary nature of our wide research field, nevertheless, his/her activity may be supported by other co-Supervisors to make stronger, sounder and more reliable his/her final research product. The main effort of the ABC-PhD Program Board is to keep Candidates research works constantly reviewed, involving every useful, available competency from the ABC Department, other Departments or other national and international Universities and Research Centers. Each Candidate is also assigned to a member of the Program Board, which serves as individual Tutor with the aim of constant independent monitoring of his/her activity.

Moreover, each Candidate is progressively encouraged to confront his/ her position, project, intermediate products and final results with any stakeholder that may acknowledge, enhance, valorize and exploit them through social or industrial collaborations. Our social and industrial collaboration starts often from the beginning: approximately 50% are thematic and the topic is defined (and the Candidate selected) together with an industry or an international research institution as funding – or co-funding – partner. Our mission is to train our PhD Candidates as self-sufficient and independent actors, able to gain – as scientist, as intellectuals, as professionals, as entrepreneurs – an outstanding position at an international level.

We are sure that our early stage openness toward stakeholders and the whole scientific world and networks is the best way to provide future PhD Holders with solid occupational opportunities for an academic career as well as for an employment in research centers and in any other enterprise, public body or private societies in need of highly qualified personnel, in particular of experts trained to innovate and to manage innovation processes.

The PhD-ABC Program deals with a wide variety of topics and related disciplines. It is not possible to list them in few rows and it is even useless, due to our fluid, adaptable nature: we look for new research questions (in the wide ABC sector) and for good ideas to give answers to them. A complex set of cutting edge, scientific and humanistic, disciplines and experts are at Candidates' service to support them to make their efforts three-time-winning (Researchers, Stakeholders, Academy) intellectual products.

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DATA-CENTRIC SIMULATION FOR PERFORMATIVE FEEDBACK IN EARLY BUILDING DESIGN PROCESS

Samir Al-Azri - Supervisor: Prof. Ingrid Maria Paoletti
Tutor: Prof. Enrico De Angelis

The research investigates the opportunities of a data-centric simulation process where Machine Learning is used as a simulation design driver to improve the efficacy of current early-phase design cycles. The study examines the possibilities of using data generated from several simulation iterations and creating a feedback process to improve the design process and reduce feedback dependency from more advanced design stages. The aim is to improve the decision-making in the initial design phase relative to standard solution searching methods, e.g., optimization algorithms. The study will examine if previous simulations can be processed and utilized to become design vectors for future projects where performance evaluation is provided in real-time. This approach moves the simulation benefits from the validation stage to the solution exploration phase, allowing for the exploration of more options with informed outcomes. The proposed methodology intends to generate data through a finite element analysis to feed into a Machine Learning model that uses Deep Convolutional Neural Networks (DCNN). This model will then process the data to predict the material volume and consequently the Embodied Carbon (EC) of a structural element from a Topology Optimization (TO) process. The proposed procedure would encourage a comprehensive iterative cycle that is structurally and environmentally sensible. The research investigates the boundaries of machine learning in the AEC design process and the possibilities of enabling a multidisciplinary integration of simulations in the design process.

Keywords
Machine Learning, Simulation-Driven Design, Multidisciplinary Design, Design Intelligence, Architecture Machine, Data-Centricity

ASSESSING SMART RETROFITTING IN RESIDENTIAL BUILDINGS THROUGH KEY PERFORMANCE INDICATORS

Joud Aljumaa Aldakheel - Supervisor: Prof. Claudio Del Pero
Tutor: Prof. Paola Caputo

In the European Union, buildings account for 40% of the total energy consumption. New buildings can achieve high-performance levels, however, up to 90% of the existing European building stock will still be standing and in use in 2050. Thus, the renovation of buildings is a key action to reach the decarbonization of the building stock in the next 30 years. In such a context there has been an increasing necessity to have buildings with interactive features, to dynamically respond to users' needs and/or changing boundary conditions such as climate and grid prices. As a result, the concept of Smart Buildings has been introduced by the Energy Performance Building Directive (EPBD) as the main enabler for the future of the building sector. In this sense, Smart Retrofitting has become crucial to upgrade the definition of energy efficient or Nearly Zero Energy Building retrofitting and reflect the new possibilities of transforming existing buildings into more responsive/efficient buildings and cities. To understand Smart Retrofitting, it is very important to clarify the concept of Smart Buildings. The revised EPBD has developed a voluntary European scheme for rating the smart readiness of buildings: the "Smart Readiness Indicator", to measure the capability of smart buildings to adapt their operation to the needs of the grid, and occupants. Yet, its' methodology is qualitative and only assesses the presence of the services and technologies without evaluating their performance. Hence, this thesis develops a framework for Smart Retrofitting and the achievable quantified benefits. Particularly, the proposed methodology evaluates the energy performance of smart retrofitted buildings by identifying specific Key Performance Indicators (KPIs) that provide a quantitative performance assessment of the building operation. The implemented KPIs measure the energy performance of the technologies integrated into the building as well as its' grid interaction. Moreover, the thesis elaborates on quantified thresholds for the indicators by reflecting on existing case studies from the literature. It identifies "Minimum Acceptable Thresholds" for the KPIs which define the basic performance level for a smart building/retrofit, and "Top-performing Thresholds", which indicate a smart building/retrofit with outstanding performances. Furthermore, the proposed evaluation methodology is tested on a case study of the Holistic Energy and Architectural Retrofit Toolkit (HEART) project, part of the Horizon 2020 program, and aims at smart retrofitting existing buildings. The final part of the thesis normalizes the indicators to have common units that facilitate comparison at a wider building scale. The outcomes of the present work are expected to quantify the Smart Readiness level and give guidelines on smart retrofitting. The proposed Smart Retrofitting framework will thus allow building designers, users, and policymakers to estimate the energy performance of smart retrofit projects and measure their success.

INTEGRATING LIFE CYCLE SUSTAINABILITY ASSESSMENT INTO BUILDING DESIGN AND OPTIMIZATION - THE CASE OF ENERGY RETROFITTING

Hashem Amini Toosi - Supervisor: Prof. Niccolò Aste

Co-Supervisor: Prof. Monica Lavagna - Tutor: Prof. Claudio Del Pero

The growing consensus about sustainability science has led to increasing research works in different fields of studies over the last decades. Building sector as one of the major contributors to sustainability dimensions is now one the main research fields in which sustainability assessment is being applied and Life Cycle Sustainability Assessment (LCSA) as a comprehensive approach towards evaluating building performance is becoming more scientifically popular these days however several challenges still exist to employ LCSA in a Decision Support System (DSS) in building sciences. The need for an integrated LCSA framework as a prerequisite to resolve the existing challenges and facilitate the implementation of LCSA into building design and assessment is highlighted and reaffirmed by researchers in building science. Therefore, this research aims to propose a new LCSA-based model for performance-based design of new buildings as well as the energy retrofit design of existing ones. The research starts with a review on the concept of sustainability and provides a new classification of the associated challenges of sustainability assessment in the decision context. Then with a focus on methodological challenges as the main concern of the research, it is continued by a systemic review on the literature of LCSA application in energy retrofit design of existing buildings. Later by clarifying the methodological advances and limitations of the existing LCSA models, a new LCSA-based model is proposed by providing a mathematical definition of LCSA in buildings. A set of interconnected equations are proposed to formulate and measure the life cycle sustainability performance of buildings. Subsequently, the mathematical model of LCSA is equipped with optimization and machine learning methods to better cope with the dynamic nature of a simulation-based building design process. The most suitable machine learning algorithms are also determined by comparing the accuracy, training time and prediction speed of 24 different algorithms. Integration of machine learning models as a surrogate model contributes to accelerating the design-assessment process and overcome the computational time limitation within an optimization process.
The novel mathematic definition of LCSA provides a balance among sustainability dimensions including environmental (LCA), economic (LCC) and social (SLCA) aspect. The new equation proposed in this research considers the concept of performance thresholds and weighting factors to form a single index representing the LCSA performance of the building and energy retrofit design options. The new mathematical definition of LCSA is also aligned with existing standard including the frameworks of sustainability assessment of constructions works publishes by European commission of standardization. Then, the proposed LCSA-based model is applied to design optimal energy storage systems of an existing building as an example to demonstrate the capabilities of the proposed model in a design process. The application of the proposed model confirms the effectiveness of the developed LCSA-based model to find the optimum design solutions in an energy retrofitting project. In this research, the model is applied to find the optimum size of Thermal Energy Storage (TES) and electrical storage for a residential complex in Italy from an LCSA perspective and its dimensions including LCA, LCC and SLCA performance (Figures 1-3).
The results verified that the application of the proposed LCSA-based model is able to find the optimum and balance solutions of energy storage systems design to improve the three dimensions of LCSA in a building. Thanks to the integration of machine learning techniques, the whole process of the design-assessment is accelerated significantly and accurately.
Moreover, the results reaffirmed that the application of energy storage systems (thermal and electrical) can contribute to enhancing the environmental, economic, and social performance of buildings from a life cycle perspective. Such results enlighten the path to develop and design road maps and policies for the building sector to achieve the decarbonization and sustainability targets in the following years.
Finally, the thesis also discusses the potential of Building Integrated Photovoltaic systems (BIPV) and thermal energy storage systems in the residential sector to reduce the CO2 equivalent emission over the building life cycle. The results reaffirmed that such a combination can reduced the emission levels of the building sector as a solution towards building decarbonization in Europe. Therefore the thesis also provided logics and insights to rethink and assess the policies that can improve the building sector's sustainability performance.

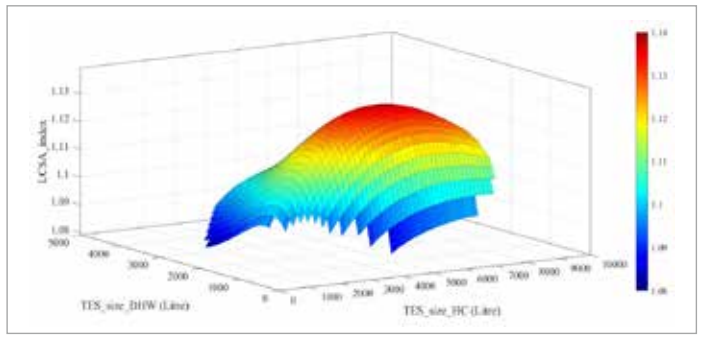

Fig. 1 - Three-dimensional view of the LCSA index's results versus different TES sizes. Higher index value (dark red) corresponds with higher LCSA performance. wtw method is used as the weighting method as described in the thesis.

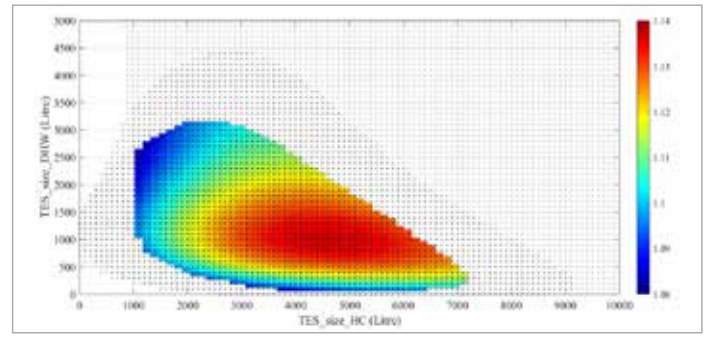

Fig. 2 - Two-dimensional view of the LCSA index's results versus different TES sizes. Higher index value (dark red) corresponds with higher LCSA performance. wtw method is used as the weighting method as described in the thesis. The LCSA optimum results are located in the overlapping dotted areas in which LCA, LCC and SLCA index are improved at least 50% of their maximum achievable improvement (as the predefined thresholds).

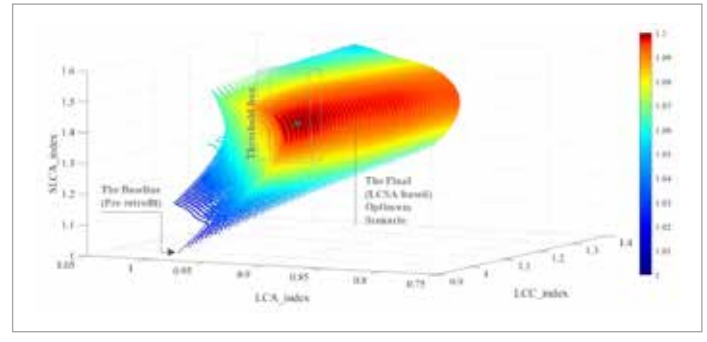

Fig. 3 - Results of LCSA index for all possible scenarios, colors represent the value of LCSA index based on equal weighting (1st step of wtw weighting method). Each dot shows a possible scenario of ESSs size combination (three variables including the size of TES for heating/ cooling and domestic hot water, and electrical battery). The threshold box contains those scenarios that satisfy the thresholds of all indices.

ENERGY-ECONOMIC ANALYSIS APPLIED TO GEOTHERMAL DISTRICT THERMAL SYSTEMS

Marco Belliardi - Supervisor: Prof. Nerio Cereghetti (SUPSI)
Tutor: Prof. Paola Caputo

The historical context we are facing is characterised by a rapidly changing climate with rising temperatures, the necessity to implement solutions that allow a sustainable use of resources and the achievement of a net nearly zero balance of CO2 emissions into the atmosphere. The current geopolitical instabilities also have implications for energy supply, increasingly causing considerations on the opportunity to enhance energy supply from local energy sources. These are among the reasons that are pushing technology to find solutions that are increasingly compatible with current requirements, also in terms of satisfying thermal demands, while always keeping a careful attention on economic aspects.
The GEO-5GDHC, i.e., a district thermal system that allows both heating and cooling by exploiting the energy of the ground through heat pumps and cooling machines, is a technology with features that fit well with the current energy efficiency requirements and future energy scenarios. Research hints are urgently needed in this field because this set of solutions are not widespread and still poorly considered at a European level.
This research work investigated the potential of this technology, taking into account both functional and economic aspects in order to assess its extendibility in various climatic contexts and applied to buildings with different levels of thermal insulation.
The PhD research started from the analysis of a real case study in the Surselva Region of Switzerland, characterized by an Alpine temperate/cold climate, where the heating and cooling demands of 4 buildings are satisfied by a GEO-5GDHC district thermal system.
Starting from the data and configuration of this real case study, it was investigated whether a similar system, applied to different building types, could also be interesting, energetically and economically, in other climatic contexts.
Starting from an assigned set of 4 administrative buildings (category characterized by higher heating and especially cooling needs than other categories of use) interconnected through a GEO-5GDHC system, simulations were carried out to assess their thermal demands, considering different variables: different climatic contexts (5 weather zones, chosen from among the most common in Europe), high or low insulation level of the administrative buildings, existence or not of a photovoltaic thermal hybrid (PVT) system. The PVT option was chosen because it is a technology that, in addition to generating electricity, is useful for the thermal regeneration of the ground, which in some cases makes it possible to reduce the number of BHE needed, and thus the related investment costs.
Applying all variables, potentially 20 case studies were identified.
Through the simulation program developed in this research (PILEDHC), an assessment was made of the energy and economic performance of Geo-5GDHC through dynamic modelling, to find an answer to the research question: could GEO-5GDHC technology be advantageous, in energy and economic terms, even in climatic contexts characterized by a temperate/cold climate?
The analysis of the results of this research has provided several considerations and conclusions:

- According to the literature review and state of art presented in chapter 2, GEO-5GDHC is interesting because of its capability to efficiently supply heating and cooling needs. However, there is not yet enough widespread experience to provide both energy and economic information to facilitate its diffusion. Many international research groups have been worked about, but the results of their studies "struggle" to reach the involved stakeholders and the decision makers.
- GEO-5GDHC systems are also economically interesting in temperate and warm-temperate climate regions. In fact, the results show that the technology allows for an optimal use of the system, particularly where there is a requirement for both heating and cooling. On the one hand, the GEO-5GDHC allows for a single system with a dual utility (generating heat and cooling), and on the other hand, it allows for an optimal regeneration of the ground. In fact, the ground in which BHE are installed, which is cooled in winter to heat the buildings, is re-heated in summer to cool the same users. This regeneration of the ground makes it possible to reduce the number of probes needed without the risk of malfunctioning, and consequently to reduce the initial investment cost. This obviously increases the overall economic benefit.
- Case study results with and without PVT show how this technology, coupled with Geo-5GDHC, is particularly useful in climates with low summer cooling requirements. In fact, PVT allows for a thermal regeneration of the ground that would otherwise be limited if done only with building cooling (limited in cold climates). Systems without PVT have proven to be technically feasible everywhere, however this technology allows for a reduction in the number of geothermal probes and, while still respecting regulatory technical constraints, therefore reduces the investment (or at least the annual cost item related to the investment, CAPEX).
- The "total thermal cost" (i.e., the ratio of annual investment costs plus operating costs to thermal requirements) is especially advantageous for low-insulated buildings that therefore have high thermal requirements. This consideration is in line with the fact that the higher the demand, the higher the cost-effectiveness and investment optimization of a DTS, which is precisely why it is recommended in areas with high heat density. This indicator is quite constant, even showing a sort of minimum for the case studies of Lugano and Rome. However, if the "building ERS cost" is considered (i.e., the ratio of annual investment and operating costs reported to the energy reference surface) it is clear that it is lower for well-insulated buildings, showing a decreasing indicator going towards warmer climates.
- Despite the investment costs of the systems in the different case studies differing significantly (much higher where there are large thermal demands such as in the case of the real case study, which requires significant heating), the "total thermal cost" doesn't differ significantly in the various case studies.
- As mentioned above, while DTS that only provides heating is widespread in cold climates, the GEO-5GDHC shows good potential to be deployed also in moderately warm climates becoming a technology to be explored, also and especially in the case of renovations of small neighborhoods or contiguous buildings. Based on the results, the technology could also be very interesting in conditions where technical and/or legislative limitations do not allow for large renovations and measures to improve building insulation (e.g., in the case of listed historic buildings).
- For this type of technology, it is very important to determine in advance, i.e., at the planning stage, the thermal requirements of the users that are going to be supplied with the DTS. This is fundamental to dimension the heat exchanger with the ground (number and depth of BHE) in order to ensure the long-term functioning of the entire system.
- The design of GEO-5GDHC systems is complex because it must involve the consideration of many interacting parameters. An outcome of this research, the PILEDHC tool, can help in this regard: it is in fact capable of evaluating, first from an energy point of view and then from an economic point of view, GEO-5GDHC systems in various contexts and under various conditions (different buildings, different geological conditions, different lengths of the distribution network, possible regeneration with PVT hybrid modules, etc.).

Hopefully, the findings of this dissertation will give an impulse, accompanied by research and practical applications, to a technology that is currently poorly known and not very widespread, especially in certain geographical areas. In particularly areas characterized by high cooling requirements could benefit from a system attractive from an energy, environmental and economic point of view.

DESIGNING THE CLIMATE-NEUTRALITY. HOW TO RE-THINK THE CONSTRUCTION PROCESS OF BUILDING INSULATION BY GROWING MYCELIUM-BASED BIOCOMPOSITES

Olga Beatrice Carcassi - Supervisor: Prof. Laura Elisabetta Malighetti
Co-Supervisor: Prof. Ingrid Maria Paoletti - Tutor: Prof. Enrico De Angelis

Introduction
European Green Deal strategy aims to cut the greenhouse gas (GHG) emissions to achieve climate neutrality by 2050. Buildings are a key leverage point to reduce GHG emissions, but the embodied emissions related with their construction remain often the hidden challenge of any ambitious policy. Considering that a complete material substitution of building elements that necessarily release GHG is not possible (e.g., concrete and steel for foundations), here called "climate-positive", in this thesis a material GHG neutralization was explored with the use fast-growing biomass insulations.

Methodology
This work, hence, proposes a methodology to design "climate-negative" insulation biobased composites by leveraging their ability to temporarily store carbon dioxide (CO_2) in the biomass and delay the emissions in the atmosphere. Moreover, to lower the impacts also in their construction phase, it investigates the creation of sustainable materials and production cycles by exploiting the mycelium growth as a binder. To promote the efficient use of resources while still achieving high-performing products, this study: i) verifies that the most suitable building application is the insulating one, together with the inquiring of bio-based materials technical potentials (carbon storage and natural fibrous structure) and limitations (fire safety and durability); ii) it suggests some material selection strategies according to the biomass local availability and industrial scalability; iii) it defines to most suited methodology and related index able to assess the climate-negativity targets here advocated to account and reward for negative emissions in the different bio-based product life-cycle stages; iv) it explores the cutting-edge mycelium-based technologies for the constitution of low-energy and waste upcycling architectural products by proposing a laboratory protocol set-up. As a matter of fact, due to the novelty of this solution, there are no unique fabrication process and testing methods in the literature. To overcome these limitations and to provide a guide to those who wish to embark on the biotechnology path, this thesis provides a practical methodology based on the three steps (CHOOSE, FABRICATE, COMPUTE). The idea is to suggest first how to strategically select biological raw materials in a world of finite resources; secondly to understand the technical potentials as mycelium-based insulation solutions and then to compare the climate-negativity potentials. Hence, a common protocol of growth and material characterization testing were suggested, and the results were compared to understand the most promising in terms of climate-negativity, tested properties and industrial scalability among the different biocomposites obtained.

Results and conclusions
As a result of the theoretical preliminary research, the design methodology for "growing" climate negative biocomposite is proposed and applied to 4 biomasses as Case Studies (rice straw, hemp shives, Posidonia Oceanica and bamboo fibers) within the European context, by analyzing both their technical and negative emissions' potentials. Their specific design and bio-manufacturing methods are specified for each biomass since they play a major role for the final calculation of the GHG emissions (here called Net-GWP). According to the Case Studies' analysis, the rice straw seems to be the most promising due to its high availability and high silicate content. With respect to the technical performances, the hemp exhibits the lower density and volume shrinkage percentage; the bamboo is characterized by an interesting water absorption behavior since it is the one that absorbed the less quantity of water (21%), and little in terms of volume (18%). The thermal conductivities are all similar (bamboo measures 0.0767 W/ (mK), the rice 0.762, hemp 0.0686 W/ (mK) and P.oceanica 0.0723 W/ (mK)), and for the heat capacity, bamboo fibers and rice straw accounted the highest ones (around 1785 J/(kg K)]). The compressive strength analysis highlighted that the hemp exhibits the lower density and higher modulus of elasticity, which makes it an interesting solution to have light insulation materials with high modulus of elasticity. The GWP net results showed the climate-negativity potentials of these biocomposite (negative GWP net values) where the bamboo solutions are the most promising to store carbon in building skins and that also is a promising emerging bioeconomy since can remediate the contaminated and abandoned lands. When looking at the negative Net-GWP values, the fact that they are higher with greater number of replacements should not favor an increasement in technical replacements. As a matter of fact, that would intensify the maintenance costs, therefore an optimization between the climate-negativity and the construction process should be promoted and further investigated. Among the biocomposites analyzed, the bamboo one is the most promising for the Net GWP values and represents an interesting growing new bioeconomy that it worth it to be scaled-up at an industrial scale. The rice straw is also a favorable solution due to both the Net GWP values and the availability in these days. Overall, the strength of such climate-negative mycelium-based insulation solutions are the fact that they are composed by **biological residues** that can be **local resources**, with the reduction in transportation emissions; they exhibit competitive **thermal conductivity** (λ) and **heat capacity** (c) values with respect to the rest of bio-based materials; they have **lower fabrication process** emissions if scaled at an industrial level thanks to the mycelium growth and **low temperatures** during deactivation; last but not least, **little waste** is created if the biocomposite is treated in anaerobic digestors where the simultaneous biomethane biogenic carbon collection reduced by 60% the emissions released in the atmosphere at the EOL scenario.
This comprehensive approach can help designers in the materials choice phase of a project while suggesting to policymakers and companies the most promising solutions to achieve the decarbonization of the building and construction sector, but not only.

Fig. 1 - Thesis overview

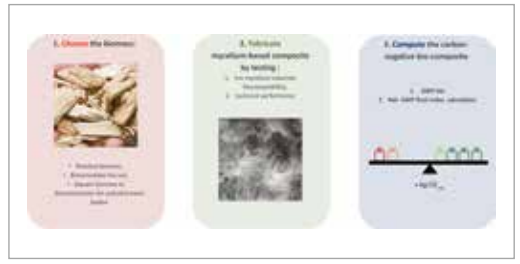

Fig. 2 - Methodology summary

REVERSO: REVERSIBLE TECHNOLOGIES TOWARDS REUSING, REMANUFACTURING AND RECYCLING

Tecla Caroli - Supervisor: Prof. Andrea Campioli
Co-Supervisor: Prof. Monica Lavagna - Tutor: Prof. Gianandrea Ciaramella

The research investigates the Reversible Technologies of the construction sector for the definition of Buildability Conditions, validated with two Pilot Projects, for the disassembly of constructive systems and for the activation of circular solutions.
The challenge is to solve the problem of the huge quantity of building components that once disassembled, at the end of their service, has still residual performances, to demonstrate that reversible technologies could optimize the construction process emissions. Considering the state of constructive systems after the disassembly, it is possible to recover them through three different circular economy strategies, reusing, remanufacturing, recycling, and the main condition is that the constructive systems are reversible.
The Reversible Technologies are analyzed on two levels: Hard and Soft. The Hard Technologies are the off-site constructive technics (materials, components, assembly methods), that are designed and built to be disassembly; the Soft Technologies consist in operative – management and assessment – aspects (phases, operators and their role, tools, evaluation methods, technical documentations, and standards) that support the construction process.
The research is structured in three parts: knowledge, development, and practice.
The Part 1 is developed with the literature and field analysis, to investigate the State of Art of the research. At present, the topics are the subject of discussion for thirty years but there are several lacks in practice that forbid the development and diffusion of reversible technologies for the application of circular economy strategies.
After the literature review, the investigation is focused on the field analysis on practical experiences: components and buildings case studies and process operators' interviews. The goal was to understand how theoretical principles are currently applied and if not, how they could be implemented, defining specific conditions on constructive (Hard) and operative (Soft) levels.
The Part 2 consists in the development of the innovative contribution of the research: the elaboration and definition of conditions on Hard and Soft levels to design and build constructive systems for reversibility, sustainability and circularity: Buildability Conditions. The previous analysis highlighted that the Buildability Conditions towards reversible processes is actualized only if there is a transition towards the reversibility, sustainability and circularity. The achievement of the transition is possible through the Pre-conditions, developed in the design and manufacturing fields and considered as the basis for the actualization of the Buildability Conditions. Specifically, the conditions are the Soft Actions, led by the operators involved in specific phases of the constructive process, and the Hard Characteristics of the constructive systems on different building levels (materials, elements, systems and building).
The systematization of the Buildability Conditions generates the Reverso Framework, conceived as a design-support tool for the realization of reversible, sustainable and circular processes, projects and products.
During the elaboration of the Framework, two Pilot Projects are elaborated to validate, adjust and apply the conditions. Considering that, the Part 3 consists in the practical phase in which are developed the Pilot Projects. The practice experimentations are realized thanks to the Field Interaction, developed in the previous phases of the research, involving stakeholders that work with prefabricated construction systems and showed interest in the research and the potential applicability of the conditions defined. The projects are the results of two collaborations with the Dutch architectural firm, Rau Architects, and the Italian manufacturing company, Cel Components.
The first application consists in the design of an architectural project, from building to element scale, for the requalification of a district of Utrecht, that follows the Hard and Soft conditions for the development of three scenario proposals. The aim is to testify the advantages to design and build reversible, sustainable and circular.
The second application consists in the generation of reversible and circular transition of the production of sandwich panel system, used for façade, walls, false ceiling, and floor systems, following the Reverso Conditions. The challenge was the definition of Hard and Soft improvements to obtain a reversible and circular panels system.
The Pilot Projects testified the applicability of Reverso and its relevant contribution in the construction sector.

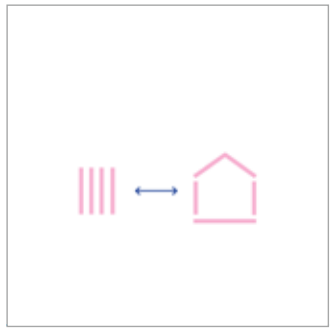

Fig. 1 - Reversibility: from element to building and vice-versa.

Fig. 2 - Schematic representation of the elaboration of Reverso.

Fig. 3 -Reversible Constructive Process towards Circularity.

LEAN CONSTRUCTION 4.0: A NEW PARADIGM TO SUPPORT THE ADOPTION OF INDUSTRIALIZED BUILDING SYSTEMS AND THE DIGITAL TRANSITION OF SMES

Marco Cucuzza - Supervisor: Prof. Gabriele Masera

Tutor: Prof. Matteo Francesco Ruta

Low levels of digitalization, fragmentation of the supply chain, traditional logic and structural slowness in the adoption of innovations are some factors that explain the productivity gap that the building sector has towards the other productive sectors (-1,8%). In this context, the **fourth industrial revolution** represents a great growth opportunity for the industry thanks to the introduction of digital technologies, which improve the information transfer process during the life cycle of construction products.

A **Construction 4.0 taxonomy** – identifying and categorizing the main tech trends – and a **market** description help understand the 2022 sector situation. The *Covid-19 pandemic*, the *scarcity of raw materials*, the increasing housing demand forecast for the future and the current need to reduce the environmental impact of highly energy-intensive buildings lead to higher sector efficiency. Only the **Industrialized Building System (IBS)** can accomplish the renovation target of the old Italian building stock (75% are older than 50 years), as the New European Bauhaus suggested. The presence of government funds for 4.0 investments *(Piano Industria 4.0)* and the tax deductions (e.g., *Superbonus 110%)* to improve the environmental and seismic performance of existing buildings are good opportunities to embrace a sector revolution.

This research introduces the new paradigm of **Lean Construction 4.0** as a theoretical framework for Small and Medium Enterprises (SMEs) in the Italian context. Its purpose is to promote the transfer of industrial concepts to buildings in **the Process, Project and Product (3P)** management activities through the sector's digitalization.

The fine line between Physical and Digital dimensions in the construction sector outlines the need for a hybrid stage: the Phygital World. The Phygital Coach, an expert in building technologies, applies the LC4.0 Assessment, a tool to evaluate the performances of individual 4.0 technologies across the building life cycle to check and improve the digital level of companies.

In addition, the research investigates a specific application of the paradigm regarding the adoption of **Modern Methods of Construction (MMC)** and precisely of **offsite technologies**, such as for the retrofitting or new construction of envelopes able to address the growing demands in terms of performance. The market growth perspective of around 5.9% CAGR until 2030 demonstrates the increasing interest in this industrialized construction method allowed and enabled by the digital revolution. By applying **Design for Manufacture and Assembly (DfMA)** concepts and a multidimensional **BIM approach (nD)**, it is possible to realize buildings and reduce the productivity gap by lowering costs (-20%), time (-30/50%), resource consumption (-30%) and at the same time increasing quality (+20%) and safety (+80%). These two approaches demand implementing the designer's profession, stressing the different architectural, technological, digital, productive and managerial skills that **PhygitArk** requires.

For these reasons, this doctoral work develops the **Panelization Design Tool (PDT)**, a decision support tool for the Early Design Stage, helping different actors involved in the design-production-construction and management process of high-performance facade components. Thanks to a script able to analyze the existing geometry and collect the various desires/ limits identified by the client, the architect, the engineer, the manufacturer and the builder, various technological solutions for the prefabricated envelope (steel, wood and concrete) can be compared through quantitative indicators. Analytical scores assess each technology's effectiveness, grouping them by type according to their BIM nDimesions, as disciplines subdivision. Geometric (2D), structural (3D), time (4), economic (5D), sustainable (6D) and management (7D) parameters are the drivers that each involved stakeholder analyzes according to its priorities without losing the whole vision of the project. Therefore, the PDT is intended as an open platform based on parametric design tools that can be easily implemented with further and additional modules to expand the involved disciplines (e.g., safety, seismic and fire protection). This optimization process aims to avoid arising risks from the late decision about technology, causing losses in terms of efficiency and overall quality. It focuses on making initial decisions that are as much as possible data-driven instead of a priori generating a new offsite value proposition that helps in growing the building sector productivity.

The proposed Decision Support System was tested on a case study of the Horizon2020 project BIM4EEB – a BIM toolkit for fast-track renovation of existing buildings – thanks to which it was possible to identify gaps and critical issues in the application and dialogue phases between the different actors. The PDT application on this building's typology underlines how parametric design can be applied functionally and efficiently not only to iconic architecture but also to ordinary residential buildings to be renovated, which are the primary target to ensure the achievement of Europe's decarbonization targets.

Fig. 1 - Lean Construction 4.0 Ontology, a DfMA and BIM n Dimensional approach to Offsite Manufacturing driven by Phygital Coach and PhygitArk

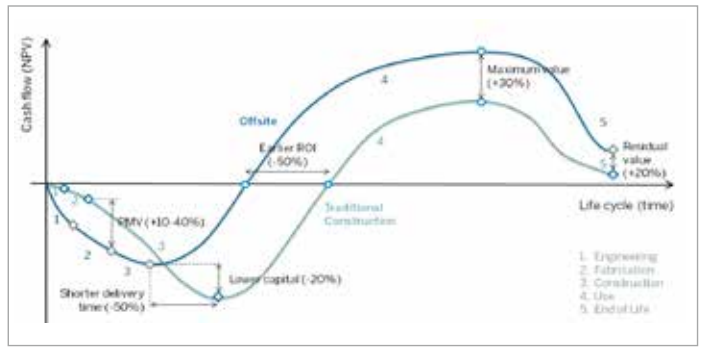

Fig. 2 - The Offsite Construction value proposition across the building lifecycle

ACOUSTIC PERFORMANCES OF BUILDING COMPONENTS BASED ON INNOVATIVE COMPOSITE MATERIALS FEATURING PHENOLIC RESIN FOAM CORES

Massimo Fortini - Supervisor: Prof. Edoardo Alessio Piana (UNIBS)
Tutor: Prof. Enrico De Angelis

Composite sandwich panels are extensively used in many application fields. Their use is constantly increasing as they combine several very interesting properties such as a high load-bearing capacity, low weight and excellent thermal insulation. Different core materials can be used, such as mineral wools, bio-based materials, polystyrene, polyurethane, phenolic or other synthetic foam, the latter being considered as the organic foam that offers the best fire-reaction (fire-proof) properties.
In this research, an in-depth investigation was carried out on core materials and components (Figure 1) realized by the Irish company Acell Industries LTD in a manufacturing laboratory in Italy. Simulation codes and experimental techniques based on vibroacoustic measurements were used to predict the dynamic and acoustic behaviour of these components.
The main aim of this investigation was to propose an innovative technology to realize internal lightweight partition for fire-resistant applications, a sandwich panel produced featuring a special open-cell phenolic foam core, as an alternative to plasterboards, featuring a good sound reduction index, together with good thermal insulation, and to develop a model of its acoustic behaviour, in response to changes of parameters of the component. This thesis presents the manufacturing technology and discusses the analytical model developed for the estimation of the Sound Reduction Index (SRI) and its experimental validation, carried out both with dynamic tests and with standard methods.

More in detail, the thesis proposes a correlation between SRI and the density of different foams.
The manuscript is divided into two eight main sections. In Chapter 2, the main concepts related to wave propagations in solids were reviewed. In particular, the equations describing the behaviour of waves in finite structures and sandwich components were laid out. An advanced least mean square method for the determination of the frequency-dependent bending stiffness of a beam was proposed (Section 2.6). The bending stiffness curve found using such a method fitted much better the experimental data set at high frequencies compared to the one derived from the standard least mean square method.
In Chapter 3, the mathematical model to predict the sound reduction index of a partition, both for a single and a double panel configuration was introduced and discussed. Estimates for the investigated components were thus obtained.
In Chapter 4 the predicted values were compared with those obtained experimentally from standard tests (Figure 2). These were carried out by specific standards, described in Chapter 5.

Fig. 1 - Sample of the investigated open-cell phenolic foam produced by Acell Industries LTD.

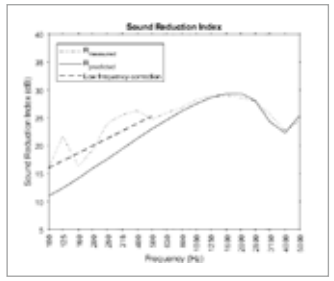

Fig. 2 - Comparison of one-third octave bands SRI curves. Solid line: predicted values. Dotted line: measurements to ISO 10140-2. Dashed line: SRI calculated from non-resonant sound reduction coefficient, limit integration angle = 84°.

A prediction tool was created and presented in Chapter 6.
To prove its effectiveness, a Multiphysics FEM simulation was also carried out (Chapter 7), to create a tool for the improvement of the acoustic behaviour of the sandwich (Figure 3). Limitations were found in this approach because the FEM approach could not take into account the variations in the material structure deriving from the manufacturing stage (Figure 4) and because of the limited possibility to model in a meaningful way the interface between the external laminate and the core. In conclusion, the FEM approach was found to be less efficient than the analytical approach for the particular application to Acell sandwich panels.

Finally, the possibility of using Acell panels in real applications was explored and discussed in Chapter 8. A configuration of two Acell Panels positioned 120 mm apart, with the gap filled with glass wool for a total thickness of 160 mm was shown to create a partition suitable for real applications, featuring a good sound reduction index and good thermal insulation.
In Chapter 9, conclusions were drawn and recommendations for future research were given.
Fig. 4

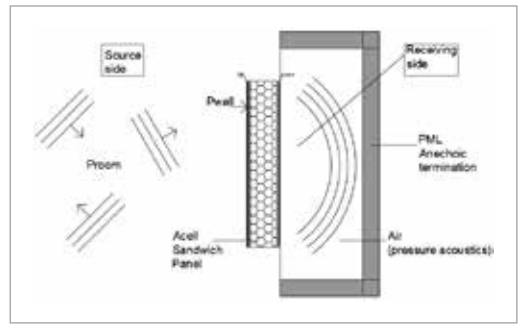

Fig. 3 - Model setup of an Acell panel with an ideal diffuse field on the source side and an ideal anechoic termination on the receiver side.

Fig. 4 - Sandwich materials samples. In the sandwich structure, the additional resin "layer" at the interface between each laminate and the core is visible.

MECHANICAL BEHAVIOR AND FRACTURE PROCESSES OF HYBRID FIBER REINFORCED CONCRETE

He Fengzhen - Supervisor: Prof. Luigi Biolzi

Co-Supervisor: Prof. Sara Cattaneo - Tutor: Prof. Marco Scaioni

Concrete, the most widely used construction material in the world, is a quasi-brittle material. Because of its brittle nature, plain concrete is susceptible to cracking, and the fracture strain is relatively low. The quasi-brittle nature not only affects the long-term durability but also limits the application of concrete. Adding short fibers is an effective way to reduce the brittleness of concrete and improve the tensile related mechanical properties.

Fire is one of the most serious potential risks to most concrete constructions. Concrete structures are likely to experience high temperature by accidental causes or by the special application purpose, leading to catastrophic consequences. The study is aimed to understand the optimum mix design of hybrid fiber reinforced concrete and the effect on mechanical and thermal behavior.

The first objective is to analyze the effect of fiber hybridization on the mechanical performance of fiber reinforced concrete. Additionally, the fracture process of the hybrid fiber reinforced concrete under flexural load was studied by digital image correlation. The second objective is to investigate the performance of the thermally damaged hybrid fiber reinforced concrete.

The results indicate the hybrid fiber including long hooked-end steel fiber produced a synergistic effect on tensile related mechanical properties. The critical fracture process length increases with the volume fraction of hybrid fiber. The hybrid reinforcement containing long hook-end steel fibers produces better a synergistic effect on inhibiting the extension of FPZ compared than the mono long hook-end fiber one. But the hybrid combination of fibers has a negligible effect on the growth trend of the FPZ length and the critical FPZ length. The thermally damaged hybrid fiber reinforced concrete including steel fibers has a better mechanical performance compared to that including polypropylene fiber. The temperatures above 200 °C seriously deteriorated the compressive strength and flexural strength and changed the fracture process. Water re-curing produced a positive effect on the recovery of the thermally damaged hybrid fiber reinforced concrete.

NATURAL LANGUAGE PROCESSING SUPPORTING THE DESIGN PROPOSALS EVALUATION IN A PUBLIC TENDER PROCEDURE. ARCHIBERTO: EXPANDING THE INFORMATION MODELLING APPROACH TO UNSTRUCTURED TEXTUAL DATA

Mirko Locatelli - Supervisor: Prof. Giuseppe Martino Di Giuda

Co-Supervisor: Prof. Lavinia Chiara Tagliabue - Tutor: Prof. Andrea Antonio Caragliu

INTRO - Natural Language Processing (NLP) is widely used to solve several tasks in different construction fields. Methods, techniques, and applications of NLP have already been assessed with satisfactory results in several phases of Architecture, Engineering, Construction and Operation (AECO) sector. However, no cases of systematic application to construction projects consider the early planning and Preliminary Design stages. Applications and studies of NLP technologies typically follow the Pre-design and planning phase.

PROBLEM IDENTIFICATION - Analyzing the Italian public design call for tenders procedure, possible information loss or misunderstandings can occur among the actors (i.e., the appointing party, the design teams participating in the call for tenders, and the evaluation external committee). In the Italian public procurement process, an external committee appointed by the Public actor is responsible for assessing the quality of the design proposals, namely the consistency between the demands declared in specific documents (i.e., Documento di Indirizzo alla Progettazione (DIP)) and the design proposals. DIP includes a critical section that identifies and describes the quality objectives to be pursued by the project using natural language expressions. The evaluation of quality objectives and characteristics, such as spatial quality, degree of flexibility, or perceptual comfort cannot be assessed through a purely numerical approach. Therefore, the traditional bid evaluation process is based on the manual identification and ranking of quality objectives translating the natural language information into a numerical evaluation/ranking system. As a result, the entire process is manual and relies on the committee's experience and ability to interpret the hierarchy of quality needs and the compliance of the design proposals. Errors or misinterpretations during the numerical translation phase of textual information into a hierarchical evaluation system may lead to an inevitable and unmeasurable quality gap.

METHODOLOGY - The study develops, assesses, and evaluates an NLP-based tool (i.e., ArchiBERTo) for the automatic processing and translation of quality demands and needs into a list of hierarchized objectives. ArchiBERTo is a Pre-Trained context aware BERT-based Language Model fine-tuned to perform a Multi-label Text Classification task. The NLP tool is developed to represent the collective intelligence and capability of a group of experts. As a consequence, the tool development involves several experts, with knowledge in the architectural, design, and construction fields in order to properly represent the knowledge domain and to avoid biases in the ArchiBERTo development. By representing a collective intelligence of a group of people, larger than the ability of a single expert to judge and classify quality objectives related sentences, the NLP system aims to avoid subjectivity in the interpretation of textual information. Furthermore, the NLP tool will likely outperform the capability of a single expert to manage the complexity of analyzing several sentences, being the representation of the group of experts' knowledge. The purpose of the whole system is to increase the compliance of design proposals and bids evaluation criteria with the appointing party's demands, improve effective communication among the actors involved aiming to reduce possible misinterpretations during the quality objectives and demands identification and translation task, minimize the quality gap between quality demand and design offer.

CASE STUDY DESCRIPTION - The NLP tool ArchiBERTo is developed, assessed, and evaluated in the context of Progetto Iscol@. Progetto Iscol@ aims to address the problem of the backwardness of the pedagogical and educational system of region Sardinia. Progetto Iscol@ aims to create a school system focused on architectural quality and, social and environmental sustainability of the interventions. At the initial phase of Progetto Iscol@, Sardinia Region shared general indications and guidelines for the drafting and definition of the main contents of the DIPs to be produced by the involved local municipalities. The use of common guidelines ensures that all DIPs follow the regional strategies, homogenizing the objectives of the interventions on the building school regional portfolio. In addition, a standardized evaluation grid/ranking for the design proposals evaluation process was established and shared with the local municipalities. On one hand, the use of a standardized evaluation grid/ranking proved to be an effective approach for leading different projects toward criteria and objectives in line with Iscol@ strategic goals; on the other hand, it turned out to be an excessively rigid approach to properly support the designers and the evaluation of school building projects that differ in geographical-environmental, socio-cultural context and consequently in quality demands. The use of fixed objectives priority and weights ultimately tends to flatten the results, without the possibility of focusing on the specificity and needs of each individual project. Customizing the ranking of objectives for each call, mirroring the semantic content of each DIP via the use of the aforementioned NLP tool, aims to reintroduce proper flexibility, mirroring the project's specific needs and demands.

RESULTS and DISCUSSION - The results show good values for the precision, recall, and F1-score metrics during the fine-tuning process, and useful results in processing samples of textual information derived from DIPs of Progetto Iscol@. According to the results, the NLP tool seems to be capable of reflecting the collective ability and sensitivity of a group of domain experts, larger than the ability of a single expert. For that reason, being ArchiBERTo the representation of the group of experts' knowledge, it can outperform the capability of a single expert to manage the complexity of analyzing several sentences. Having tested the capabilities of the tool, the ranking generated by ArchiBERTo, representing the DIP numerical counterpart, can be shared alongside the documentation to the design teams participating in the call for tenders to improve the communication and allow the designers to have full knowledge of the appointing party needs and quality objectives. Moreover, it can also be shared with the external committee as support in the evaluation and comparison of the design projects. The definition of the hierarchy of objectives improved by the NLP tool is expected to enhance the communication between the actors during the Pre-design phase generating a positive impact on the overall quality of the competing design offers, facilitating at the same time the evaluation activity.

CONCLUSIONS and FURTHER DEVELOPMENTS - The proposed methodology, based on the NLP tool ArchiBERTo, allows to preserve the possibility for the public appointing party to express quality demands and needs through natural language, by acting exclusively on the subsequent translation phase. The digitalization of the Preliminary quality objectives and needs by means of NLP systems could enhance the delivery of quality buildings and foster the introduction of digital methods and technologies into the construction process, both crucial steps for the future of the construction sector. A proposal about the possibility to pair NLP technology and embedding it in a Digital Participation Platform to enhance citizens' involvement in Participatory and Co-design processes supporting the sustainable transformation of the built environment is also theorized.

INTEGRATING OCCUPANT BEHAVIOUR MODELLING IN SIMULATION-AIDED BUILDING DESIGN: A FIT-FOR-PURPOSE APPROACH

Juan Camilo Mahecha Zambrano - Supervisor: Prof. Graziano Salvalai
Co-Supervisor: Prof. Roberto Lollini (EURAC) - Tutor: Prof. Monica Lavagna

Building Performance Simulation (BPS) tools are extensively deployed to reduce uncertainty when estimating building performance and assist the design decision-making process. Yet, a disagreement between predicted and actual building energy performance is often observed, the so-called performance gap. The literature shows this gap could vary by a factor between 0.2 – 4, where measured energy consumption is higher in most cases. The leading causes include weather deviations, differences between building design vs as-built, and occupant behaviour (OB). In BPS, occupants are generally represented through standard and fixed schedules and occupant-related power densities. This representation is oversimplified. Hence, the research community has focused on investigating the human-building interaction and understanding the drivers behind occupant behaviour. As a result, advanced occupant behaviour modelling approaches have been integrated to represent the complex, stochastic nature of the human-building interaction.

Despite BPS users, i.e., architects, energy modellers, engineers, etc., frequently acknowledging occupant-related uncertainty as a significant challenge, they based their assumptions on standards and energy codes which rely on outdated and simplified representations. In other words, the progress that has been made by the research community in understanding the human-building interaction and modelling occupants has yet to pertain significantly to the building design practice. Barriers such as time constraints, the substantial effort required, and lack of guidance and tools are among the leading causes. Consequently, a critical literature review has been conducted to map the gap between the occupant behaviour research field and the application of occupant behaviour models in simulation-aided building design. Here, three main areas are defined: i) Fundamental knowledge, i.e., understanding the human-building interaction and its role in BPS, where significant progress has been achieved yet, guidelines and protocols are required; ii) integrated knowledge, where it is critical to answering questions such as: which is the applicability of developed occupant behaviour models? To which extent can they be transferred to different contexts? How to choose a model depending on the simulation purpose? iii) Developing/advancing supporting tools necessary to integrate occupant behaviour into simulation-aided building design. Furthermore, it has been demonstrated that the impact of occupant behaviour on a design decision is case and context-specific thus, defining general guidelines is likely unfeasible. As a result, a fit-for-purpose strategy is required.

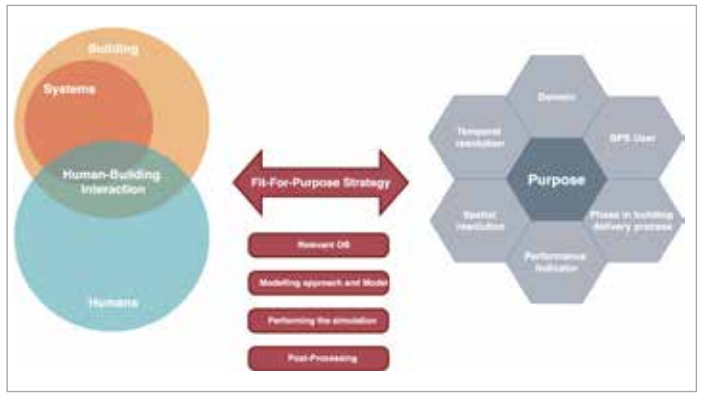

Fig. 1 - Deployment space and Fit-For-Purpose Strategy

Consequently, this PhD Thesis aims to bridge the gap between the occupant behaviour research field and the building design practice by contributing to the integrated knowledge and supporting tools fields. The main objective is to answer how occupant behaviour models can be integrated into the simulation-aided building design workflow to support decision-making using a fit-for-purpose strategy. To this end, the thesis defines the following specific objectives: Proposing a systematic simulation framework for integrating occupant behaviour models into BPS studies using a fit-for-purpose approach; Advancing and implementing quantitative methods for fast and efficient identification of the relevant occupant behaviour; Proposing a conceptual design for a tool that integrates occupant behaviour into simulation-aided building design; Demonstrating the fit-for-purpose strategy through a case study.

The simulation framework is designed to assist the BPS user step by step, from problem definition to informing the design decision, in addressing the critical issues that arise when integrating occupant behaviour into the workflow. Additionally, the thesis advances and demonstrates two methods, the Impact Indices Method and Diversity Patterns Method, to identify relevant occupant behaviour, which will aid the user in selecting an appropriate modelling approach. Moreover, critical issues on the implementation, simulation and communication of results from BPS using stochastic occupant behaviour models are addressed using a prototype tool pyFFPob-EP (python Fit-For-Purpose Occupant Behaviour–EnergyPlus).

This Doctoral thesis demonstrates the methods, workflows, and tools developed through a case study based on an office building. Monitored data is used to verify the results, and pyFFPob-EP is used to integrate the systematic simulation framework and fit-for-purpose strategy with EnergyPlus. The integration enables assessing and improving relevant occupant behaviour aspects in the BPS. The study shows that lighting and plug load are the most influential aspects when considering the total electric energy use and the total electric peak load. Two occupant behaviour modelling strategies are tested: reducing the epistemic uncertainty using inputs derived from monitored data and increasing the modelling complexity using stochastic models selected and adapted from the literature. The entire workflow is successfully applied to enable an analysis of Key Performance Indicators (KPIs), the performance gap, and the influence of each modelling approach. The proposed methods and tools, including the systematic simulation framework and the fit-for-purpose strategy, enable the user to incorporate occupant behaviour into BPS and reduce the performance gap between predicted and actual building energy consumption.

The outcomes of this research demonstrate the added value of integrating occupant behaviour models into simulation-aided building design. The study shows that non-influential occupant behaviour can be modelled with low-complexity models, such as fixed schedules. In contrast, influential factors should be modelled with higher-complexity models such as stochastic. The results also demonstrate that it is possible to guide and simplify the process using a fit-for-purpose approach, thereby opening a path for the building industry to close the performance gap. Ultimately, this PhD thesis fosters the endeavours of the research community and the building industry to design a resilient and robust built environment. The thesis concludes with a discussion of the limitations of this research, the possible applications and implications within the building design industry and recommendations for further investigation.

BIM AND REAL-TIME DATA FOR FACILITIES MAINTENANCE MANAGEMENT: STRATEGIES FOR OPTIMISATION AND INNOVATION

Antonino Mannino - Supervisor: Prof. Mario Claudio Dejaco (UniTn)
Tutor: Prof. Fulvio Re Cecconi

Digitisation is among the major factors of changes in the Architecture, Engineering, Construction, and Operation (AECO) sector, even if it has a relatively low level compared to other industries.
Several improvements in technologies and methodologies are under development focusing on design and construction phases and, in recent years, an increasing number of publications are also investigating their application in the facilities operations and use phase.
New buildings are increasingly integrated with new technologies proposed by industry 4.0, and therefore are increasingly connected and increasingly performing from different points of view. However, on the other hand, it is appropriate to evaluate how to best integrate existing buildings with these new technologies to improve processes and services. In this research, a multi-parametric monitoring and intervention strategy is proposed to optimize maintenance processes by reducing intervention times, avoiding disruptions and, through the possible use of advanced analytics and artificial intelligence, the prediction of machine failures before they occur or the anticipation of maintenance needs before they become urgent; this topic has not been addressed in this thesis, but has been defined as a process development (and improvement) possibility.
Furthermore, it is investigated how, through the same data used to optimize maintenance processes, it is possible to offer additional services to users, improve environmental well-being and adapt the facility to the users' needs.
In this context, it is essential to identify the criteria to define components and functional spaces criticalities. In this way it will be possible to select the most suitable maintenance strategy. This research proposes a maintenance strategy based on the facility continuous monitoring to define its functional status. The main purpose is to improve maintenance processes in existing buildings through information management supported by new technologies.
Technologies taken into consideration in this context are mainly Building Information Modelling (BIM) and Internet of Things (IoT). BIM has become a well-known term associated with AECO sector and its related fields. This methodology is the first answer to the need for optimisation of time and resources during the whole lifecycle of the building, from the design phase to the management and maintenance phase. BIM methodology enables collaboration and improves communication among projects' stakeholders. Underpinned by other technologies such as the IoT, BIM could provide more efficient results in buildings management during their whole lifecycle, giving new opportunities for innovation of traditional practices. On the other hand, the integration of real-time data with static BIM data, could provide new possibilities in optimising and innovating facilities maintenance management.
However, to date, what technologies potentially offer is not fully exploited in the AECO sector and, if used, it is not always used optimally. The main challenges on BIM-IoT integration for FM that emerged from literature review concern 1) Lack of FM data, 2) Data fragmentation and dispersion, 3) Interoperability issues in data management and 4) Lack of clear roles, responsibilities, contract and liability framework.
These issues open to a new discussion on how to use new technologies to manage the FM complexity, particularly facilities maintenance management.
The definition of four research questions defines the framework proposed in this research.
The framework is divided into four phases, starting from a first phase of "data definition" in which the criticalities to be monitored, sensors to be installed, monitoring strategies and tools to be used are defined. The second phase concerns the real-time data collection not only through the installed sensors, but also through feedback and users reports. The third phase concerns the data analysis, followed by request for intervention by the maintenance technician (fourth phase).
To trigger the request for intervention, a scoring system has been proposed. Scores are defined based on the monitoring thresholds defined in the first phase and are divided into categories (based on the monitored component or space).
Regarding the component condition index, vibration sensors and triaxial accelerometers have been used for monitoring. The condition index can be defined both in a more simplistic way using the machinery operation hours, and in a more complex way through the analysis of data collected by accelerometers to predict machine failures or to anticipate maintenance needs.
Once the maintenance request has been triggered, the technician can promptly intervene on the fault, also through the support of the digital model which provides further information on the physical component, on its technical characteristics, set-point, on its location within the facility.
The methodology has been tested on nine case studies. After the data collection phase in the existing facilities, through a process of standardization and analysis, the critical issues have been highlighted and a monitoring strategy for maintenance purposes has been defined. In this first phase, the users feedback collection process has been defined, as well as the IT tools necessary for developing a shared digital platform where monitoring and data collection takes place. Furthermore, considering the IFC open standard, the maintenance information requirements of the facility digital model have been defined.
Then, through the real-time monitoring and BIM data integration, it has been possible to improve information management and promptly intervene in several critical failures, avoiding further disruptions to building activities. These improvements in information management have led to a reduction in intervention times and failures duration.
Furthermore, the same data used for maintenance have also been exploited for other purposes, including energy optimization, improvement of environmental well-being, adaptation to user needs, highlighting design deficiencies.
In conclusion, new technologies and methodologies have been applied to existing buildings to improve their maintenance processes. The study found that significant maintenance improvements and optimizations can be achieved, although a key issue remains that of managing and analysing large amounts of data. Centralizing data, both as-built and those collected in real-time, is crucial for the entire process. Data leakage means data loss or inaccuracy.
The research also showed how the same data could be applied (analysed) for a multi-objective strategy: if on the one hand the aim is to improve the maintenance processes of an HVAC system, on the other, it is shown how the same data could be used to enhance the user experience inside the building, detect envelope energy inefficiencies or "incorrect user behaviour".
Furthermore, another consideration can be made on the necessary skills. It is evident that by now, the advent of the fourth industrial revolution and the IoT is generating large amounts of data. In every sector, in-depth skills in data management and, more generally, in IT skills are increasingly needed, at any level. New professionals (e.g. data managers or cyber security specialists) must inevitably be involved in the processes. Technical training of operators will be necessary to remain competitive in a context where digitization is a common goal.
Among the future developments, there is undoubtedly the need for a better integration of the BIM models with real-time data detected by sensors. Creating a digital replica of the building can be the basis for a better implementation of other digital technologies such as Augmented, Virtual and Mixed Reality.
These technologies will make maintenance processes easier, faster, and more effective, reduce interventions times and human errors, and improve productivity and communication.

TOWARDS A «TAILOR-MADE» METHODOLOGY IN THE ENERGY RETROFIT OF HISTORIC BUILDINGS: DEVELOPMENT OF A REASONED HANDBOOK

Sara Mauri - Supervisor: Prof. Valeria Natalina Pracchi
Co-Supervisor: Prof. Giovanna Franco (UniGe) - Tutor: Prof. Enrico De Angelis

Over the last decades, the improvement of the energy efficiency of historic built heritage has taken on increasing importance. Considering that approximately 30% of the European building stock consists of historic buildings, any energy management and performance improvement in those buildings may lead to a significant reduction in global energy consumption and greenhouse gas emissions. Therefore, their energy retrofit is undergoing a strong acceleration. However, it is commonly assumed that historic buildings are not energy efficient, a belief contradicted by the latest scientific research works. So, how to preserve this heritage for future generations by addressing energy efficiency and sustainability issues is still an open question.
Nowadays, the diffusion of a renewed retrofit approach based on balancing different aspects is gradually finding clarification thanks to specific Guidelines such as the Italian Ministerial guide (2015) and EN 16883:2017. However, these tools are neither known, nor widespread and nor used for some critical issues: they lack reliable applicative examples, control over the whole building and the interactions generated among building components, and, finally, they seem to be designed only for experienced users such as professionals.
This highlights a gap between theory and practice. Currently, there are some good examples of booklets and handbooks that, for their practical approach, can be considered a good starting point to find an effective way to support stakeholders in the retrofit process and overcome the limits of the official tools.
However, Italy seems to be late with respect to other countries such as the UK, which boast a well-established tradition in this field.
In order to bridge this gap in the Italian context, the research aims to define a methodological framework for developing a Reasoned Handbook (Fig. 1), providing complementary content to institutional guidelines.
The first step was to identify a holistic way of thinking about the retrofit of historic buildings in order to move from a reductionist approach, where retrofit measures are unconnected to each other and the context and where only quantifiable elements such as energy and costs are considered valuable, to an overarching approach that values qualities such as conservation and people's health and well-being taking into account the complexity of interactions and context. In this regard, the "Whole Building Approach" was considered particularly well suited: it uses an understanding of a building, its context (environmental and social) and all the factors affecting energy use (fabric, service, and people's behaviour) as the starting point for devising an energy-efficiency strategy.
The second step was to identify the roles, interests, goals, and needs of stakeholders, whose involvement is decisive in achieving truly effective project outcomes. This was done by investigating the dynamics between socio-technical aspects throughout the various stages of the whole building retrofit process.
The first two theoretical steps were then supported by a third more "experimental" and practical step consisting of a pilot study that involves two real-life case studies: an office building in Como (Italy) and an educational centre in Berkshire (UK). Thanks to the collection of technical and social data through short-term monitoring campaigns and the qualitative thematic analysis of semi-structured interviews, it was possible to delve into the socio-technical issues arising in retrofit projects.
The last step was reviewing the broadest possible range of historic buildings undergoing retrofit projects, defining a method for their analysis encompassing all the knowledge, skills and expertise acquired in the previous steps. First, a collection and selection of existing projects were carried out through primary and secondary sources, with a total of almost 100 European (and beyond) historic buildings identified (called "case studies" for simplicity). An Excel file including all their relevant data and information was then created.
Finally, the case studies were examined by employing two levels of reading and interpretation: (i) at the scale of the overall building project, they were analysed through a global process perspective; (ii) at the scale of individual building components (walls, windows, roofs, floors etc.), they were analysed from the point of view of the project results (while maintaining a comprehensive vision of the interactions between retrofit measures). The insights provided by these analyses cover the entire range of topics and concepts to be addressed in the handbook, thus setting its narrative.
Therefore, the result of applying this framework is a Reasoned Handbook that, starting precisely from the analysis of the existing projects collected, accompanies the reader on a "guided path" through an overall methodological process and an abacus of retrofit measures (Fig. 2). These constitute the two main parts of the Handbook. Part 1 on the process provides case studies offering both positive and negative examples to illustrate how its different stages can be carried out in practice. On the other hand, Part 2 introduces an abacus of retrofit measures divided into three levels of increasing impact on the heritage (low, medium, high), describing, through the case studies, the pros and cons of each solution in different context and situations, the main points of attention in the interaction with other measures, as well as pre- and post-retrofit data.
The main goal of the Reasoned Handbook is to offer reasoning, effective approaches and indications that should help readers to define projects that fit their historic buildings by adopting a tailor-made methodology (intended as a non-standard approach that allows exploring different options including unconventional solutions well-suited for built heritage) that encourages informed decisions and appropriate choices during all stages of the retrofit.

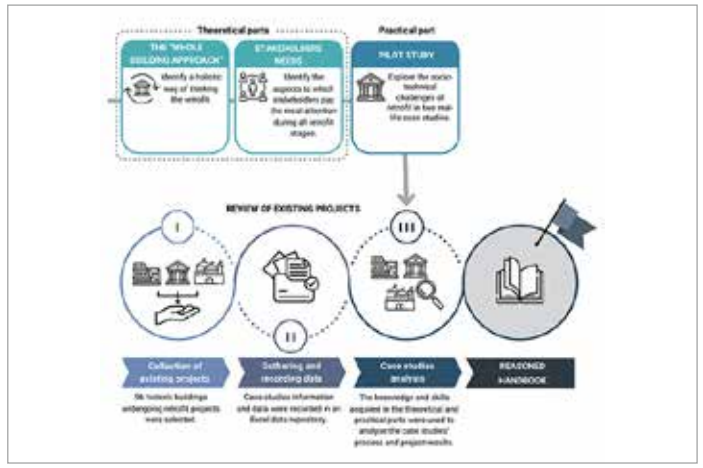

Fig. 1 - Framework for the development of the Reasoned Handbook (Source: author's elaboration).

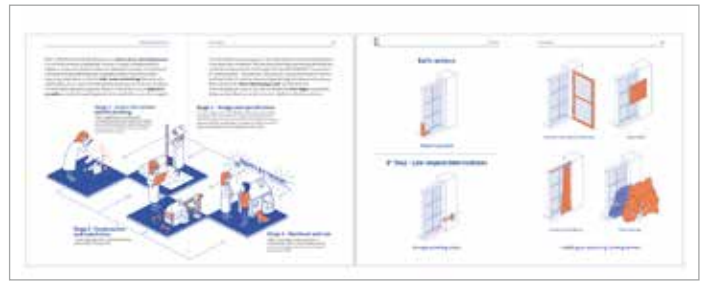

Fig. 2 - Sample pages of the Reasoned Handbook for Part 1 (left) and Part 2 (right) (Source: author's elaboration).

IN SEARCH OF AN ALTERNATIVE WORKSPACE: DISCLOSING ACADEMICS' SPATIAL PRACTICES AND PRODUCTIVITY WITHIN AND BEYOND THE CAMPUS

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Work autonomy, low degree of formalization, and unconventional organizational structure characterize academic work. These features make academics free to choose their work location, differently from other knowledge workers, whose work location choices are more constrained.
In recent decades, thanks to the diffusion of information and communication technologies, academics have increasingly performed their research work[1] outside university campuses, in off-campus locations (*e.g.*, their own houses, public libraries, dedicated laboratories, firm premises, or even coworking spaces, cafés, and parks).
The university campus moved beyond a static space to a more blurred place that alternatively includes multiple locations (*i.e.*, the university, the home, and other third spaces). The recent pandemic exacerbated this trend. Despite the increasing diffusion of this phenomenon, up to now, scholars have paid little attention to *why* and *how* academics choose the location of their research work. Moreover, it is not clear whether such choices influence their work outcomes. This PhD project explores academics' spatial practices for research on- and off-campus and the role of the physical workspaces in influencing the choice to work either on- or off-campus, stimulating academic productivity, and shaping the academic work experience. Overall, this thesis takes advantage of the Covid-19 pandemic period as a privileged time frame to study academic work. This research aims at providing a first interpretation of the disruptive Covid-working period and its potential long-term consequences on academic work. Namely, this research aims at (a) identifying academics' location choices for research activities among university, home, and other third spaces; (b) measuring the effects of these location choices on- and off-campus on academic productivity; and (c) understanding key spatial implications of academic work in those multiple locations (university, home, and other third spaces).
To reach these objectives, this thesis adopts a mixed-method approach, including econometric analysis of survey data (7,865 responses) on the whole population of Italian tenured academics, secondary data, scraped from public databases on academic productivity (*i.e.*, Scopus Database), and 22 interviews with academics from three public universities in Milan as well as visual data.
Drawing upon these analyses, this thesis posits four important scientific contributions.
First, this research brings new empirical evidence about academic location choices by recognizing four clusters: *Home-centric, Between home and university, Multi-located* and *University-centric*.
Second, this research synthetizes the different determinants of location choices in academia. Each of the four clusters is explained by different determinants. Mostly, *work-related* factors (*i.e.*, discipline) influence location choices. However, workspace-related factors (*i.e.*, on-campus workspace spatial quality, the need for a laboratory and commuting time) are crucial factors for work location decisions. Finally, *private life-related* factors (i.e., living with school children or a partner) and *demographic* factors (i.e., gender) push academics in increasing work-from-home.
Third, this thesis finds that working from the university during the Covid-19 pandemic increases academic productivity more than any other location choice, while working from home negatively influences productivity. Noteworthy, the relation between each location choice and academic productivity strongly depends on the characteristics of the workspace at home and on-campus as well as on individual traits such as gender.
Fourth, referring to Lefebvre's spatial theory, this thesis reveals how academics *produce* their workspace within and beyond the boundaries of their university campuses. Spatial practices across multiple workspaces span from losing the workspace in favour of the accelerated rhythms of academic work and university obligations (*i.e.*, domination of space), towards recovering the workspace through strategies for protecting work freedom and autonomy (i.e., appropriation of space).
From a practical perspective, this thesis identifies some approaches that universities decision makers and academics themselves should consider when designing future policies and future spaces for academic work.

Keywords
Academic workspace; Academic productivity; Work-from-home; University Campus; Third space; Covid-19.

1. Teaching activities are out of the scope of this study as they are usually subjected to specific university policies that limit the "free" decision of scholars on where and when to hold their classes and other learning activities.

THE EXPLORATION OF INFORMATION MANAGEMENT BASED ON BLOCKCHAIN: THE INTEGRATION OF AUTOMATED BIM VALIDATION AND SMART CONTRACTS IN THE DESIGN PHASE

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Co-Supervisor: Prof. Lavinia Chiara Tagliabue - Tutor: Prof. Matteo Francesco Ruta

The thesis proposes and validates an innovative framework that aims at improving BIM validation during the design phase by automating the verification of information quality and consistency and integrating blockchain-based smart contracts to shorten the appointment completion, assure the requirements fulfilment and secure the reward to the parties involved. The ambition to investigate this topic is sustained by some existing challenges such as incomplete design specifications, client's inability to carefully review the design and late integration of emerging technologies. In addition, a survey among industry experts detected both poor implementations of automated information validation and a lack of knowledge and testing of blockchain technology. These findings represent the research gap that confirms the thesis valuable scope and leads to the research questions about how digital tools could impact the reduction of overdue deliveries and payments and improve the reliability and accuracy of the design phase.
Stated the scope of the thesis, the state of the art related to information management pursued in the digital transformation of the industry allows for the investigation of the main topics. Information management using BIM is firstly discussed as the driver of structured information production, delivery and validation using CDE solutions. Its principles, regulatory standards and guidelines are provided through international cross-country comparisons. Despite the expectations, the adoption of BIM showed complications associated with the management of an extensive information flow that makes information monitoring and verification significantly time-consuming and error-prone, causing potential delays, reworks and unforeseen costs. For these reasons, the second part of the state of the art investigates blockchain as an emerging technology spreading in other industries. Principles, main functionalities (such as smart contracts and tokens), regulatory standards and current areas of application are presented. Since the thesis intends to integrate blockchain-based smart contracts in the design phase, a detailed literature review on the state of exploration of blockchain in construction is provided, enabling the identification of potential areas of use. The state of the art concludes with the collection of interviews conducted with industry experts that allow for the confirmation of the research gap and the value of the thesis.
The first part of the thesis leads to the explanation of the framework of the research (Figure 1) that intends to exploit the digital transformation by proposing a structured information validation through the adoption of tools for the automated verification of information quality and consistency and implementation of blockchain-based smart contracts. The framework involves three main actors, the client, the information model verifier and the design team. The main phases in which the framework evolves are (i) the automated validation of the information contained in the delivered BIM models according to the client's requirements, (ii) the notarisation of delivered BIM models and verification reports on the blockchain network and (iii) the automation of the approval of payment withdrawal and the issue of rewarding tokens. The first phase involves the configuration of rule sets in compliance with the client's information requirements and the adoption of these rules for the automated verification of BIM models. The second phase involves the setup of the blockchain network and the configuration of smart contracts that allow the responsible parties to notarise essential information, such as each delivered BIM model, the verification reports for each BIM model and the results of each verification. Finally, the third phase involves the execution of configured smart contracts for the approval of payment withdrawal and the eventual release of rewarding tokens to the design team, according to the verification results. The conditions under which the BIM models are validated, thus payment can be withdrawn and tokens can be issued, are established by the client at the start of the appointment.
The innovation of the framework lies in the shortening of the design phase by automating, using rule sets, and notarising, using smart contracts, the information validation and connecting these procedures to blockchain-based rewarding systems, such as payment and token. The framework offers a novel point of view which makes it possible to move away from traditional approaches by minimising validation errors or misunderstandings due to human intervention, limiting the occurrence of disputes through transparent information tracking and incentivising the parties involved with secure rewards and recognition. The framework is validated through a proof of concept that uses a real project based on the digitalisation of real estate assets of a large Italian client. This client has developed a proprietary BIM guideline based on which real estate digitalisation is appointed. In this project, the rule sets for automated validation of information are created and tested, as well as smart contracts for the notarisation of information and approval of payment withdrawal and token issue.
The outcomes of the proof of concept enable the comparison between the innovative framework and traditional approach, especially in terms of shorter time, accuracy and reliability of delivered information and guaranteed reward. The comparison reveals improved accuracy of the information, reduced time required for verification activities, transparent and reliable tracking of essential information, and guaranteed prompt payment from the implementation of the framework on a real project. The proof of concept also enables the economic analysis of the performance of the technologies showing that, after the initial investment in their setup, long-term use is not expected to have a major impact on total costs and proves to be cost-effective.
In conclusion, due to the disruptive nature of the technologies, the main limitations and further developments of the thesis are identified. The privacy of notarised documents, the link between a centralised environment and a distributed network and the use of cryptocurrencies are the main limitations detected. Therefore, the exploration of hybrid blockchain networks and the identification of other forms of currency are the main further developments.

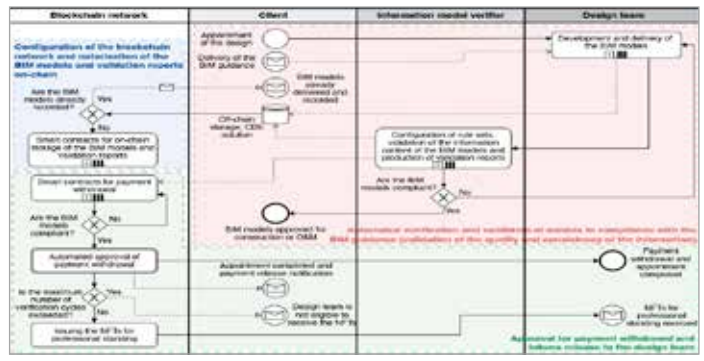

Fig. 1 - High-level framework of the research.

DECISION SUPPORT SYSTEM FOR OCCUPANCY-ORIENTED FACILITY MANAGEMENT

Laura Pellegrini - Supervisor: Prof. Giuseppe Martino Di Giuda
Co-Supervisor: Prof. Lavinia Chiara Tagliabue - Tutor: Prof. Graziano Salvalai

INTRODUCTION. It is essential to ensure actual and efficient management of buildings during the Operation and Maintenance (O&M) phase. Occupancy and space use, which are highly variable and can change over time, strongly affect organizational effectiveness and functioning during the operational phase. In addition, actual occupancy and space uses may be significantly different from the setup considered during the design phase, during which spaces are typically sized according to use-based standardized occupancy data. Consequently, actual occupancy values can differ from the values considered during the design phase, and spaces may be unsuitable for actual uses, leading to inadequate levels of space use and cleanness, which in turn are related to the well-being and satisfaction of users. Furthermore, the current COVID-19-related situation accelerated the spread of remote working practices, an already growing process, drastically increasing the variability of workplace occupancy. The increasing variability of building occupancy, the gap between design and actual occupancy values, and the growing phenomenon of remote working practices highlighted the limitations of facility management (FM) strategies based on historical databases and static occupancy values. Continuous real-time building monitoring and analyses are needed to achieve effective and efficient FM processes and to improve existing building use. In addition, the decision-making processes during the O&M phase should consider occupancy patterns of existing buildings to define accurate, up-to-date, and efficient strategies for a better planning of FM services over time.
The main goal of the research project is to define a Decision Support System (DSS) based on a dashboard, integrating occupancy levels and building uses from Post-Occupancy Evaluations (POEs). Insights and results of analyses of the dashboard would support the decision-making processes of facility managers during the O&M phase. The research aims at improving existing building management considering actual building occupancy from continuous monitoring, allowing for optimized planning of FM services, such as space management and cleaning services, and the definition of a flexible system that enables the working environment to adapt to changing conditions and needs.
METHODOLOGY. The methodology is divided into three main steps: (1) Indicative POE for building preliminary analyses; (2) Diagnostic POE by means of an IoT sensor network, defining the methodology for planning and calibrating the network, which is critical to ensure the collected data accuracy and quality, and the proper functioning of the sensor network; in this phase the respect of user privacy is crucial and five user privacy protection strategies are described; (3) DSS, which is defined as a dashboard, planning, and setting; this phase includes the definition of three indicators. The dashboard is a dynamic online tool integrating data from POEs and monitoring data, allowing for data analytics and comparison of optimization scenarios, by means of the integration of a selected set of tools. The DSS is defined as a dashboard, based on collected data and the evaluation of current building conditions and optimization scenarios via the three defined indicators.
The investigated and evaluated scenarios allow optimizing space organization and possible different FM service strategies. The system aims at supporting the decision-making processes during the O&M phase while delegating the facility manager for the ultimate choice of the optimization strategies to be finally tested and adopted.
PILOT STUDY. The proposed approach and system were tested on a pilot study building hosting the Department of Architecture, Built environment and Construction engineering (DABC) at Politecnico di Milano, and, among the FM services, focused specifically on the optimization of space management and cleaning services.
RESULTS AND DISCUSSION. The system application showed promising results. The analysis of current conditions in terms of occupancy showed that the pilot study building is used for around 25% of the available time and by 51% of users. The first scenario application highlighted that even while maintaining current building occupancy levels, cleaning activities can be optimized with reductions of around 30% in the entire building, especially optimizing cleaning activities on the first and second floors, which are the least used. The second scenario, aiming to optimize both space usage and cleaning service planning, highlighted that the average usage time and number of users can be increased by around 54% and 37% respectively considering the entire building. The advantages of the second scenario application are highlighted with considerable increases in average usage time and number of users and also optimizations and some savings in cleaning activities, with decreases of around 10% for cleaning activities in the entire building. The outputs showed the capability of the system to analyze current conditions and propose optimization scenarios. The investigation revealed limited usage of the building by the users. The low occupancy rates are also due to the wide time frame in which the building is open and accessible. Even considering the most used floor, i.e., the ground floor, in which users are required to work on-site, most spaces are used for around 8 or 9 hours, which is the standard length of a working day, while the building is open for about 14 hours a day, causing the low occupancy rates.
The optimization scenarios highlighted the possibility of optimizing cleaning activities and space usage according to current or hypothesized occupancy levels, ensuring optimizations and savings over time. Furthermore, the second scenario uncovered the possibility to host new users in the building or turn the available spaces into areas that can be used by reservation, increasing the building flexibility, especially considering the growing levels of remote working which will likely and hopefully be maintained in the future.
CONCLUSIONS. In conclusion, the reorganization and redistribution of spaces due to staff or activity changes over time can be supported by the proposed system, thus increasing the workplace adaptability to changing conditions and needs. In addition, insights and occupancy trends from the dashboard analysis can enable the optimization of cleaning activities. The successful application of the proposed methodology to a university facility can enable the consequent future application to a larger set of university facilities, resulting in even greater benefits considering the high FM costs and resources needed to operate university campuses.
In the short-term view, it will be possible to optimize cleaning contracts that are currently based on building floor areas. At the same time, this will ensure increased satisfaction and well-being of users regarding their workplaces. The proposed research project sets the foundation for the future definition of a Digital Twin (DT) for FM, investigating some critical preliminary steps.
In the long-term view, it will also be possible to define criteria for the optimized design of future office buildings with similar functions and expected occupancy values, and guidelines for proper occupancy monitoring, analysis, and simulation during the operational phase. This will ensure a continuous improvement of existing buildings use, and the increase of building adaptability to unavoidable changing requirements in the lifespan.

TOWARD SUSTAINABLE MANAGEMENT OF CULTURAL HERITAGE FOR LOCAL RESILIENCE; RE-DEFINING CULTURAL HERITAGE AS A CIRCULAR RE/GENERATIVE 'PROCESS', WITH CRITICAL REFLECTIONS ON INDIAN STEPWELLS

Mehrnaz Rajabi – Supervisor: Prof. Stefano Della Torre
Tutor: Prof. Corinna Rossi

By the third decade of the 21st century, the need to aim at comprehensively planning for any (peri) urban sustainability/ resilience scenarios of management and development is more prominent today than ever before, especially when all attempts are coordinated around global goals such as SDGs and climate resilience. Nevertheless, one can argue on the notion of such comprehensiveness, on the one hand, for how the international documents are being interpreted, adapted, and implemented in national contexts, particularly if one is concerned about heritage and its related fields, and on the other hand, for the current role and load of heritage and its related fields in those documents.
In such a context, this dissertation deals with built cultural heritage management-related concerns and the current and possible active role that heritage can play in contemporary challenges like climate change, risk reduction, and mass tourism. The research generally aims to explore the gaps and limits that exist in the current landscape of international documents with their respective interpretations/ adaptation at national levels, as well as the needs/requirements for planning a contemporary "heritage management system" dealing with a "comprehensive" and "holistic" way with those challenges/goals in the context of built (peri) urban environments and societies, particularly within a comparative study with India.
In the Indian context, the research depicts the Historical Underground Water Infrastructures, particularly stepwells, in their historical and emergent contexts. Such a heritage is selected as a model to contextualise the gaps and issues of the Indian counterpart. And it undertakes the current – and often rapid – development process of those contexts, which present various externalities, making the stepwell cases very appealing regarding contemporary challenges for any integrative cultural heritage management with a "long-term local resilience" perspective.
The significant feature of this research is its "systems thinking" approach and "holistic" point of view regarding all aspects of its investigation, as it seeks to further capture and highlight the "regenerative" role of heritage in those debates. And within the findings of the research, the most primary is the identification of the common ground well oriented toward the contemporary role of cultural heritage, either on gaps, potentials, or strategic suggestions for a contemporary heritage management system.
In that regard, the research also critically reflects upon integrative management methods like the "Preventive and Planned Conservation" for such heritage and explores their social, cultural, economic, and environmental values as engines for sustainable development, as well as their compatibility/adaptability in the Indian context.

ARTIFICIAL INTELLIGENCE ENHANCES DIGITAL ASSET MANAGEMENT

Luca Rampini - Supervisor: Prof. Fulvio Re Cecconi
Tutor: Prof. Graziano Salvalai

Architecture, Engineering, Construction, and Operation (AECO) is a crucial sector in many nations. Recently, a new set of dynamics has emerged in the industry due to the digital revolution fostered in other sectors. Servitization is one of them, and it occurs when the asset is no longer viewed solely as a physical entity but as a component of the services delivered to the end user. Since roughly 80% of an asset life cycle cost is spent during O&M activities, the focus is widely shifting towards this stage to ensure minimal financial and environmental impacts of a building project. As a result, Asset Management (AM), once regarded as a non-core function supporting the organization's primary business, is becoming a crucial function that balances costs, opportunities, and risks to optimize the asset's performance and realize value. Despite being historically less innovative than other industries, the construction sector is undergoing a technological revolution. Mimicking the innovations brought by the 'Industry 4.0' technologies, a new paradigm called 'Construction 4.0' is emerging. Construction 4.0 encompasses the fusion of cutting-edge industrial production systems and digital technologies redefining all assets' lifecycles. Due to this digital transformation, massive amounts of data are produced, and systematic analysis combined with predictive modeling can improve operational and construction safety, lower operational and construction costs, speed up construction, and increase sustainability. However, it is impractical for humans or traditional computer programs to analyze enormous amounts of data and identify patterns using rule-based approaches. In this context, Artificial Intelligence (AI) can process massive volumes of data, spot patterns, and build large-scale statistical models; therefore is a key driver of possible innovation in AM.
In this context, the proposed research will support construction companies in growing and implementing AI strategies.

Overall, three distinct yet related research issues are formulated and highlighted:

- What is the level of AI readiness in Construction, and how can it be measured?
- How can AI techniques bring more value to AM processes/ products at different scales (strategic, tactical, and operational)?
- How can AI be integrated with other digital technologies, such as IoT, as envisaged in the Construction 4.0 framework?

To answer these questions, the thesis structure is organized according to Figure 1 and presents the following contributions:
The first contribution of this research focuses on modeling a new, tailored metric to evaluate the AI readiness level of the AECO sector: the AI Readiness Index (AIRI). The proposed methodology integrates and broadens the Technological Readiness Level (TRL) concept and applies it to the Construction industry. The process of metric creation comprises an online survey sent to experts and practitioners of the industry which effectively produces a snapshot of the current situation. The results identify the main issues AECO firms encounter in their AI journey and guide them through investments and possible solutions.
The second contribution of this research focuses on a generalized methodology to support decision-making processes. This contribution involves the implementation of data-driven methodologies to discern meaningful information from big, unstructured, and inaccurate data usually collected at the strategic level. The case study in the thesis focused on a Decision Support System for energy retrofit policy using Clustering techniques and Monte Carlo simulations. This application benefits policymakers in deciding which buildings are worthy of renovation within a limited resource scenario.
The third contribution of this research focuses on implementing AI techniques, together with the Internet of Things (IoT), for creating smart, virtual sensors. Although the growing adoption of IoT in many applications, there are still some situations where the number of possible installations or the cost limits IoT introduction. This study introduces virtual sensors, which deploy AI for in-situ calibration or a more semantic understanding of the surroundings (for instance, Figure 2 shows how a CO_2 sensor can understand when the window was opened during school hours following safety procedures introduced after the Covid-19 pandemic). This application helps AECO companies and policymakers perceive and interact more with the environment without using resources to purchase expensive and delicate advanced sensors.
The fourth contribution of this research focuses on a methodology to augment data availability through AI for applications that suffer from data scarcity. This contribution proposes a scalable method where a small dataset of facility management objects is augmented using synthetic images generated from existing 3D object drawings. The proposed methodology is strictly linked with our sector, where Building Information Modeling (BIM) is increasingly used also in the operational phase, creating the foundation for data augmentation with synthetically generated images. This application helps researchers in training more efficient object recognition models inherent in facility management, solving any problems related to privacy and data quantity.
In conclusion, the contributions of this thesis are several: the introduction of the AIRI metric identified the current adoption of AI in the construction sector (still at its infancy level) and may help AECO firms identify where investments are most needed. Furthermore, the case studies presented demonstrated three ways in which AI can add value to AM at all levels (strategic, tactical, and operational) by: i) improving existing processes (i.e., making them more automated and productive), ii) introducing new products (e.g., virtual sensors), and iii) introducing new processes (e.g., decision support tools that extract relevant information from big data). Overall, through the development of the Ph.D., it was possible to answer the research questions and identify several ways that show how AI improved AM.

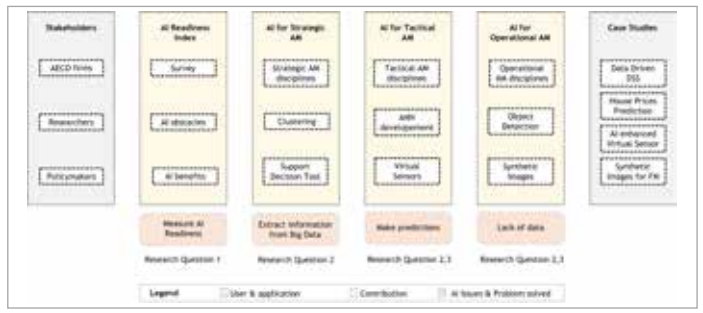

Fig. 1 - Thesis structure.

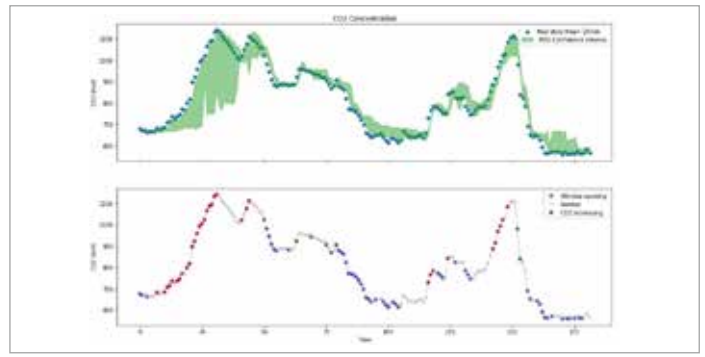

Fig. 2 - Flagging results with the CO_2 concentrations time-series by applying the quantile regressor method. Top: data and prediction interval; Bottom: data with flags showing above or below the prediction interval.

POINT CLOUD PROCESSING FOR PHYSICAL ACCESSIBILITY EVALUATION IN HISTORICAL URBAN ENVIRONMENTS. THE CASE OF UNESCO SITE OF SABBIONETA

Daniele Treccani - Supervisor: Prof. Andrea Adami
Co-Supervisor: Prof. Lucía Díaz-Vilariño (UVigo) - Tutor: Prof. Marco Scaioni

The management of physical accessibility in the urban environment is a topic of great interest at national and international level, where it is addressed by both United Nations and European Commission.
At national level, the topic is addressed by Italian legislative framework, but also by specific legislation issued by Regions through the predisposition of Plans for the Elimination of Architectural Barriers (PEBA).
It is also worth mentioning the recent push given by the PNRR National Recovery and Resilience Plan towards sustainability and inclusion, where accessibility is recalled both in Mission 2 and 3.
The management of accessibility could be fostered by the use of Information Technology. The support of Geomatics could play a crucial role while dealing with physical accessibility, intended as the ability to move in a physical environment independently of the motor abilities of the individuals (e.g., the users of baby prams, wheelchairs, walking sticks). Plus, it is precisely when managing physical accessibility in historic urban settings that the topic becomes even more interesting and challenging. Indeed, the non-standard organisation of historical urban scenarios is a feature that makes more difficult to identify approaches that exploit artificial intelligence to analyse spatial data and generate an inventory of urban elements and issues specifically related to accessibility. Specifically, in this thesis two different approaches were proposed in order to analyse and process a point cloud of a historical city, in order to extract useful information for a better management of physical accessibility. The historic city analysed was Sabbioneta, UNESCO site since 2008, and the element automatically detected were the roads and the sidewalks of the city. The work started with a survey of the physical form of the city, conducted with a Mobile Mapping System: Leica Pegasus:Two. The accuracy of the resulting point cloud was validated and it was used as the beginning dataset for the subsequent steps of the research.
Two processing methods were defined, a first one, developed by implementing different algorithms and original pieces of code, named knowledge-based method, and a second one that exploited a Random Forest classifier through a Machine Learning (ML) approach. In both the cases the point cloud of Sabbioneta was semantically segmented into urban ground elements. The two methods were also tested on other datasets, acquired on small portions of two Italian cities, Mantova and Domodossola, and on a Portuguese city, Porto.
In all cases, the ML method showed better results; an average accuracy of 89% could be assessed for the ML method, while 76% could be assessed for the knowledge-based method.
ML method (Figure 1) was also considered to be the most promising due to its better adaptability to the different urban contexts tested and the greater simplicity in calibrating the operating parameters. The focus of the research shifted at this point to the greater characterization of sidewalks, which were identified as the preferred routes of movement for all city users, and thus the objects on which to develop accessibility management. The computations were made on consequent portions of sidewalk, one every 2 metres. Specifically attributes computed were: the width, the elevation respect the road, the slopes in the two main directions, and the material used for the paving. From the spatial position of sidewalks, a vector network made of nodes and edges was generated, representing the sidewalks of the city. The test area was only Sabbioneta. A total of 1780 nodes and 1720 edges were generated, and the attributes were stored within the edges representing sidewalks in the network. The shapefile generated in the last phase of the work was then used to demonstrate its multiple possible uses. In fact, it was used to create thematic maps (Figure 2), it was exploited for the calculation of accessible routes within the city, it was tested for its possible use on a webGIS platform, it was evaluated by OpenStreetMap Italian community and will be uploaded to OpenStreetMap to update the existing map data.
The various uses demonstrated the flexibility of the generated file, and its great usefulness for different users at various levels (public entities, urban planners, social associations, citizens, tourists) and for different purposes (city management, plan interventions and maintenance, develop touristic routes, etc.).
This research work presented a complete method for the inventory and management of the sidewalk network of a historic city, with a focus on accessibility related analysis, starting from spatial data. From this work emerges the importance and benefits that can be generated by interdisciplinary research as a meeting point of different fields. In this specific case, it was necessary to involve experts from the field of Geomatics, but also data processing and accessibility experts in order to develop processes that can lead to a technological and methodological improvement of some urban management procedures. Future developments in this research could investigate its use for automated implementation of urban management plans (e.g., PEBAs); its benefits for BIM/GIS integration processes and for the development of 3D City Models; the use of Deep Learning techniques for the characterization of urban pavements; the possibilities of inventorying other urban elements as well and their impact on the management of urban physical accessibility.

Fig. 1 - View of a portion of the point cloud after segmentation by Machine Learning method. The point cloud was segmented into 'road' and 'sidewalk' classes exploiting a Random Forest classifier. Buildings are depicted in greyscale, points identified as sidewalks are represented in blue, and points identified as streets are in green.

Fig. 2 - Map of a portion of the historic city of Sabbioneta. The sidewalk network computed in the thesis is shown using a thematism based on one of the computed attributes. The width of each segment of sidewalk is compared with the reference value of the Italian regulations on urban physical accessibility (minimum 0.9 m) and colored green when the regulations are met and red when the regulations are not met.

SEISMIC VULNERABILITY ANALYSIS OF LARGE-SCALE MASONRY BUILDING AGGREGATES AND MONUMENTAL BUILDINGS OF MAJOR IMPORTANCE

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Tutor: Prof. Tommaso D'Antino

The thesis first presented a full 3D DEM (Distinct Element Method) Limit Analysis approach for a fast evaluation of the seismic vulnerability of masonry pagodas. At the same time, the author also applied the method development to the damage assessment of masonry aggregates.
The model discretization relies on hexahedron elements connected by inelastic quadrilateral interfaces, where all internal dissipation occurs (Figure 1 and Figure 2). On each interface, six internal actions act, namely the centroid velocities along the assumed frame of reference axes and the rotation rates around the centroid. Equilibrium is imposed on hexahedrons and admissibility on interfaces, where a homogenized out-of-plane Kirchhoff-Love strength domain is assumed for masonry. According to the features of the model, a quite simple Linear Programming problem with few variables and constraints has been obtained, which has allowed providing at the solution point the collapse load and the distribution of internal actions at failure. In the framework of the classic theorems of limit analysis, the dual problem has also allowed an estimation of the associated failure mechanism. It is particularly suitable in the failure analysis of massive masonry structures, like pagodas. The main advantages are the reduced computational time needed to evaluate the ultimate load-carrying capacity, the possibility to consider complex 3D geometries, and the possibility to perform analyses with spatial distributions of external loads, making thus possible the reproduction of the behavior of the structure under the application of seismic loads with a direction different from that of the principal axes of the cross-section.
To demonstrate the feasibility and convenience of the method, three ancient Chinese masonry pagodas (Longhu pagoda, Zhongjiang south pagoda, and Huqiu pagoda) were selected as case studies. The meshes used in limit analysis exhibited a good level of fidelity, at the same time maintaining the computational burden extremely limited. The research assumed two material properties (c = 0.05 MPa and c = 0.20 MPa) for the masonry pagodas and applied G1, G2 distribution seismic loading from 0°, 15°, 30°, and 45° direction (the angles respect to one of the principal axes of the pagoda cross-section).
The activation of longitudinal cracks along the central axis of the pagoda body and bottom bending in the base is the most common damage. The acute angle part of the eaves boundary of the masonry pagodas is often damaged, because these parts are easy to be pulled due to fewer constraints. The results reflect the high dependence on the seismic performance of the masonry material properties. When the material cohesion is good, three damage mechanisms can be seen, they are vertical splitting in two parts, base rocking, and overturning with diagonal cracks ("a la Heyman"). When the material strength is low, a combination of splitting and diagonal overturning damage mechanisms is activated. In addition, the author also carried out pushover analysis and non-linear dynamic analysis on the pagoda cases based on the CDP (Concrete Damaged Plasticity) model in the Abaqus environment. The numerical simulation results are consistent with the limit analysis results.
Typical masonry aggregates at the center of three historical masonry structures ("La Vecchia Forestale" aggregate in Arsita, Italy, "Yungay's historical urban center" aggregate in Santiago, Chile, and Special aggregate in Arsita, Teramo, Italy) were selected as cases to validate the limit analysis technique. The research assumes that the masonry material gradually decreases from a very high tensile strength until it is infinitely close to 0, and observes its different collapse mechanisms at different strengths. When the masonry aggregate is built with inferior materials, the internal power dissipated by the masonry material is low, and the overturning mechanism is more likely to occur. When the material performance is better, the flexure mechanism is activated.
C.I.N.E. (The Italian application C.I.N.E version 1.0.4) manual seismic calculation analysis was also carried out for the first two historical masonry aggregate cases. The result of manual operation is the same as the result of limit analysis operation. Part of the discrepancy is possibly due to the estimation of the partial data for the masonry aggregate structure in the excel sheet.
Overall, these predictions of the 3D failure mechanisms of masonry pagodas and aggregates appear extremely accurate and beyond the present state of art models available. Since the 3D DEM limit analysis approach proposed is identical in the pre-processing phase to a standard FEM (Finite Element Method) and limit analysis requires a computational effort that can be managed even with low-cost laptops, the model may represent an excellent tool for all practitioners interested in a fast and reliable evaluation of the seismic vulnerability of masonry structures with complex geometry.

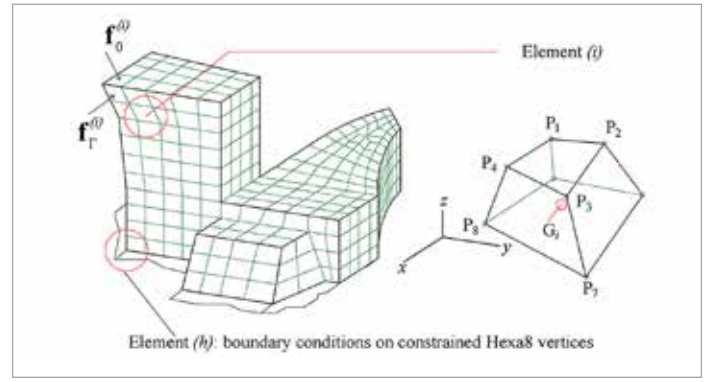

Fig. 1 - Generic DEM discretization of a structure with 3D Hexa8 rigid elements for the pagoda.

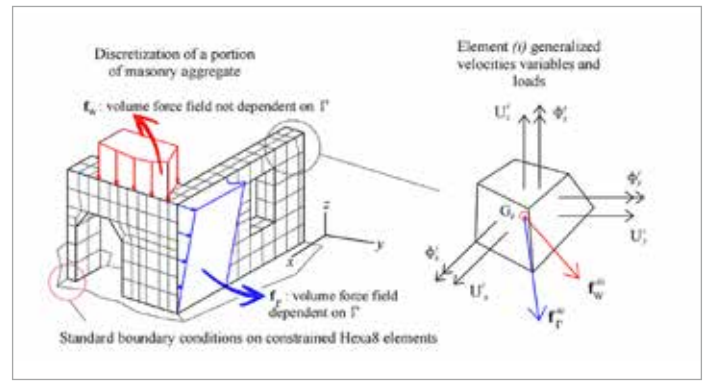

Fig. 2 - Generic DEM discretization of a structure with 3D Hexa8 rigid elements for aggregates.