



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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THE STADIUM AS A CULTURAL ASSET BETWEEN MEMORY AND CONTEMPORANEITY

TOOLS AND STRATEGIES FOR THE ENHANCEMENT OF SPORTS INFRASTRUCTURE AS OPPORTUNITIES FOR URBAN AND SOCIAL REGENERATION IN THE ITALIAN CONTEXT

Silvia Battaglia – Supervisor: Prof. Maria Pilar Vettori

Co- Supervisors: Prof. Emilio Faroldi, Arch. Matteo Biasin – Tutor: Oscar Eugenio Bellini

Established and developed in the second half of the 19th century as places called to host competitive events, the stadiums reached the peak of a development parable in the 20th century in conjunction with the full evolution of economic and territorial systems as places with high functional specialization by cyclical and segmented temporality but the transformation of post-industrial territorial economies, leading to assigning a central role to well-being and leisure, determines a phase of profound change for the stadiums which makes them crucial places for territorial development strategies. The policies undertaken in the last two decades towards these places have had as their main objective to question the concept of the stadium that from a simple container of events has turned into an infrastructure able to promote and produce services destined for the city becoming a centre of profit able to generate opportunities.

Italy exhibits a situation characterized by the presence of a vast existing built heritage that declined within the framework of sports infrastructure and takes on very topical characters generating an original and unprecedented debate in the

European scenario.

The Italian context is characterised by a widespread system of places intended for sports practice and activity whose value assumes, at the same time, an objective relevance and a significant commitment related to the memorial respect of the places; at the same time the sports plant, built at the beginning of the 20th century based on single-functional assumptions and interrelated to a culture very different from the current one for numbers, economic values, types of users, is now inadequate, no longer able to respond to the needs expressed by contemporary society.

The presence of imposing buildings and sports venues throughout the territory largely obsolete, the different protection regimes that weigh on a large number of such facilities, the difficulties of adapting existing structures with obvious morphological rigidity, the public nature of the properties, the strong identity of these buildings within the different contexts are just some of the main issues peculiar to the understanding of the Italian situation and the relative critical issues that are directly proportional to the potential of this system.

In Italy the process of enhancement of sports facilities is lagging far behind, it is precisely in this condition that the innovation potential is identified where the assessment of current conditions, of the changes of use and context, is interfaced with the open question concerning the future of the architectures of the 20th century.

Within the contemporary city that grows on itself, in a perspective of non-consumption of soil regenerating the underused portions, the hypothesis is advanced that the sports infrastructure can be considered as one of the fundamental components for the development of the urban fabric and it is a candidate as one of the more interesting strategic asset to convey the processes of urban regeneration and valorization of the built environment.

The work is organized in such a way as to constitute an original reading attempt on the subject in question and is articulated through five cognitive parts: (1) introduction, (2) topics, (3) elements, (4) tools, (5) perspectives.

The **first part**, the introductory part, outlines the scenario within which research moves. Starting from the framework of cultural

approaches, this part illustrates the approach and development of the work, clarifying the main content and methodological aspects.

The **second part**, analytical-cognitive, represents the reconstruction of the state of the art, which is proposed as a synthesis of the theoretical-cultural scenario and provides a systemic vision of the topic, rarely addressed by the literature of reference, which, although with clear references to the international sphere, highlights the specificity of the topic at a national level. In particular, the first chapter concerns the definition of the subject matter, sports infrastructure, in its complexity as a territorial cultural product in the urban environment characterised by specific relationships between the elements of the built environment within the contemporary European reference scenario. The second chapter illustrates the main evolutionary moments of sports architecture throughout the 20th century up to the current attempts to relaunch the system undertaken in the last two decades. Finally, the research work, through a reflection on the current state of sports architecture as cultural heritage, carries out the characteristics of this system, posing the main questions from which the research hypothesis develops. Starting from a framework on the systems of cataloguing and digitalization as tools for enhancing the architecture of the 20th century, the **third part** focuses on the Italian

context and, in particular, on the preparation of a mapping (GIS-based) 200 Italian stadiums selected thanks to precise criteria and analysed, first, thanks to a series of data strictly necessary for a summary inventory and, second, deepening a part of these (111/200) and investigating them through a detailed reading able to understand aspects regarding the context of belonging and the characteristics of architecture. Through transversal readings of the emerged information, the potentialities and the criticalities of this system of architectures are evidenced.

The **fourth part**, as a synthesis-evaluation and orientation phase, is structured through the systematization of the main topics that emerged during the research, as well as through the definition of an opportunity assessment tool that can indicate the readiness of an existing stadium to accommodate a valorisation project and following which guidelines.

The research work ends in the **fifth part**, outlining, based on the reflections and analyses that have emerged, as well as the construction of the instrument for reading opportunities, some guidelines for the planning and design of the redevelopment of existing stages through the identification of some interpretative keys that attempt to synthesize the different thematic areas with which a contemporary stage must compare today if interpreted as a nodal infrastructure of the processes of urban and social regeneration.

In this context, research has a dual objective. As a general objective, the work aims to generate a systematic and scientifically rigorous vision, able to constitute a valid support to the development of a sector that increasingly manifests a strong need for renewal and requires appropriate skills for this purpose. As a specific objective, the research aims to promote awareness of an interesting, complex and delicate framework, that of the Italian context, in which the close relationship historically established between cities, stadiums and cultural heritage is so unique that it requires specific approaches and tools. This work aims to identify tools, strategies, indications and perspectives that can not only support interventions to enhance the value of the built heritage but, in a perspective logic, accompany the processes of change management, innovation and strategic development of existing sports infrastructure. The proposed work aims to develop a typically Italian specificity: the widespread presence on the entire territory of a vast system of places for sport, in particular stadiums, waiting for transformation: urgent theme and full of opportunities, little investigated material in an organic and systematic approach that poses pressing questions and requires urgent answers for the future of our cities.

THE GALLONE SAMPLES ARCHIVE: KNOWLEDGE MANAGEMENT THROUGH TIME. THE LAST SUPPER COLLECTION ONLINE INFORMATION SYSTEM

Serena Benelli – Supervisor: Prof. Stefano Della Torre

Co-Supervisors: Prof. Cristiana Achille, Prof. Ezio Puppini – Tutor: Prof. Corinna Rossi

This project is about the study of samples from artworks conserved in the Gallone Archive, housed at the Physics Department of the Politecnico di Milano. The archive is the legacy of Antonietta Gallone (1928–2015): a physicist, researcher at the Politecnico di Milano, who from the mid 1970s decided to dedicate herself to the diagnostics of Cultural Heritage, with a particular emphasis on the Italian pictorial heritage. She pioneered the modern figure of the Conservation Scientist, contributing to the then-emerging discipline of Heritage Science.

The proposed research aims at developing an innovative methodology for the management of physical and chemical data related to decorated surfaces of historic buildings, artworks, and archaeological objects. Indeed, these data are obtained by means of non-destructive onsite techniques or by laboratory analyses which require taking samples: the latter can be a delicate operation, not to be repeated. Alongside, the project intends to safeguard and valorise the samples collection, documenting, cataloguing, and relocating the fragile and delicate

materials it comprises.

This work focuses on multidisciplinary research. The study sets new analyses on a selected number of samples from Gallone's collection, applying the most advanced techniques available in the laboratories of Politecnico di Milano and other collaborating institutions in Italy, such as ISPC-CNR, and abroad. The main case-study is focused on the samples taken from the Last Supper by Leonardo da Vinci, certainly the most notable restoration to which Antonietta Gallone contributed with her investigations. The Last Supper collection conserved in the Gallone Archive counts about 450 samples, including raw micro fragments and cross sections. To be able to investigate the same samples some years later, implementing more advanced techniques, could open to important perspectives. Therefore, a selection of samples has been re-examined with tools that, in addition to having evolved and refined over time, have become available in several facilities. The opportunity to deepen the data on existing samples, without the need to take new ones, demonstrates how important the conservation, archiving and documentation of

samples are, because those can be observed again and analysed with the instruments that will come, providing further and more detailed analytical data in response to future needs, also the result of extensive research aimed at cultural heritage conducted at an international level in numerous projects. The significance of the information is exalted by the possibility to cross data from different sources and to reference the samples and the datum itself: the selected samples, both punctual and areal, have been localized on a photoplane of the surface of origin (Leonardo's Last Supper). Data obtained by means of laboratory analyses have been cross checked with data obtained through other methods, by non-destructive techniques.



Fig. 1 - Antonietta Gallone

The results have been critically evaluated, to test the reliability of the old samples conserved in the archives, and the influence of ageing as well the conservation conditions.

The goal is to acquire and collect all the materials and related results of the research carried out by Antonietta Gallone on the Last Supper, locating (when it is possible) the sampling points on the surface of the mural painting, punctually referencing data; to make this information accessible to scholars and to the personalities involved in the conservation of Leonardo's masterpiece a dedicated Information System (through the QGIS software tools) has been developed within the 3DSurvey

Lab. The result is a sort of digital repository for the Last Supper diagnostic materials, to be added to the Gallone Archive website. The GIS-based IS has been developed as a proof of concept in order to verify the feasibility of the method. The result proved to be an effective tool to support the research approach: the visual referencing of the sampling points significantly contributed to structure and systematize the archive of samples and supported the decision process of the attribution of uncertain samples to the most probable point. The research path, together with the Heritage Samples Archive Initiative promoted by ICCROM – a project involving the major representatives of conservation

and restoration institutes from all over the world – have highlighted the shared need to standardize archiving methods for sample materials, and to orient the work in order to facilitate the exchange of digital information, according to the FAIR principles. Thus, the foremost targets of this project are to produce a first document on post-sampling procedures to safeguard the Cultural Heritage samples archive, and to propose a nimble work methodology oriented to knowledge management on the long run, also implementing digital techniques to enable the maximum exploitation of data of this kind in the various activities concerning Cultural Heritage.



Fig. 2 - A few samples and materials from the Last Supper collection in the Gallone Archive

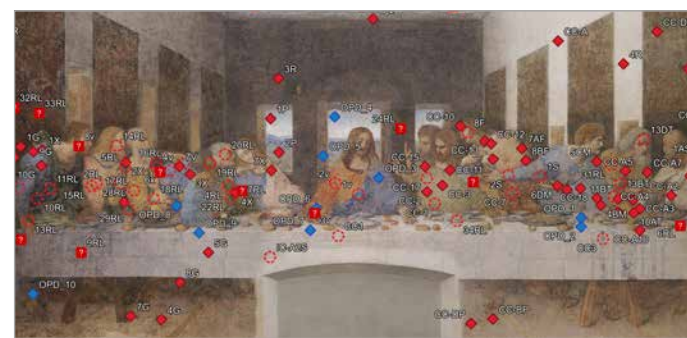


Fig. 3 - The Last Supper Samples Information System

ARCHITECTURAL HERITAGE DIGITISATION THROUGH A LEVELS OF GEOMETRIC INFORMATION – BASED APPROACH. THE CASE STUDY OF THE GHIRLANDA OF THE CASTELLO SFORZESCO IN MILAN

Francesca Biolo – Supervisor: Prof. Franco Guzzetti

Tutor: Prof. Corinna Rossi

The research addresses the domain of architectural heritage digitisation, with an emphasis on developing an approach for the digital transformation of the geometric information of such objects. Specifically, the primary concern is a matter of collecting in a single 3D model the profusion of information typical of an architectural asset. The purpose is to develop a 3D that comprehensively describes the structure, including elements that are no longer in place or visible, by managing heterogeneous information. This work, therefore, aspires to provide a solution, capitalizing on state-of-the-art methodologies and technologies of survey and digitisation, which are precious in comprehending complex structures. The work carried out has indeed started from the architectural heritage itself and from the idea that a comprehensive knowledge of it is essential for conscientious manipulation thereof.

The knowledge of cultural heritage is the result of a multifarious and composite data collection, derived through variegated processes and products. The proposed approach aims at creating a

3D model able to gather the heterogeneous geometric data available while concurrently facilitating the management of the progressive expansion and change of the information package. The resultant model encompasses information of various natures, and due to its heterogeneous sources, will inevitably have to handle data characterised by different levels of accuracy. This is typical when working with built heritage, whose sources have accumulated over time in discordant forms. The blueprint of the 3D model requires the harmonious coexistence of objects at different Levels of Geometric Information (LOGI)(figure 1) so that all data is correctly arranged in defining the overall geometric information, including both the reference documentation and the tridimensional elements in its subdivision, according to their respective levels of accuracy. In such a way, it is possible to incorporate what is obtained from a modern geomatic survey and information from historical sources in a consistent collection that encompasses all elements of the building, from those surveyed to those hypothesized. Furthermore, thanks to the rigorous use of georeferencing,

the object can be updated with emerging information or additional research and survey activities. The modelling phase has been designed to be reiterated whenever new data are available, so that the 3D object will be constantly updated. Due to this approach, knowledge never stops at the first supply of information, while it accumulates and evolves progressively into an increasingly complete vision of the object. The digital twin of the architectural asset is completed by inserting the information useful for the identification and description of the sources that provided the geometric information. This is accomplished within the modelling environment itself, exploiting the functionality of the chosen software (Rhinceros) and setting up a

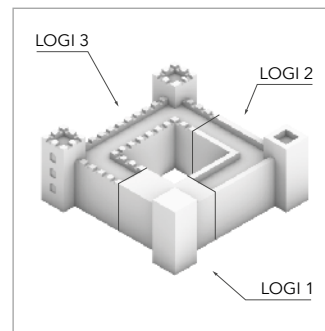


Fig. 1 - Representation of the concept of the digitisation approach.

structure for metadata (figure 2). This metadata framework then links to an external database, containing the material used, that maintains its accessibility and consultability.

To develop this work, the case study chosen has been the Castello Sforzesco in Milan. Specifically, the area analysed consists of the northwest corner of the Ghirlanda, between Torre della Colubrina and Porta del Soccorso (figure 3). The history of this building, the articulated architectural evolution and its multiple roles give to this architectural cultural asset a remarkable degree of complexity. This abundance of information

about this building has set valuable conditions for the experimentation conducted. Such attributes collectively render the Castello Sforzesco an ideal case study to evaluate the effectiveness of the paradigm proposed in the research work. It is worth noting that while the experimental phase is anchored in the specifics of this historical building, the overarching ambition pertains to the formulation of a methodological framework of broader applicability within the realm of architectural cultural heritage.

This doctoral research describes a possible approach to the description and digitisation of the

geometric information apparatus of an architectural asset. The modus operandi is intended to be an instrument tailored to those involved in the management of the building as a whole, thereby helping to understand its spaces and its interconnections with external systems. In light of this, the present research seeks to address this exigency by encouraging the organic collection and sharing of knowledge directed towards the conservation and valorisation of our heritage. Moreover, by aggregating information of a different nature, this instrument unveils pivotal points and issues requiring further investigation and research, thereby fostering additional refinements of the model and progressively enriching the information dataset.

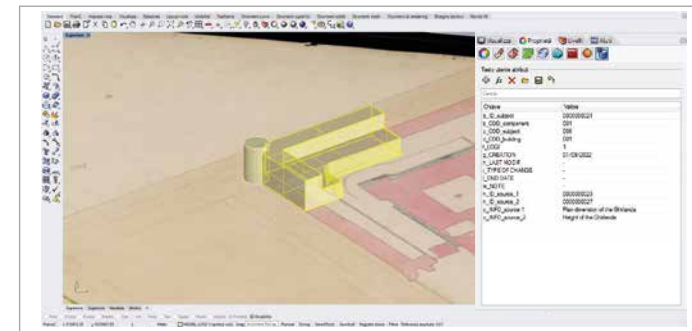


Fig. 2 - Model of the structures included in the case study. The volumes of the Ghirlanda and the Spanish Bastions, which would have covered most of the other elements, are not present.

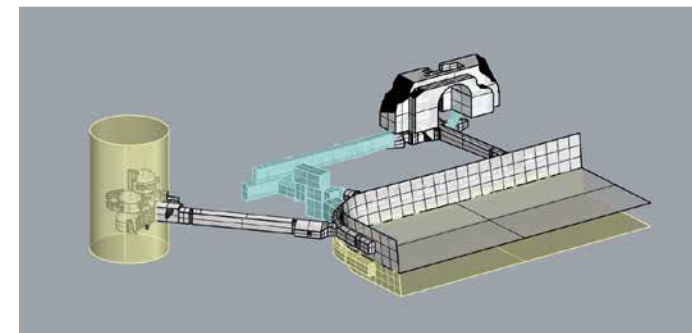


Fig. 3 - Rhinoceros attribute table for the hypothetical original volume of the Ghirlanda.

DEEP LEARNING BASED LABEL-EFFICIENT SEMANTIC SEGMENTATION OF BUILDING POINT CLOUD AT LOD3: LEARNING FROM WEAK SUPERVISION

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Co-Supervisor: Prof. Mattia Previtali – Tutor: Prof. Andrea Tartaglia

Three-dimensional (3D) building models provide metric reconstructions of scenes without occlusion or scale ambiguity. In general, the 3D representations are in the form of point clouds, meshes, and geometric models. Among these data structures, point cloud models are an expressive and high-fidelity representation of surface-based geometries, capable of representing geometric details while occupying relatively small memory space. On the other hand, the points in the point cloud are unorganised and the point density is uneven, so the use of building point cloud representation still faces challenges.

3D building models can be classified into different Level-of-Details (LoD). According to the LoDs and their variants there are different applications. In recent years, high LoD 3D building point cloud representations, such as LoD3, have enabled and promoted various applications in many fields, such as energy efficiency, cultural heritage, construction engineering emergency decision-making, smart cities, simulation, monitoring, 3D semantic modelling, and geographic information management.

However, creating comprehensive and semantically rich 3D models of buildings is challenging due to the diversity of objects encountered in buildings and the variety of potential applications. Currently, only handful approaches have been successful in delivering on promise of such detailed 3D building models. Specifically, these applications are still in their early stages, with most of them focusing on the representation of the whole building (LoD0 and LoD1) or a few types of semantic subsurface (LoD2), and a few applications applying to the more detailed subsurface of the building (LoD3). To enhance such applications, it is essential to acquire LoD3 representations that include fine-grained semantic information.

Semantically rich building models are crucial and fundamental for many applications. Thus, building semantic modelling and semantic segmentation has emerged as significant and challenging. The former takes a point cloud as an input and determines which object is represented by that point cloud, while the latter assigns a class label representing an object type to each point of the point cloud.

Inspired by the success of deep learning (DL) used in computer vision (CV) to accomplish the corresponding tasks (i.e., image classification, semantic segmentation, and object detection), these approaches have been also applied for 3D point cloud semantic modelling. In this domain DL methods have emerged and achieved high performance on various benchmark datasets. Compared to traditional point cloud analysis methods such as region growing, K-means clustering, Hough transform, and RANSAC, DL methods provide an end-to-end fashion without the need for hand-crafted features as input. In the building modelling domain, numerous DL techniques have also been developed for indoor, urban, cultural heritage, and coarse-grained building scenes.

Despite their impressive performance, most existing DL approaches for 3D point cloud analysis tasks are heavily supervised. DL algorithms require much more finely-labelled data than traditional machine learning methods, and assume that a large amount of ground-truth labelled training data is always available for point-cloud analysis. For many real-world problems,

generating such large amounts of labelled building training data is not feasible. For example, very few publicly available 3D Light Detection and Ranging (LiDAR) datasets with point-level annotations support the generation of high-resolution LoD3 building models.

Furthermore, pointwise annotation is exceptionally time-consuming and expensive to accomplish. For instance, the order of magnitude may increase dramatically to millions of points for a real indoor scene, which means that very accurate labels for billions of points in a dataset are required to train good semantic segmentation models. Therefore, it is necessary to develop a label-efficient semantic segmentation method using 3D point cloud data without or with only a tiny set of supervised data.

This thesis aims to address this issue through an innovative label-efficient DL framework that can obtain semantic labels for LoD3 building point clouds using weak supervision and a tiny amount of finely labelled data. The label-efficient DL framework consists of three branches:

a) the first branch proposes an unsupervised learning network

- b) the second branch introduces a transfer learning method that allows the selection of source datasets and the extraction of semantic patterns from cross-domain datasets. This transfer learning method is extended to various applications ranging from semantic; and
- c) the third branch presents a novel 3D Building Indoor Outdoor (BIO) dataset along with a weakly supervised learning network that combines the advantages of the previous methods and reduces the annotation cost by exploiting the abundance of incompletely labelled open-source data.

By using three types of weak supervision (e.g., unlabelled, cross-domain labels, incomplete supervision), these three branches reduce the dependence on domain-specific finely labelled data, resulting in a “label-efficient LoD3 building point cloud semantic segmentation framework”. In addition, a semi-automatic pipeline is proposed, along with the novel BIO benchmark dataset that

covers both indoor and outdoor environments with highly accurate labels.

In summary, this thesis presents an innovative solution to the challenge of acquiring large amounts of finely labelled building point clouds for semantic segmentation and paves the way towards saving annotation costs. Through a label-efficient DL framework and the creation of a comprehensive BIO dataset, significant advances can be made in the accuracy and efficiency of various applications in the field of 3D building point cloud semantic segmentation.

PUBLIC-PRIVATE PARTNERSHIP FOR SOCIAL INFRASTRUCTURE. THE DUE DILIGENCE FOR SOCIAL IMPACT

Genny Cia - Supervisor: Prof. Gianandrea Ciaramella

Co-Supervisor: Prof. Angela Silvia Pavesi - Tutor: Prof. Andrea Antonio Caragliu

Framework. There is a great deal of static evidence demonstrating that an expansion and adaptation of a country's infrastructure supply has a significant positive impact on growth and productivity potential (Ercolani, 2021), however, the High-Level Task Force (HLTF) on Investing in Social Infrastructure (2018) estimated that the gap between real and necessary investments in social infrastructure in Europe is between 100-150 billion euros per year. An infrastructure, the social one, that is extremely significant for the advancement of human development, for the improvement of quality of life and living standards, and therefore, functional for social inclusion and cohesion (Howes and Robinson, 2006). The serious consequences of the recent worldwide Covid-19 pandemic have further demonstrated the urgency to act in this area. In particular, in Italy, the health emergency has revealed the critical nature of the infrastructural and services systems, increasing needs and leading increasingly large groups of population towards known and new fragilities (Quinto Rapporto Secondo Welfare, 2022; Next Housing, 2021).

To face the emerging challenges, Europe approves in 2021 the

extraordinary fund "Next Generation EU" (NGEU), of which Italy is the main beneficiary with a share of over 200 billion euro flowing into the National Recovery and Resilience Plan (PNRR). EUR 30 billion will be allocated to Mission 5 "Inclusion and Cohesion", more than a third of which will finance interventions in component 2 "Social infrastructure, families, communities and the third sector". The opportunity provided by NGEU funding underlies the need to launch public-private partnerships (PPPs) - already anticipated HLTF (2018) - to scale up and expand the scope of projects and the resulting positive impacts on citizens and territories. A partnership that, already in the title of component 2, extends to Third Sector entities and/or social private bodies devoted to the mutualistic organisation of needs, highlighting the role they play in the construction of social infrastructure. A declination of traditional PPPs that is not new to the scientific literature (Coulson, 2005; Weihe, 2008; Wettenhall, 2010; Dalla Longa, 2017) nor to current practice (Ostanel 2017; Zamagni 2015, 2016; 2018; 2018a), but of which a codified intervention practice nor

a coordinated set of operational tools is not yet apparent.

Purpose. In the context briefly outlined, the thesis aims to identify methods and tools to enhance the synergy between the public, private and social private sectors in the construction of social infrastructure. Research Questions. To achieve this aim, the research sought to provide plausible answers to two research questions: (1) "How can public-private collaboration be improved to close the social infrastructure gap?" and (2) "How can interventions be developed that are feasible and sustainable over time?"

Methodology. The thesis applied two different methodologies: desk research and Action-Research. The first methodology, through the literature review, the study of European and national policies and legislation (in particular D. lgs 50/2016 and D. lgs 117/2017), defined the state of the art and the scenario of the three converging fields in the topic of social infrastructure: PPPs, Services of General Interest (SGIs) and regeneration of public real estate assets for collective interest purposes. The second methodology was applied to research projects and scientific consultancy, in which

the author participated, selected on specific criteria, representing the experiential field of the thesis. These projects are experiences of PPPs and social private sector for the construction of social infrastructure. They were an opportunity to co-design the toolkit and an opportunity to test its usability, as well as an opportunity to acquire skills and know-how in the field of investigation. The decision to adopt the Action-Research methodology, although it originated in the field of pedagogical research (Lewin, 1946), lies in its founding characteristics: (1) it is functional for interdisciplinary and multidisciplinary research; (2) it is suitable for investigating an object of research rooted in reality; (3) it focuses on the process and changes resulting from the application of the continuous process of "observation, reflection, action" (Action-Research Spiral).

Results. Scientific evidence and results of research and consultancy projects have shown how the process of constructing social infrastructure, despite its current development and deepening, is characterized by wide areas of ambiguity and lacks codified intervention and project evaluation practices. For these reasons, the thesis defined a toolkit named Due Diligence for Social Impact (DDforSI). This is a coordinated set of tools aimed at enhancing the synergy between the public and private sectors for the construction of social infrastructure, proposing an integrated model of supply chain

action and at the same time a tool for the pre-feasibility assessment of social infrastructure projects. The pre-feasibility assessment interconnects social, technical, economic, financial, governance and process feasibility choices. The toolkit borrows the tools traditionally used in the assessment of real estate development projects by declining them according to the achievement of social impact and to characteristics of services.

Originality/Value. The results obtained represent the first codification step of the social infrastructure construction process and a first functional result for the prospective engineering of the process. According to the bottom-up approach typical of co-design, tools are the outcome of dialogue and discussion with the network of stakeholders involved in the research and funded research projects. The toolkit valorises the specialist contributions that a multistakeholder network is characterised by; it relates the individual choices in a circular and repeated process, which is functional for the definition of the project's sustainability; and finally, it can be used independently of the scale of intervention as it is strictly related to the necessary competences and not to the size of the project.

Limits. The research tested the toolkit in already implemented or started projects, thus in an ex-post condition of the projects. The specialised nature of the toolkit requires the search for a partner with that specific competence, know-how and

experience. At the same time, the partnership needs to equip itself with governance with an overall and unified project vision and strong leadership.

Future Developments. The research work conducted thus far lays the foundations for three future areas of in-depth study. The first, building an observatory of public-private partnership practices for the construction of social infrastructure to broaden knowledge of the topic and refine DDforSI. The second, the digitisation of tools to improve their adoption and usability. The third, identifying pilot projects (in ex-ante stage) in order to test ex-ante the toolkit.

MACHINE LEARNING-AIDED GENERATIVE DESIGN METHODOLOGY FOR A MARS HABITATION

Gokhan Dede – Supervisor: Prof. Massimiliano Natri

Co-Supervisor: Prof. Ingrid Maria Paoletti – Tutor: Prof. Paola Caputo

The objective of this dissertation is to develop methodological approaches that lead to a high-performance habitation concept in the extreme conditions of the Mars environment, while remaining responsive to human-based design requirements and defined data and simulating this concept through an iterative creative process involving environmental data and computers. The subsequent problem statements guide the inquiry and contribute to the achievement of the objectives. How architects can optimally identify, acquire, and employ environmental data, such as that provided by Mars missions, to balance competing quantitative objectives, is a key problem in the discipline of computational design.

How architects can transform a data-driven process into a data-driven, autonomous computational design method to construct a Mars habitat that can withstand the harsh climate is the second most major challenge. The dissertation addresses novel methodologies that combine data science, a machine learning algorithm, and generative design methodologies to enable multi-objective investigation

during the early phases of Mars habitation design to provide answers to the pointed questions. It then justifies the need to incorporate a semi-supervised machine learning algorithm to make typology decisions using a label propagation approach. The developed design methodology suggests using structural simulations with environmental forces as structural loads to generate self-generating habitation enclosures. It concludes with implementation examples of novel design methodologies, describing them in detail to illustrate the effects of environmental influences on various analyses of habitation shells.

At the first phase of the research methodology, an analysis of the physical requirements

for an extraterrestrial habitat is conducted based on the literature and analog Mars missions. The collected requirements are used to construct three adjacency matrices for habitation plans based on the findings. The defined matrices are examined using social network analysis (SNA) in the Python environment, and the adjacency relations between spaces are reinterpreted in light of the analysis. Following SNA analysis, the Label Propagation Approach (LPA) is a semi-supervised machine learning (ML) technique that employs a community detection algorithm, is used to detect communities within the network graphs that are generated with SNA analysis. Upon completion of the community detection

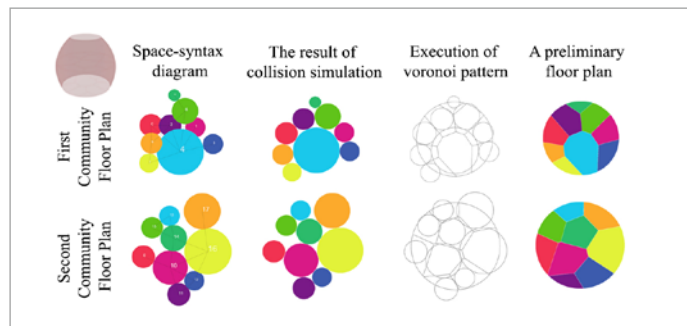


Fig. 1 - The layout and form generation results for the first adjacency matrix

process, three investigated matrices revealed two, three, and four communities. These communal areas are functional spaces on a floor plan and should be located on the same level. Next, the communities are used to construct space-syntax diagrams at the beginning of the habitation design process, and floor plans are generated after a space-syntax diagram configuration, a physics simulation, and a Voronoi pattern definition have been implemented. After generating floor plans, their boundary curves are used as floor areas to construct a lofted preliminary habitation form, as shown in Fig. 1. This is accomplished by aligning the curves along the Z-axis. The created preliminary form is offset by 1.5 m in order to create a dual habitation shell,

with the inner layer defining the envelope of habitable space and the outer layer defining the protective shell of inhabited volume. When openings are defined on the exterior shell, the space between layers is proposed as a vertical circulation area to reach the upper floors and a volume to distribute natural light to lower floors.

Subsequently, the specified environmental forces are inserted into the generative design process utilizing a structural simulation tool to create a habitation shell resistant to the harsh conditions of Mars to safeguard future explorers on the missions. However, micrometeoroid impact was precluded because it is neither a continuous nor a constant design element. As

depicted in Fig. 2, the effects of environmental forces on habitation shells are displayed and explained following the design process to illustrate their implications for various design instances.

Consequently, the defined design methodology is successfully implemented in three distinct cases, as depicted in Figure 3. However, the methodology requires additional research on topics such as creating openings on the shell with structural durability and radiation in mind, providing natural light for the habitable volume, sound insulation, the use of color, implementing the methodology with different in-situ materials, and defining additive construction phases with an exoskeleton.

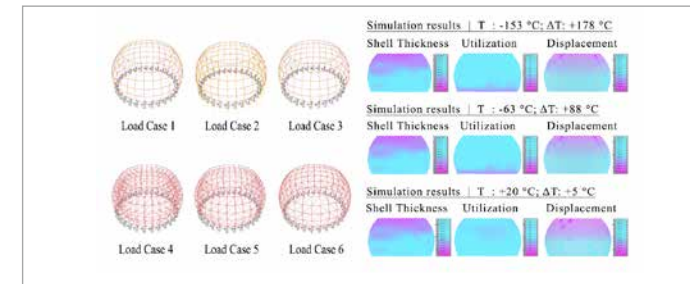


Fig. 2 - The simulation results and illustration of first adjacency matrix-generated habitation.

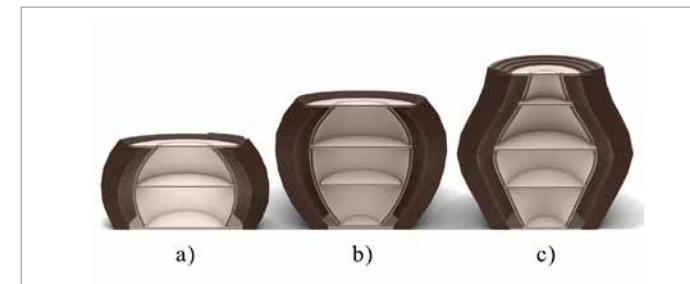


Fig. 3 - Perspective sections of simulated habitation proposals with 2-story buildings (a), 3-story buildings (b), and 4-story buildings (c) for 4 crew members.

VERTICAL GREENING SYSTEMS: DESIGN AND FUNCTIONAL OPTIMIZATION TOWARDS POLLUTION ABSORBING GREENED FACADES

Martina Di Labbio – Supervisor: Prof. Marco Scaioni

Tutor: Prof. Laura Elisabetta Malighetti

In today's interconnected global society, where economic prosperity hinges on the relentless consumption of goods and services, we witness a mass exodus of populations from rural areas to sprawling metropolises. European authorities grapple with the imperative to mitigate the repercussions of this urban migration, stemming from profound shifts in economic dynamics. This influx strains urban ecosystems and healthcare systems alike, subjecting individuals to a relentless pace of life that induces psychophysical stress. Such stressors arise not only from the demands of high productivity but also from exposure to biological and chemical pollutants, heightening susceptibility to various diseases and exacerbating burdens on healthcare and social support systems.

Yet, amid the challenges, globalization also heralds positive advancements, democratizing access to technological innovation, even among those less economically privileged. Nonetheless, it is imperative for Western societies to confront the grave consequences of climate change and environmental degradation, particularly in the most vulnerable regions

worldwide. Rivers choked with pollution, aquifers tainted by contaminants, and oceans acidified by carbon emissions exact a toll on biodiversity and escalate the frequency and intensity of natural disasters like typhoons and hurricanes. To recalibrate our urban landscapes from artificial constructs to thriving ecosystems, we must pivot towards reestablishing a harmonious balance with nature. Architect Stefano Boeri's visionary concept of the "Forest City" exemplifies this ethos, envisioning urban centers transformed into verdant sanctuaries, breathing new life into the concrete jungle and serving as a bulwark against climate change.

This imperative calls for a paradigm shift in urban planning and development, prioritizing the integration of green spaces as essential components of sustainable cities. By embracing nature-inspired design principles and fostering the creation of urban "green lungs," we can mitigate the impacts of urbanization, restore ecological equilibrium, and chart a course towards a more resilient and vibrant urban future.

The purpose of this study,

devoted to maximizing the vertical greening systems (VGS) performance, is to develop a design method that considers the absorption of pollutants starting from the analysis of the physiological component of the planting by analysing data from different samples of greenery and their respective diversities, and to test their performance by describing the results through physical models. Direct and indirect methods, visualizations in vivo and of non-viable sample, characterize the first experimental part of the thesis work, thus allowing to extrapolate the functional indices to the design against urban environmental pollution of VGS technological solution. The testing followed with



Fig. 1 - Multiparametric detection applied on indirect VGS for the detection of Temperature, Relative Humidity, Pressure, Altitude, Soil Humidity, Lux.

the design, construction and installation of a prototype connected to sensors, while the plant absorption potential has been empirically determined with a sealed in-box testing of the specific VGS greening. With this purpose outlined, the abstract turns to the methodology employed in the study to achieve these objectives where a second practical-design part reviews current regulations and guidelines for the performance design of building systems, identifying design gaps on the case history of vertical green design, extrapolating three main green schemes for modelling in thermal and structural simulations, contextualizing design by regulatory scope, considering both the built environment and new construction.

Process and design schemes of technological solutions are proposed, accompanied by examples of existing projects and issuing indications for the correct execution of the preliminary phase – i.e. feasibility study –, of the design phase (considering all the possible aspects that the design of vertical green can involve), the construction and maintenance phase considered in the global aspect, giving an impetus towards the concept of compulsory and scheduled ordinary maintenance in the implications it entails from the point of view of the use of machines, equipment, provisional works and specialized personnel. Finally, the work comes to an end with a section entirely dedicated to the analysis of the resilience of VGS, focusing especially in the

first part on the technical and environmental defects recorded on the VGS in a real case study reported in the literature. The chapter continues focusing on the technical green and the estimate of the average service life, the loss of service during the life cycle, on the modalities for the modelling of the various variable parameters on the behavioural uncertainty of the vertical green, proposing measures to ensure high levels of performance over time of the building with VGS, analysing the management of the entire life cycle. The quantitative estimate of the resilience of the green system was performed by focusing on the performance parameter of the product disconnected from the absorption component, and one connected to the absorption of pollutants. In this case, calculation methods and performance graphs linked to the unit of time are presented, obtained thanks to the collaboration with vertical green production companies that answered a questionnaire containing the various questions regarding resilience, the magnitude of adverse events, and the extent of the damage compared to different classes of adverse events that are recorded above all in today's era subjected to climate change. The analysis of the resilience was in fact carried out mainly on the technical green and the resilience of each single component of the vertical green was evaluated.

Finally, the resilience of the vertical green system was also assessed in a qualitative

way, assuming a massive adoption on an urban scale and therefore proposing a method for the management, control, and monitoring of a green infrastructure network with unified management delivered by the technical office of urban and metropolitan cities, giving a greater adaptive capacity to an extensive use of this technology. Also, in this case some application examples of system diagrams are proposed, in analogy to the structural monitoring sector, adding to the case of vertical greenery on an urban scale the input of climatic data, wind, pollution and earthquake, imagining a remote management of plant health monitoring in urban cities.

This study's exploration of vertical greening systems not only addresses the pressing issue of urban pollution but also offers practical solutions for sustainable urban development. By addressing these aspects, this study contributes to the advancement of sustainable urban development practices, offering practical solutions to the pressing challenges of urbanization and air quality.

ϕSENSE. PHYGITAL AND COGNITIVE PARADIGM FOR ACTIVEHOUSE IN-USE RATING - EFFECTS ON COMFORT DURING SUSTAINABLE OPERATIONAL MANAGEMENT PRACTICES ESTIMATED VIA IOT DEVICES IN A MULTI-PURPOSE AND BIM-BASED FRAMEWORK

Nicole Di Santo - Supervisor: Prof. Marco Imperadori

Co-Supervisor: Dr. Lone Fejfer - Tutor: Prof. Valter Carvelli

The Next Generation EU Recovery Plan has acknowledged the significance of incorporating efficiency and intelligence in construction to attain a climate-neutral continent by 2050. Nevertheless, throughout the building process, the construction industry appears immature and typically exhibits a fragmented structure compared to other industrial sectors in digitalisation. Especially during the in-use phase, this results in a gap between predicted and actual building performance. Current approaches that try to manage building operational performances, like BIM-based tools with live monitoring and IoT tech, often fail to consider metrics beyond energy efficiency, such as occupant well-being and quality of spaces. However, the energy performance building directive prioritises healthy indoor environments, energy efficiency, and occupant well-being. It includes building performance certifications and a smart readiness indicator for evaluating a building's operational features and performance. This research project has developed a theoretical framework that incorporates the concept of "Cognitive Buildings" (CB). By utilising BIM-BMS-IoT

technology, this framework creates visual representations and real-time control of building systems and occupants' roles while employing Sustainable Building Certification (SBS) to bridge the gap between predicted and actual building performance. The goal is to enhance current digital building management practices for more holistic performance control and assessment through the use of digital technologies towards green and digital transformation. Additionally, the project aims to include contextual data from BIM models and real-time IoT data in a building monitoring system (BMS), which are often overlooked due to their closed format. The outcome of this vision was the development of a paradigm called ϕsense for live monitoring and validation of building performances. This process-oriented framework employs multi-criteria analysis to evaluate sustainable buildings' actual comfort performances, promote stakeholder communication and foster building sustainability and intelligence. Therefore, this study introduced the concept of a Phygital Twin: a digital replica of a physical building digitalised through IoT devices and BIM-based

platforms. The PT enables hybrid action functionality within a building, which requires human intervention and limits virtual action on the management system. The study highlights the significance of balancing automation and human intervention when digitising the control and management of buildings. It suggests that excessive automation may result in a lack of control or comprehension over the building's performance. This stands in contrast to the increasing reluctance of users to interact with products that imitate the neuro-ergonomics of human actions, which can only be managed by experts. The ϕsense paradigm seeks to attain this balance by incorporating IoT devices that educate and engage users in their interaction with the building. This integration enables semi-automation (e.g., virtual butlers) but also real-time monitoring on a BMS platform leveraging the Active House (AH) rating system to validate the performance of CBs. The ϕsense paradigm consists of five crucial steps: stakeholder categorisation, developing a stakeholder map, implementing a Phygital Twin architecture, evaluating building

performance based on mixed metrics, assessing building performance and their cognitive level using the AH protocol and the smart readiness indicator (SRI) assessment, respectively, and conducting appraisals. The paradigm was refined through case studies to analyse actual comfort performance assessment in real application scenarios, resulting in a robust and reliable solution for sustainability evaluation. The model's robustness is built on real-time measurements using sensors installed in the S-size VELUXlab case study as the baseline case and the S/M-size CPH Village one, emphasising the value of integrating different data-driven technologies and human engagement to enhance building performances. After evaluations, the building data analysis reveals a very small delta between predicted and actual comfort performances in Daylight, Thermal Environment, Indoor Air Quality, and Acoustic Quality metrics. Findings on comfort measures showed that good building design positively influences user satisfaction and enhances the ongoing quality of spaces of the



Fig. 1

operative building. Further, the semi-autonomation control of the building shows a positive influence on the improvement of comfort and user-friendliness, as well as energy efficiency, balancing automation and human intervention. Thanks to voice commands and acoustic signals, this enhanced the user experience and interaction with the building. Some limitations in data availability are acknowledged. The VELUXlab case study and the CPH Village experiment demonstrated the need for a comprehensive approach that balances objective and subjective comfort. Leveraging technology to monitor comfort can promote sustainable practices, enhance property value, ensure regulatory compliance, and support data-driven decision-making. Applying this approach to actual case studies made it possible to tackle the difficulties associated with comfort assessment in operative buildings effectively. The study highlights the impact of users on promoting building sustainability through digital-assisted guidance. It suggests

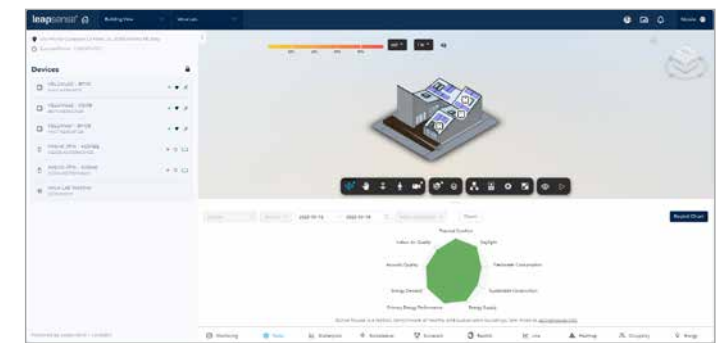


Fig. 2

facilitators' involvement in monitoring building performance and offers five recommendations to improve indoor comfort and energy efficiency further. Hence, this vision for using a building management system for cognitive buildings aligns with EPBD directives and is geared towards enhancing property value. The ϕsense paradigm can be further scaled to other case studies like the Living Places pavilion in Copenhagen. By applying the AH 3.0 specification and incorporating smart technology, new business opportunities are emphasised toward creating and linking technological innovations to new demands. In this sense, expanding the paradigm can add value streams and reflect the ecosystem between stakeholders and services on a sustainability basis. Further studies should also focus on blockchain technology toward delegating sensor data publishing authority to the cloud and empowering users to generate finances through successful small business models for IoT stakeholders.

ENGINEERING ARCHAEOLOGICAL RESEARCH: SUBMILLIMETRIC X-RAY CT SCAN OF ANCIENT EGYPTIAN MUMMIES

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Co-Supervisor: Prof. Michele Ezio Ruggero Maria Carboni - Tutor: Prof. Marco Scaioni

The research work presented in this thesis aims at demonstrating how technology can contribute in a novel and significant way to the archaeological research by searching for innovative scientific solutions to answer specific questions springing from the realm of humanities. The specific target of this work is to define the guidelines for the production of submillimetric 3D virtual reconstructions of objects made of metal and hard stone contained inside ancient Egyptian mummies, with the purpose of applying this study to the mummy of Kha (Museo Egizio of Turin) in the future. The main challenge is the need to create such virtual reconstruction without removing the bandages and without causing any direct or indirect damage to the object. In particular, this thesis describes the decision-making process leading to the choice of the instrument, that is, X-ray computed tomography, of its parameters and of the type of sample to be examined in order to perform a preliminary test and complete a feasibility study, before applying the process to an actual mummy. In fact, in order to avoid spending long set-up times on the mummy, irradiating it unnecessarily, it was decided to verify the feasibility

of such 3D models by means of a preliminary test on ad hoc samples. The objectives of this preliminary test were to define the instrument to be used and its parameters without generating digital artifacts and damages to the biological tissues. In fact, a mummy cannot develop cancer, but its DNA molecules can be irreversibly damaged. In this way, tomographic scans were performed with an industrial experimental system, but designed according to the traditional medical configuration called "gantry", on three samples, containing high density objects, that had been mummified for this specific purpose. This configuration allows to calibrate high voltages and current values to identify the quantity of high-energy photons which can pass through the metal objects contained inside the mummy. Moreover, the gantry structure allows to avoid any kind of geometrical limitation, as typical industrial tomographs consist of small, closed "boxes" meant to host objects a few tens of centimeters wide. Regarding the samples they have been produced in order to replicate the mummy of Kha and its jewels, using materials with similar atomic numbers and densities,

on which the absorption of X-rays mainly depend, and thermal coefficients. In this way, three porcine shanks have been washed by means of gin, in order to disinfect them, desiccated by means of three different artificial natron compositions, in order to avoid putrefaction, and coated with resins and oils derived from coniferous plants due to their antibacterial properties. To conclude, objects made of gold and hard stones with some engravings, that would have act as a reference in the reconstructions, have been placed on the samples and fixed by means of some linen bandages. The analysis of the three samples was performed primarily in order to obtain information regarding the parameters necessary for the production of digital reconstruction. In parallel, considering the large amount of energy compared to the common medical CT, the opportunity was taken in order to verify also the safety of the historical objects. In particular, it should be considered that in an X-ray source, accelerated electrons dissipate about 99% of their energy as heat. It means that the instrument and the X-ray beam should not generate a temperature variation in the mummy. The chance

was thus used to monitor the temperature trend inside and on the surface of the samples. This study was then completed with the analysis of the absorbed dose. In this way, it will be possible to minimize the effects of ionization on the different tissues and on the ancient DNA molecules. In particular, in the literature, a limit of 200 Gy has been found so the absorbed dose had to be lower than this value. Moreover, the results have been also compared with the Diagnostic Reference Levels (DRLs). Once the test has been completed, it was possible to confirm the effectiveness of the used tomographic system. In particular, with the parameters chosen, it is possible to carry out analysis of the surface and internal structure of both objects made of stone and metal alloys with a not particularly high density. The only difficulties that were faced were given by the gold rings. They were, as expected, characterized by the presence of metallic artifacts. However, both the insertion of brass filters and the use of high parameters combined with well-established software methods of reduction of these artifacts, allowed to obtain good results. So, with the instrument used in this test, important steps forward have been made with respect

to the axial tomographic scans performed until now on mummies with simple medical equipment. To conclude, starting from the test parameters, simulations have been carried out using the CIVA^{nde} software. Different parameters have been changed, like the number of filters and the current. However, improvements have been obtained only by increasing the voltage, exposure time and the number of frames. The first one requires a radical change in the instrumentation while the other two allow to obtain a better quality with the same tomograph used during the test. Once completed the test and the simulations, it has been possible to complete a reliable feasibility study to then scan the real mummy of Kha in the near future. First of all, the validity of a hybrid configuration between the medical and the industrial ones has been confirmed. The brass filters, high parameters (210kV and 2mA), and metal artifact reduction methods used during the test allow to obtain important information regarding high-density objects wrapped together with mummies without any kind of possible damage to the archaeological find. However, simulations performed using the CIVA^{nde} software suggested that further improvements are

possible and a greater number of acquisitions (360° rotation of the source-detector group) and a longer exposure time (two times longer per acquisition than in the test) can lead to a better overall quality. So, with the device and parameters of the test or with those of the simulation by CIVA^{nde}, it will be possible to apply this technique to actual mummies and obtain 3D models of similarly invisible high-density archaeological finds not visible by eye. This will lead to new and more detailed information on the material culture of ancient Egypt within the ethical principle of respecting the dead and their funerary beliefs.

SOUND-RESPONSIVE 3D SPACERS FOR TIME-CHANGING SIGNAL-TO-NOISE RATIO IMPROVEMENT IN MULTIPLE-SOUND SOURCES CONDITIONS. THE CANTEEN ESTABLISHMENT AT POLITECNICO DI MILANO

Andrea Giglio – Supervisor: Prof. Ingrid Maria Paoletti

Co-Supervisor: Prof. Giovanni Maria Conti – Tutor: Prof. Matteo Francesco Ruta

The demand of open spaces able to adapt their internal fit out spatially and formally to several functions is increased in the last decades. This led to the development of any floor plan that makes use of large, open spaces and minimizes the use of small, enclosed rooms. In museum context, for example, spaces can be adapted according to the exhibition need by designing layouts with temporary partitions that lead the users to a better understanding of the curators' reading of the works.

In other conditions, these spaces are able to host different programmes at the same time. One emblematic example is given by open plan office, where workers can perform their activities facilitated also from the different furniture. Phone booth can provide privacy without annoying colleagues, collaboration desks can be used for temporary team working etc. Nevertheless, the presence of several activities creates a variable sound condition that, without a correct analysis and design strategy, can bring to have more negative consequences rather than positive.

This is mostly clear in other functions such as the canteen. University canteen are open

spaces that host, eating area with tables and chairs and self-service kitchen facilities where users can collect food.

The presence of multiple sources emitted by kitchen facilities and users' speech leads to an important level of acoustic discomfort during working time.

The research thesis is conceived in the frame of the interdepartmental fellowship call between architecture and design departments of Politecnico di Milano that required to explore the acoustic performance of 3D spacer fabrics to develop functional systems.

Within these premisses, the research thesis aims to validate their effectiveness to cope with complex sound conditions in the canteen of Politecnico di Milano. We can affirm that the clear distinction between two-dimensional textiles (from here on 2DT) and three-dimensional textiles (from here one 3DT) should be made by the criterion that "the former group includes only those fabrics which contain a single set of yarn places in each of the designated direction with the fabric", whereas "the latter group includes all those that contain two or more such yarn layers" (Sontag et al. 2015).

3D spacers (from here on 3DSF) are a subcategory of 3D textile characterized by two horizontal layers and a vertical one named pile. This internal structure led to a wide application in several fields including AEC. The acoustic performance, explored in the frame of the fellowship call, finds a deep interest in the literature. The systematic review of acoustic performance for normal sound incidence underlines the challenging behaviour compared to traditional acoustic material. The analysis of multi-directional incidence is run at a spatial scale by taking into consideration a real case study.

The canteen is architecturally and acoustically characterized. The sound performance of the space is run with measurements that helped to obtain a reliable simulation model. A comparison between scenario 1 (with classic acoustic material in the false ceiling) and scenario 2 (with a 3D spacer in the same position) shows a deep improvement (in scenario 2) in reverberation time (According to the UNI ISO 11532:2-2022). Nevertheless, the analysis in the time domain shows some limitations in controlling the signal-to-noise ratio (SNR) and therefore the speech intelligibility.

According to Rindel, the SNR is the difference between the ambient noise level $L_{(N,A)}$ (dB) and the equivalent continuous A-weighted sound pressure level of the direct sound in front of a speaker one meter far from the mouth, $L_{(S,A,1m)}$ (dB). The higher the number of speaking people, the higher the $L_{(N,A)}$ (dB) and the $L_{(S,A,1m)}$ increasing the Lombard effect and making it difficult to communicate with consequently causing low comfort and satisfaction of the diners. A passive traditional approach regards two solutions that can improve the SNR: the decreasing of $L_{(N,A)}$ by increasing the amount of absorbing surface in the space. the "protection" of the conversation area by bouncing away the disturbing sound rays coming from other sources and by absorbing the same rays. Moreover, Rindel identifies six ranges in which the SNR are defined from "very good" to "very bad". The equivalent continuous A-weighted sound pressure level (SPL) considers the value of SPL in a specific time and, if we consider this value every 15 minutes, we see that in scenario 2 (with a 3D spacer in the false ceiling) the percentage of SNR in "very bad" range occurs in almost the 50% of the time analysed and it is not so far from the values getting from scenario 1. Therefore, a passive approach to Italian regulation (UNI ISO 11532:2-2020) considers the RT parameter but "it doesn't fulfil the necessity of a good conversation in the space according to Rindel. The thesis intends to explore if sound-responsive

3D spacers can add effective results in coping with the time-changing variations of the SNR and, in this way, increase acoustic comfort by increasing the speech intelligibility and by decreasing SPLs in the kitchen. Responsiveness in architecture is adopted to optimize and make more effective the function of specific systems in respect to time-changing inputs (such as sound). In the context of sound responsiveness, the passive strategies can be enhanced: By changing the inclination of reflective surfaces to orient the sound rays away from the listener. By either decreasing or increasing the distance between absorbing material and annoying sound sources. In the case study the thesis demonstrates that since the occurrence of several conversations at the same time, the first strategy cannot be pursued since this can cause an increase of SPL in other conversation areas. Instead, the second strategy is adopted by working only on the distance between absorbing the 3DSF surface and annoying sound sources. Considering the best scenario (with the noise of the kitchen and one speaker) and the worst scenario (with the higher number of speakers) the geometry of the 3D spacer fabric mounted in the false ceiling of the canteen is explored according to several modes to bend and decrease the distance with the speaker. The acoustic simulation in the time domain is performed with one of the most used 3D modelling software Mcneel Rhinoceros 7 and the specific plug-in, Pachyderm (in

Grasshopper environment). This choice is led by the idea of allowing architects to be able to apply responsive behaviour in the design process. A specific algorithm is developed based on the impulse response approach, exploits the component of the add-on Pachyderm for acoustics simulation and adds a specific part to control Rindel's theory. The analysis shows a deep improvement in the percentage of SNR values in the six ranges defined by Rindel. The Sufficient, satisfactory, and good ratio percentages are increased by all 25% and none of the SNRs is in the very bad range. The research outcomes demonstrate the consistent effect a sound responsive behaviour can have in a multi-purpose space such as a canteen in which good speech comprehension has to be provided. A passive behaviour of acoustic surface in space is still economically convenient but basic and applied research in sound responsiveness can overcome this barrier. Moreover, companies that provide acoustic panels can have a key role in experimenting with these systems in real case studies. For this reason, future implementation of this research should deal with the construction of a prototype and test it at a spatial scale.

DESIGNING THE GREEN URBAN BUILDING ENVELOPE IN THE MEDITERRANEAN CLIMATE: AN ARCHITECTURAL APPROACH

Rola Hasbini - Supervisor: Prof. Nerantzia Tzortzi

Tutor: Prof. Laura Elisabetta Malighetti

Currently, climate change is a critical global issue. Greenhouse gas emissions are closely associated with the construction sector, particularly building envelope (BE) performance. Addressed for Architects, and aiming to enhance external atmospheric conditions, this innovative PhD thesis conducts a comprehensive technical study of the green building envelope performance (GBEP) from the most general and theoretical to the most practical and microscopic such as micro-algae symbiosis with concrete, using state-of-the-art techniques.

The PhD thesis is divided into three main Parts: Part I - Learning, Part II - Optimizing, and Part III - Thinking Negative, each with a Focus Chapter presenting a case study on concrete building material. The Methodology adopted is: first, to perform, a thorough literature review, through Part I - Learning, to determine the main parameters impacting the green performance of the BE; second, to study the optimized green impact of these main retrieved parameters in a virtual laboratory and in application to an urban Mediterranean BE model, through Part II - Optimizing; third, is to fill the wide gap of

missing negative (absorbent and scrubbing) solutions from literature and real-life situations by proposing technology-ready solutions, through Part III - Thinking Negative.

Accordingly, the theoretical set-up of the green BE is, first, investigated in Part I. Main parameters impacting the performance are identified and categorized under passive strategies and active technologies. A Bibliometric / Biblioshiny review over 2,846 publications shows that factors/parameters impacting the GBEP have importance weight where energy efficiency is effectuating highest consideration. Accordingly, a novel theoretical scientific model/

equation is derived allowing an estimated assessment of the BE green performance - implementable during the architectural design process; this model describes the overall GBEP as the sum of the separate various weighed performances in function of the reviewed parameters - Equation (1) as follows:

$$\Sigma(n-z) = \alpha n + \beta m + \dots + \gamma z \quad (1)$$

Where n, m, z are the parameters related to the chosen performing factors such as the energetic performance, cost, or urban integration, etc.; And where α , β , γ are the related weight assessed amount.

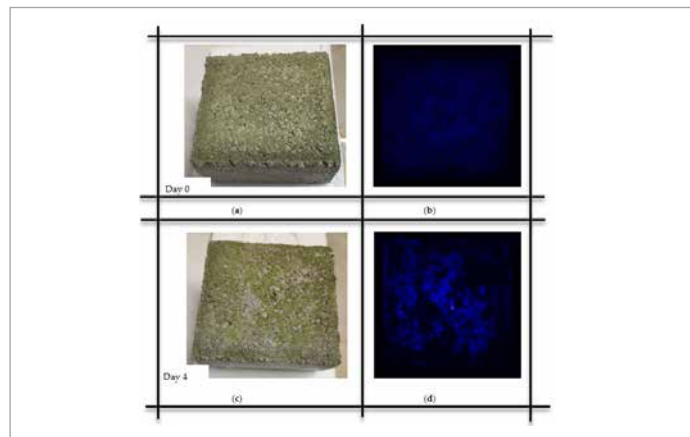


Fig. 1 - Increase in chlorophyll fluorescence - fluorescent imaging

This equation allows evaluation, in one scientific model, disparate factors such as energy efficiency, cost, and urban integration i.e., from the three sustainability spheres of Environmental, Economic, and Social - Table 1 below. In focus and due to the significant impact of cement production, a dedicated literature study is conducted researching the main parameters impacting green concrete performance through the life-cycle phases of the worldwide adopted construction material. Through Part II a step-by-step design protocol for the green BE, in an urban Mediterranean climate, is presented, addressing Architects at their early design conceptual stage. Investigating the impact of main passive design strategies, the protocol assumes a location in Milan; it, then, derives the energy use summary impacted by

the setting of the initial mass, and the modification of the following parameters: layout, orientation, form, and volume as well as building materials, while fixing the parameters location, footprint area, and function. The optimized energetic performance is assessed to relate to the reduced exposed eastern and western walls case i.e., form parameter. In focus and due to the significant impact of concrete building material adopted for the envelope, a case study is undertaken: heat transfer phenomenon is simulated through a single-wall concrete BE, and then through a double-wall concrete one for a prototype dwelling, at assumed peak winter and summer Mediterranean conditions. The double-wall concrete case with insulation interstitial air layer shows non-interference of the internal temperature with the external one - except at structural jointing continuous

elements. Validation of the results shows an approximate reduction to half of the yearly energy use and, consequently, the related pollutants emissions. Part III proposes a methodology to research BE negative greenhouse gas emissions solutions from three different realms: the physical, the chemical, and the biological realms. As for the physical one, the CO₂ absorption capacity of a pressurized cork panel is studied; measurement of atmospheric CO₂ reduction is performed with Arduino sensor. From the chemical realm, the dissolution capacity of running fresh water is investigated based on literature review and calculations. Third, a highly novel Living Concrete experiment with macro-algae *Ulva lactuca* is performed, in relation to the biological realm. In focus, and to ameliorate results, the Living Concrete experiment is re-conducted over ASTM (American Standards Tests for Measurements) certified concrete samples - where micro-algae *Chlorella vulgaris* is grown in symbiosis. The living concrete block "lived" for eighteen days i.e., *C. vulgaris* cells remained photosynthetically active - with increasing photosynthetic activity - until the deliberate ending of the experiment. This was realized by soaking the concrete block in Blue Green-11 solution up to 2 cm, and by pouring nutrients five days a week, in a controlled laboratory environment, at a temperature of 23°C. In conclusion, this Ph.D. thesis is a methodological reference and a comprehensive research document for the various aspects of the contemporary green BE scaling down a global issue to the level of the building envelope in the urban Mediterranean climate.

Note: The PhD thesis is patented under the French Law - E-Soleau - 92 Institut National de la Propriété Industrielle (INPI) - DSO2023012898.

Area / Field	BE Sustainability Main Factors	Method / Tools
Environmental (Mediterranean / Climate Zone 4A)	Energy Efficiency	Optimization Appendix B.3.
	Form	
	Orientation	
	Construction Materials (Roof / Walls / Floors Assemblies)	
	Windows-to-walls ratio (Fenestration & Doors)	
	Insulation	
Economic	Life Cycle Cost	Life Cycle Cost Assessment
	Cost of Raw Materials	
	Cost of Manufacturing / Construction	
	Cost of Use	
	Cost of End of Life	
	Cost of Transportation	
Social	Urban Integration	Architectural Assessment
	Urban Identity	
	Insertion in urban fabric & circulation network	
	Functional Adaptability	
	Scale	
Language		
Harmony & Art		

Tab. 1 - Main factors impacting GBEP

MACHINE LEARNING FOR RISK MANAGEMENT IN CONSTRUCTION PROJECTS

Ania Khodabakhshian – Supervisor: Prof. Fulvio Re Cecconi

Tutor: Prof. Matteo Francesco Ruta

Introduction

In construction projects, inherent risks and uncertainties necessitate effective and intelligent Risk Management (RM) to safeguard project success, timeliness, budget adherence, objectives fulfillment, and worker safety. Traditional RM approaches are manual, time-consuming, inefficient, and rely mainly on experts' subjective and experience-based judgment, hindering knowledge transfer and generalizability to future projects. With the increasing application of Industry 4.0 technologies and data-driven methods in construction, the shortcomings of conventional RM methods can be addressed by leveraging Artificial Intelligence (AI) and Machine Learning (ML) capabilities, improving analytical capabilities across the RM domain while offering a high granularity and depth of predictive analysis based on factual data from previous projects. ML approaches can establish a comprehensive RM framework, improving risk assessment accuracy through high-resolution analysis and experience-based knowledge integration with historical project data. Despite their potential, practical implementation faces obstacles, including inadequate structured risk data in companies' databases, overreliance on subjective judgment, isolated risk analyses without considering causality between variables in risk paths, improper choice of ML algorithms for a given problem regarding its data availability and role

of uncertainty, and the construction sector's resistance to digital transformation.

Research Objectives

This research proposes a Machine Learning (ML)-based, systematic Risk Management (RM) framework for construction projects, aiming to overhaul current RM practices by addressing their bottlenecks, inefficiencies, and problems with tailored ML solutions. The main objective is to automate and optimize the construction risk identification and assessment processes using probabilistic and deterministic ML models. The framework intends to tackle data scarcity by merging

expert qualitative and subjective insights with objective project data and by data augmentation using Generative Adversarial Networks (GANs). Furthermore, it aims to investigate the role of database size and data type in various ML models' performance by applying probabilistic and deterministic ML models to two databases of various sizes. Finally, the research addresses practical implementation aspects, ethical considerations, and potential biases or harms associated with deploying ML-based models in real-world settings.

Methodology

The research is conducted in systematic

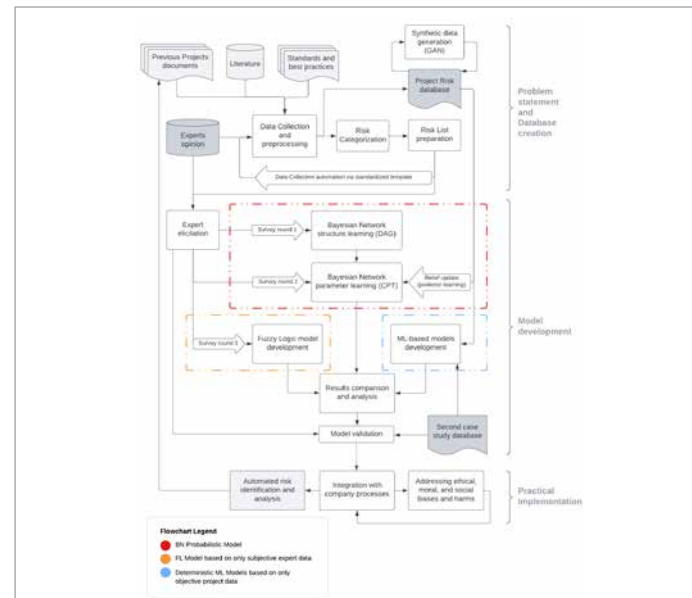


Fig. 1 - Research Scheme and phases

phases based on a case-study approach, given that the research has industry partners, Jacobs Italy SPA. The proposed ML models learn the relationship between influential project variables like budget and delivery method and occurred risks in previous projects and generalize these patterns to new projects, being able to predict possible risks and their probabilities given the project characteristics. Three models, namely a) Probabilistic ML model (the Bayesian Network) based on both project data and experts' opinions, b) Deterministic ML models based on merely objective project data, and c) Fuzzy Logic model based on merely subjective experts' opinions are developed and applied to two different case studies: a) a limited database of 44 construction projects constructed by the industry partner, and b) an extensive database of 11000 projects in New York. The main stages, as presented in Fig. 1, are:

a) Data collection from previous

projects and interviews with experts in the company;

- Data preprocessing and quantifying experts' opinions through elicitation;
- Structure Learning of the Bayesian Network (BN) based on experts' data;
- Parameter Learning of the BN through integrating the objective project data and subjective experts' data;
- Synthetic data generation using GANs and repopulating the BN model with the augmented data (Fig. 2),
- Implementation of deterministic models like Artificial Neural Networks, XGBoost, and Decision Trees, and the Fuzzy Logic model on the database to compare the results;
- Model validation;
- Implementing the same ML models on the more extensive second database to explore and compare the performance of each algorithm;
- Integrating the proposed model with the company's current project management processes and

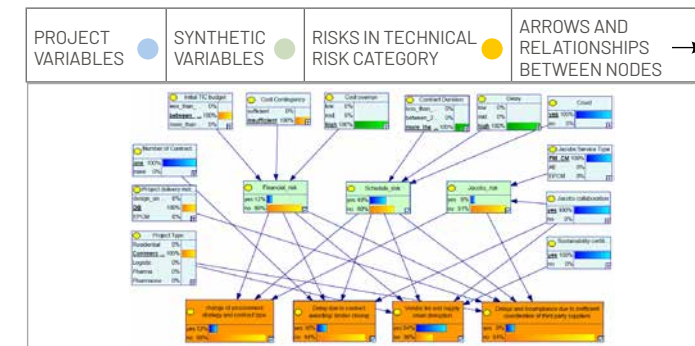


Fig. 2 - Example of case-based risk assessment by the procurement risk network

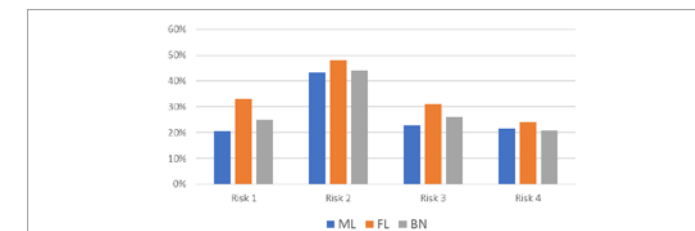


Fig. 3 - Comparison of Risk Probabilities assigned by each of the three ML, FL, and BN models

addressing the potential challenges, as well as ethical and moral considerations, will facilitate the broader application of the model.

Results

The findings of this study suggest that probabilistic ML models like BN and FL have a better performance in small databases, where the elicitation-based expert opinion integration with project data, as well as the synthetic data generation, compensate significantly for the data scarcity issue, guaranteeing a minimum of 85% accuracy of the model prediction. However, in large databases, the deterministic models, especially the XGBoost with the ability to capture both linear and nonlinear relationships in data, outperform the probabilistic ones, although they cannot assign a probability to each risk like the probabilistic models. Moreover, the comparison of the risk probability assigned by each of the models indicated that while judgment based on merely expert data in FL is over-conservative, and the one merely on project data in deterministic ML models is not reflective of the actual situation and underestimates the risks, combining the two sources of judgments in BNs balances the estimates, offering the most realistic risk probability estimates (Fig. 3).

Conclusion

ML algorithms can model the complex interrelationships and causal inferences between a project's key variables like budget and duration with consequent risks, proposing an accurate and realistic estimate for upcoming projects. This enables project managers to proactively take preventive actions and make strategic decisions to mitigate the risks' impacts for a more prosperous, safe, on-budget, and on-time project delivery.

TECHNICAL RELIABILITY, ENVIRONMENTAL SUSTAINABILITY, AND ECONOMIC FEASIBILITY OF TEXTILE ENVELOPE INTEGRATED FLEXIBLE PHOTOVOLTAIC SYSTEM

Qingxiang Li - Supervisor: Prof. Alessandra Zanelli

Tutor: Prof. Claudio Del Pero

The concept of textile envelope integrated flexible photovoltaic (TE-FPV) systems emerged in the late 1990s. It has been one of most promising technologies to promote the development of nearly zero energy buildings with renewable energy utilization, due to its advantageous properties. However, different from conventional building integrated photovoltaics (BIPV) that have created mature products, the majority of TE-FPV products are customized and applied in the pilot products. TE-FPV technology is still not widespread in mainstream BIPVs for three primary reasons: Technical data is not sufficient to understand, long-term thermal performance, electrical performance, and acoustic comfort of the integration system. And environmental assessment and economic analysis are missing to perform decision making in the context of carbon neutrality and no subsidies. It is significantly urgent to provide representative and typical data and guidance for the diffusion of TE-FPV technology.

This thesis dedicates to the feasibility of the TE-FPV systems for the near future

commercialization and diffusion. Technical reliability, environmental sustainability, and economic feasibility of representative TE-FPV prototypes are investigated. Technical reliability is based on on-site measurements. Environmental sustainability is based on life cycle assessment methodology. Economic feasibility is based on life cycle cost analysis methodology. Based on the analyses above, the improvement solutions are provided to meet the market requirements.

This thesis shows that the TE-FPV technology is promising but still face challenges. On the one hand, the assessments show the application of TE-FPV systems still face the challenges, which are mainly because of the stability of PV modules. The wobbly structure causes microcracks of PV cells in the windy or rainy conditions, which is hidden danger for the long-term operation. PV short lifespan is another important concern in the application. On the other hand, TE-FPV systems show significantly favorable performance in the environment sustainability and economic feasibility

compared to traditional BIPVs. The development in the PSC technology is highly possible to facilitate the popularization of TE-FPV technology. In the future, the concern should put on directly printing PSCs on ETFE foil envelope by large-scale industrial R2R manufacturing, whose success can realize the widespread application of TE-FPV technology on the building vertical façade in urban city.

The thesis is structured in five parts. Introduction part contains theoretical background and challenges of TE-FPV diffusion, objectives and innovation, as well as methodology for the research. The research overview is also provided. The second part investigates materials, integration forms, fabrication process, applications, and regulations in EU to provide a guideline for the application of TE-FPV systems to architects and engineers. Six representative TE-FPV prototypes are selected based on the investigation. Next, the study provides a state-of-the-art review on research methods of technical measurements, life cycle assessment, and life cycle cost analysis to guide

following chapters. In the fourth part, the technical reliability, environmental sustainability, and economic feasibility of TE-FPV technology are investigated by on-site tests and simulation. Finally, the conclusion part contains the guidance for the diffusion and further development of TE-FPV technology.

CURRENT CONDITIONS AND NEW PERSPECTIVES OF URBAN AGRICULTURE FOR METROPOLITAN AREA OF CHENGDU

Hang Lu – Supervisor: Prof. Lionella Scazzosi

Tutor: Prof. Marco Scaioni

As we can see, with the accelerating urbanization, ecological environment of the city has attracted increasing attention, so the resulting problems have become key research focuses in all countries. Food safety and expanding urbanization could be two intractable problems for China at present. Against this background, urban agriculture(UA) has been applied as one of the effective approaches for relieving urbanization, especially for China. The main aim of my research project is to analyze and compare different situations between western cities and Chinese cities, in order to find the effective way or strategy including preserving operations for the existing agricultural landscape, enhancing methods for the local agricultural culture and strengthening the relationships between urban and agriculture. Because of the globalization, more and more regional characteristics and local culture is being swallowed, especially in China. The pace of urbanization is destroying the cultural heritage in the city, which are accumulated rich historical and cultural information, agricultural landscapes are no exception. UA could be a feasible and useful way to connect with human, natural and culture.

This research proposed to guide local planning, farmers and public in providing recommendations, suggestions and strategies for future urban development, in the landscape and cultural heritage point of view. At the very beginning, reviewed relevant literatures and researches to identify the common weakness and problems for UA area at both global and China level. After that, the relevant case study and the investigation and analysis of current situation in Chengdu, which is a significant big city in southwestern China. It would give applicable experiences and better understanding, which could be the support for the proposal. Europe case studies will be identified in order to present best practice cases in Italy and throughout Europe. Through these case studies, successful experiences can be summarized. The main result of the research is an UA proposal for Chengdu, which could be a model and example for other cities in China.

A review of China's existing policies, laws and regulations on rural and agriculture shows that UA is currently not mainstream in China and has not been fully officially recognized. Although UA in some big cities is gradually

developing widely and has gradually attracted the attention of the government, it has not been considered at the level of policies, laws and regulations. At present, the vast majority of urban agricultural activities are bottom-up activities based on satisfying customer needs, without specific policy support. But at the same time, the current rural strategy and some specific agricultural guidance policies implemented in China are conducive to the development of UA. The contribution of UA in the fields of economy, society, ecology and culture is also in response to the development orientation with sustainable development goals. The existing "Rural Revitalization Strategy" at the national level is beneficial to the development of UA in terms of cross-sectors integration and innovation, eco-friendly agriculture, creating livable villages, and promoting Chinese excellent traditional culture.

Chengdu is a city that nurtured the development of urban agricultural activities, which are distributed in different areas within the Chengdu metropolitan area. According to different characteristics and administrative divisions, the Chengdu metropolitan area can

be regarded as consisting of the central urban area, peri-urban area, and sub-urban area. The agrarian landscape also has its own characteristics in different areas, which also makes the urban agricultural activities in different locations have their own characteristics. Through the investigation, it can be found that, like most cities, within the Chengdu metropolitan area, UA can be divided into two categories, urban food gardening and urban food farming. Urban food gardening activities are mainly distributed in central urban area, are usually small in scale, and are relatively intensive in land use. These urban gardening activities include non-profit activities for self-sufficiency or educational purposes, as well as commercial activities. However, in the peri-urban area and the sub-urban area, urban farms are almost always operated for profit, either focusing on the production of food products, or focusing on agri-tourism. In these two areas, local food farms and leisure farms are the main types, and there are also a few multi-functional farms. At present, the stakeholders of UA in Chengdu are not diverse, whether they are promoters or users, and they are almost all bottom-up activities.

In this study, the current status of UA and related agricultural landscape in Chengdu was compared with European cases, especially the representative and distinctive city- Milan. The characteristics, advantages and disadvantages of existing UA in Chengdu are presented after

comparing with Milan in terms of agricultural conditions, agrarian landscape, business models of UA, and actors of UA. The dynamism and potential of UA in Chengdu is remarkable, but there is a lack of policy support, public awareness, diverse stakeholders, and diverse UA activities and models. In addition, there is a significant difference between Chengdu and European cases in the relationship between UA and agricultural heritage. The integration of agricultural heritage conservation and enhancement into UA projects is not new in Europe. But in Chengdu's case, very few urban agricultural activities involve heritage conservation. This is a weakness of UA in Chengdu at present, but it is also a new perspective for Chengdu in the future. Chengdu has great potential in this field, and the promotion of traditional culture is supported by the current Rural Revitalization Strategy. In Milan and other European case studies, heritage is used as a huge resource for the development of UA. The Chengdu Plain has a long agricultural history, especially the traditional Linpan settlement landscape system is a unique feature of the Chengdu Plain and is still in use today, it is regarded as a local cultural heritage. This study analyzed and discussed the Linpan landscape system's historicity, traditional landscape elements, and traditional landscape structure using historical analysis and landscape systemic approaches. Agricultural heritage also could be a potential resource for the UA development of Chengdu.

This study draws lessons from excellent European cases and combine the characteristics of Chengdu to proposes some strategies for reference by local UA actors, including local administration, farmers, citizens, etc. The proposed strategy is guided by the sustainable development goals and the current Chengdu rural strategy, and proposes strategy suggestions from six different entry points: UA identification, UA participation, UA network, UA and traditional agricultural culture transmission, education and training of UA and agricultural heritage, and improvement of support policies for UA. Moreover, policy recommendations are divided into general for metropolitan area and specific recommendations for central-urban, peri-urban and sub-urban areas. Due to the special focus on the Linpan landscape system, this study also proposes a brief guideline for the preservation of the Linpan landscape system, hoping to make a little contribution to the conservation and enhancement of the local agricultural cultural heritage. The results of this study are expected to contribute to UA development and agricultural heritage conservation in Chengdu and other Chinese cities.

RE-INTEGRATING PRIVATE SPACES WITHIN THE URBAN GREEN INFRASTRUCTURE. A CULTURE-BASED APPROACH TO IMPROVE HISTORICAL DISTRICTS RESILIENCE TOWARDS CLIMATE CHANGE

Maria Stella Lux - Supervisor: Prof. Nerantzia Tzortzi

Tutor: Prof. Marzia Morena

Considering the fragility of cities and anthropic systems in the face of increasing risks of extreme weather events, one of the key issues in recent decades has been the adaptation of urban structures to achieve improved resilience. This doctoral research started from the reference framework provided by the H2020-MSCA-RISE-2019 YADES project, which recognised the need to develop adequate risk management and adaptation strategies for historical urban contexts. The research work thus focused on the intersection between the three fields of: i) urban Cultural Heritage management, ii) Climate Change and related risks, and iii) Green Infrastructures as a mean for urban adaptation. The integration of Green Infrastructures and Nature Based Solutions into the built environment plays a key role in improving the resilience of urban systems. Indeed, natural components and processes can deliver multiple benefits and provide a more flexible answer to many stresses affecting urban areas. Green planning, however, does not affect all urban territory in the same way. The current Urban Green

Infrastructures (UGI) strategies are mostly based on large-scale interventions to ensure the connectivity of biophysical systems. These strategies almost exclusively address public space and have major limitations in dealing with the compactness and the scarcity of transformable space of historic centres. As a result, historic city centres are usually excluded or only marginally affected by the urban re-naturing process, even if they can be considered sensitive contexts from cultural, social, and environmental perspective with a specific need for adaptation measures. Thus, the ability of UGI strategies to involve private open spaces and their extension in historical districts emerged as complementary aspects.

This thesis answers to the need to develop ad hoc strategies for these contexts, having as a priority the protection and enhancement of Cultural Heritage. The methodological hypothesis is the need to start from the historical and cultural specificities of the context and the recognition of “green history” of the city as the basis for the “green planning” of the future. The research

methodology has been defined through the synthesis of the current UGI planning process in four stages (knowledge, design, implementation and monitoring) and the proposal of integrative actions for each stage, in order to grasp the complexity of historic urban landscape. The main proposed innovation concerns the temporal extension of the knowledge phase to combine the current UGI planning process with the dynamic perspective offered by the Historic Urban Landscape approach. Additionally, it is proposed to integrate the “green network” approach, which aims to create a continuous biophysical system in the urban environment in line with the principles of landscape ecology, with the concept of “green fragments”. The proposed methodology is applied through

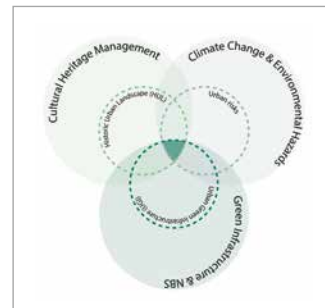


Fig. 1

four sequential analytical steps (historical, spatial, policy, and social analyses) and has been tested and validated in the case study of Milan, where the relevant role of private spaces and urban courtyards emerged. The four-steps analysis done for Milan included the study of land uses evolution over two centuries, the comparison of the municipal green strategy of PGT Milano 2030 with other ongoing programmes such as FORESTAMI, on-field surveys carried out in 96 courtyards, the overview of the current regulatory framework, online questionnaires to 355 citizens, 2 focus groups and 2 interviews.

Three international cases were then used as comparative benchmark to learn about innovative solutions, namely the cities of Hamburg, Rotterdam and Barcelona. Leveraging the theoretical knowledge and empirical insights drawn from the comparative case studies and taking advantage of the in-depth analysis performed in Milan, the doctoral research provides two separate final

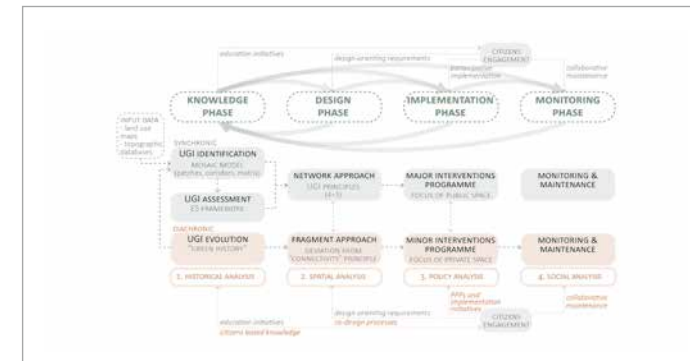


Fig. 2

outcomes. The primary scientific product consists of the methodology for extending the UGI approach to Historic Urban Landscapes. This method is the theoretical output of the research and its replicability to different contexts is ensured by the fact that it was developed independently of the case study and emerged from research and practical gaps evidenced by the literature review. Its relevance goes beyond the solely historical areas, as the fragment approach can complement and strengthen the green network even in more recent urban areas. The second specific output of the thesis is referred to the case study. Indeed, the culture-based approach produced a comprehensive integrative methodology regarding the phases of investigation, mapping, and planning of the municipal ecological network for the city of Milan. It also highlighted inconsistencies and discrepancies between current sources of data on urban greenery and proposed synergies between different urban greening programs,

especially FORESTAMI and the PGT Milan 2030. The research thus proposed a systematic set of actions to supplement and harmonize the existing tools and procedures employed in Milan including: a revised procedure for integrating data sources and recognising green fragments as the structural component of the UGI in the centre; a procedure for selecting and prioritising clusters of private courtyards for the future extension of the UGI based on criteria of proximity and numerosity; a toolkit of 18 actions that can be done by citizens in their residential private open spaces to contribute to the UGI extension; a proposal for indicators to improve the neighbourhood-scale and the user-centred monitoring of the UGI.

The major limitation faced concerns the scarcity of theoretical and practical references to UGI programs for historical centres and the lack of plans or other regulatory programmes for green management in private spaces. This gaps, observed at the European level but likely existing elsewhere, mean that the proposed recommendations do not find immediate applicability but must contend, on a case-by-case basis, with the specificities of existing regulatory frameworks and the decision-making processes.

SOCIO-CULTURAL VALORIZATION AND MANAGEMENT OF THE TRADITIONAL TOWNS AND VILLAGES ALONG EASTERN ZHEJIANG CANAL

Dongqing Ma - Supervisor: Prof. Stefano Della Torre

Tutor: Prof. Laura Anna Pezzetti

The canal flows through many cities, towns and villages in China. With the successful declaration of the Grand Canal as a World Heritage Site, these settlements have attracted great attention. As the southern end of the Grand Canal World Heritage Site, the Eastern Zhejiang Canal connects the Maritime Silk Road World Heritage and the Beijing-Hangzhou Grand Canal. It is characterized by its cross-regional, large scale, variety of heritage, a combination of tangible and intangible cultural remains, huge economic value, and complex natural ecosystem. However, it has received less attention than the main Beijing-Hangzhou Canal.

As an essential part of the world cultural heritage of the Grand Canal, the settlements through which the canal flows are not only a large number of heritage sites but also a daily production and living space for villagers. They were flourishing due to canal navigation function and now declining, especially in the vast rural areas. During this process, rural communities gradually lose their cultural and social values with the disappearance of local tangible and intangible cultural heritage. However, the revival of the rural

areas along the Eastern Zhejiang Canal faces great challenges. On the one hand, there is a lack of governmental and social attention, thus presenting a single method of conservation and utilization; on the other hand, most of the canal heritage sites in rural areas are scattered, making it difficult to organize a large-scale conservation project, especially for some small historical villages and towns. Unlike Zhouzhuang, Tongli and other towns with high historical value have received great attention to developing tourism and real estate economy; these residential-oriented small historic villages and towns are more likely to show and represent the typical relationship between "small towns" and canals in general. Therefore, the main goal of this study is to discuss how to develop the daily life and production space of the residents towards the sustainable valorization of the Grand Canal heritage. In this thesis, Wufu (traditional village), Xinyiting (traditional villages group) and Fenghui town (traditional town), which are typical representatives of historical small villages and towns along the Shangyu

District of the Eastern Zhejiang Canal, are selected as the research objects. By utilizing Environment-Behaviour studies (EBS), Photogrammetry, Co-creation and social innovation research methods, the research analyzes the spatial structural, architectural and node types of the three typical ancient villages along the East Zhejiang Canal; meanwhile, carries out a co-creation project based on the "place" theory and residents' behaviour. This dissertation is mainly structured into four parts: introduction, construct conceptual mode, field research and analysis and discussion and conclusion. The introduction phase defines the importance of the topic and the main issues and contents, while the second chapter introduces the policy and current situation of the research object. The conceptual model composition stage establishes a basic framework of social innovation. Among these, Chapter 3 explores how the socio-cultural value of cultural heritage contributes to regional growth and its synergy with economic value. Meanwhile, the case study Distretti Culturali project in the Lombardy region

was analyzed, which is of great relevance to the following conceptual model construction. Based on the conclusion from the last Chapter, Chapter 4 build a basic social innovation model for the renewal of historic villages, which is mainly constructed by four clusters: supporting and strengthening their tangible and intangible identities, establishing co-creation platforms, improving resident communication, and increasing the knowledge of the whole territory, and most of these enhance the soft capital in the whole region. By narrowing the study to towns and villages in the canal basin, the findings of the Field research part will finally validate and refine the conceptual model specific in the canal basin. It including

the renewal and management of settlements in villages and towns along the East Zhejiang Canal (Chapter 5) and the settlement morphology and spatial structure of the three studied villages and towns (Chapter 6). The findings of these two chapters enrich the local heritage knowledge and provide the research base for implementing the co-creation project in Chapter 7. Chapter 7 summarizes the co-creation activities carried out in Fenghui Ancient Town, focusing on the revitalization of daily spaces. Through summarizing and synthesizing the results of the co-creation activities in Chapter 8, different tools like a toolbox for place revival, co-creation network for project management, capital

framework in rural basin areas and local knowledge platform were concluded to support four clusters of the social innovation model, thereby a social innovation system based on the revival of canal culture was finally established. Among them, canal culture is used as a tool for territorial development, especially in fragile areas. Finally, these proposals aimed to boost the awareness of local culture and identify comprehensive strategies for the valorization and management development of traditional canal towns and villages at both cultural and social levels, contributing to the whole region. It must be mentioned that social-cultural aspects do not contradict the economic value but interact and create synergy to create a better environment to achieve high value.

Key Words: canal culture; living heritage; social sustainability; rural capital; co-creation ; public space; place attachment

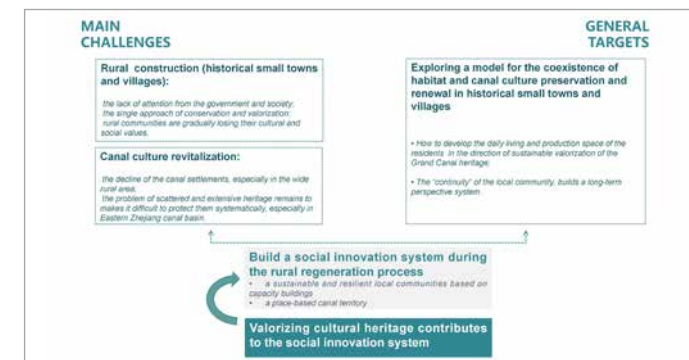


Fig.1 - Research framework. Source: Drawn by the author.

INNOVATION AND CHANGES IN THE DIDACTIC SPACE

Francesco Martinazzo – Supervisor: Prof. Francesca Bonfante

Co-Supervisor: Prof. Federico Acuto – Tutor: Prof. Laura Daglio

The thesis studies the evolution of school architecture in primary and secondary schools, taking part in a debate rather frequented by architects in recent times, not only about specific school spaces, but also in general about the interpretation of a pedagogical program that would rightly like to be innovative, but that often considers the spaces deputed to implement it rather indifferent to the mandate. The research therefore began by considering the period of the 1960s-1970s (often referred to as the “golden age of school”), with an extensive literature review, particularly investigated through the architectural journals of that period.

The work is composed of two distinct and complementary fronts: a narrative one (“vol. 1 | Text”), which attempted to critically reposition the debate of specific operational experiences on the theme of school architecture; an iconographic one, which made it possible to construct a critical and selective handbook of operational experiences around the typological theme through a detailed review of national and international periodicals and is divided into two parts: – “vol. 2 | Atlas”, where case

studies emerged from the bibliographic review are analyzed; – “vol. 3 | Zibaldone”, where a reworking of the categories that emerged through prototypical projects is experimented with. It is precisely from this critical-figurative relocation represented by the Atlas that four basic categories have emerged that, while linguistically belonging to a precise period of architectural debate (the 1960s-1970s), are to be considered crucial and clarifying concerning the current debate: “Pedagogical key: Program”, “Constructive Key: Prefabrication”, “Social Key: Civic Centre”, and “Technological Key: Machine”. The research has therefore developed prototypical experimentation capable of demonstrating a certain ductility in the organization of architectural space and contradicting the supposed figurative irrelevance or typological undifferentiation that connotes much of the contemporary debate. The challenge, of course, is also not to fail to meet the requirements of versatility and adaptability of spaces, now indispensable alongside an equally unquestionable typological characterization.

The topic is thoroughly investigated starting with coeval

trade journals and then expanding to a broader literature and archival research conducted in person at the Rockefeller Archive Center, the latter occasion allowing the “rediscovery” of largely unpublished materials. In confrontation with the contemporary debate, the research, on the one hand, links architectural-pedagogical issues to the economic-political contexts investigated, returning a complex picture of the school events of the last sixty years; on the other hand, it proposes an original prototypical experimentation on typology, identifying invariants and variables of architectural composition and the relationship with urban insertion. The thesis aspires to an ambitious and at the same time concrete

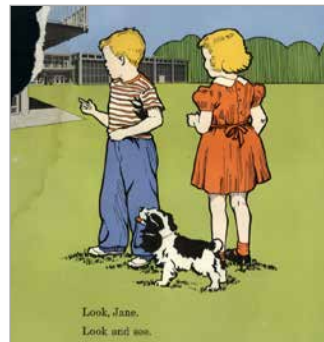


Fig. 1 - Magazine cover, “Progressive Architecture”, monographic issue Schools, February 1965

goal: the elaboration of a “booklet of principles” (summarized in ten key concepts) for the design of new schools, supported by an “Atlas of school architectures” (assembled according to the comparative criterion) and a “Zibaldone of types and figures,” developed through the assembly of spatial prototypes. In this original perspective, the investigation of the ideational and creative process in the school buildings of the “past” is thus projected into a future where the experimental approach is confirmed and precise.

The results achieved acquire definite relevance both from the point of view of the originality of the critical-design method and the advancement of research in the specific field.

The selection of case studies and their comparative analysis, deduced from the reconstruction of key events and personalities of those years, highlighted the emphasis placed in the 1960s and 1970s on technological-typological and figurative-pedagogical problems according to a decidedly experimental, pragmatic, and eclectic approach,



Fig. 2 - Charles Colbert, Learning carrel, Rice Design Fete, Huston, Texas, 1967

which achieves significant results on the typological and expressive level. The four categories identified demonstrate the necessary actualizations of their propulsive potential also for responding to today’s questions of transformation. The research finds its turning point in the observation (through the consultation of ARES “regional school building registry” data) that, in quantitative space-functional terms, the school, while changing typology, has never managed to truly renew itself. For this reason, the thesis seeks to “operationally” bring the issues discussed back to contemporary design practice in an attempt to redefine the aforementioned categories through the development of prototypes that consider both demolition-reconstruction and adaptation of existing structures. Depending on the type, order, and grade of school on which it is intended to operate, such an “operational dossier” seeks to explore design interventions through a marked gradient of versatility, establishing a “bridge” between “upstream” theoretical

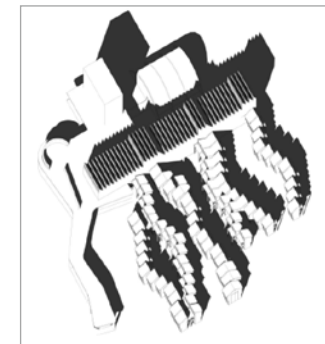


Fig. 3 - Francesco Martinazzo, School prototype, 2023

research and “downstream” design. The prototype is thus understood as a critical synthesis, capable of generating knowledge that is “autonomous” and “parallel” to the verbal discourse/logos; in other words, a tool for counter-verification of the research hypothesis and its theoretical acquisitions. The thesis achieves a high degree of originality from an innovative viewpoint on the subject, which sheds new light on a crucial period for school architecture, particularly about the U.S. case that has been little investigated in the Italian and European literature, and partly “forgotten”.

The thesis devised as an open and experimental process, offers ample scope for future work on the development of design and programmatic reflections on the subject of the school building.

SETTING UP THE SUSTAINABILITY DIGITAL TWIN. AN INNOVATIVE, OPEN-SOURCE, MODEL-BASED APPROACH TO ENHANCE WASTE MANAGEMENT EVALUATION IN GREEN PUBLIC PROCUREMENT

Silvia Meschini – Supervisor: Prof. Giuseppe Martino Di Giuda

Co-Supervisor: Prof. Lavinia Chiara Tagliabue – Tutor: Prof. Laura Elisabetta Malighetti

Despite the advancements in BIM, construction productivity is hindered by project complexity, fragmentation, and paper-based approaches, impeding collaboration and digitalization. Key issues include competitive practices, interoperability gaps, and deficient Information Management, worsened by digital and normalized processes shortcomings preventing tasks automation.

Public Procurement represents 14% of European GDP and faces similar challenges with inefficiencies and long processing times. The Public Clients can lead the green and digital transition of the construction industry through more efficient, green, and digital processes. Nonetheless, despite regulations promoting digital tools adoption, paper-based practices persist and Green Public Procurement (GPP) is hindered due to inadequate staff training with issues in drafting sustainability criteria. Italy was pioneering by requiring GPP as mandatory through the Minimum Environmental Criteria (i.e. CAM criteria) and MEAT (Most Economically Advantageous Tender) criterion, but GPP and CAM are still poorly adopted. Digital and data-driven methods would enable easy project

performance checking and evaluation, promptly displaying design choices' impact at single and global level, in terms of performance and sustainability. A shift towards more complex approaches such as Product Lifecycle Management (PLM) would be key to providing a multidisciplinary and systemic performance view throughout the lifecycle, and managing processes with a significant amount of information. Digital Twins (DTs) are emerging as the solution to manage construction complexity from a PLM perspective, providing a holistic approach with data consistency, reduced information loss and asymmetry, strengthened interoperability, and seamless connectivity among the stakeholders. This can enable the dynamic and simultaneous evaluation of several performances and aspects with great potential in GPP. Introducing the DT Prototype (DTP) and DT Instance (DTI) concepts from PLM can revolutionize construction procurement and performance assessment. GPP adoption can be enhanced through data-driven bid evaluation, rather than relying on implicit knowledge from documents. At this aim, Design-Build (DB) is suitable both for the introduction of model-based

approaches and DTs, as the building geometry is defined and the tender is based on the evaluation of improving proposals. Full digitalization, tasks automation, and a more objective, transparent, and efficient tender evaluation can be supported by consistent and complete information. The bids Information Requirements (IRs) can be settled as the basis to develop a Sustainability DT for CAM criteria and environmental impact evaluation via tailored KPIs throughout the lifecycle. Few research investigated DTs across the lifecycle so far, and several gaps concern the early design and disposal phases. Defining the IRs across the lifecycle is needed for valuable DT application in a PLM perspective, in addition to information protocols and standards. The awarded bidding model can be enriched in the executive design phase to develop the Sustainability DTP, exploitable during the construction to optimize design scenarios with respect to environmental criteria. Then, it can be enriched, becoming the Sustainability DTI for monitoring performance in the operation and maintenance phase with further parameters and KPIs, up to the decommissioning phase. An axiom of the research is that

the awarded bidding model, and particularly the Sustainability DTP, should be “reusable” and enriched throughout the lifecycle, otherwise, it’s a mere simulation model.

The main aim is to redefine the current Italian DB tender procedure in a model-based, open-source, and fully digitalized one. This involves the definition of a PLM framework for Sustainability DT creation, and a replicable methodology integrating process normalization, openBIM, and Information Management, defining the IRs for semi-automated evaluation through MEAT criterion. The analysis of the current procedures, regulations, tender guidelines, and standard tender notices enabled the current DB procedure mapping and its re-engineering. The automatable tasks were identified, focusing on bids evaluation through the MEAT criterion. A replicable methodology was developed, involving: (i) BPMN 2.0 normalization of the evaluated criterion; (ii) individuation of related IRs, mapped in IFC (Industry Foundation Classes); (iii) score calculation, after exporting IFC bidding models in Excel sheets; (iv) development of analytic dashboards to compare bids scores at the level of the single criterion and the whole tender.

The research promises significant impacts as the PLM framework provides a complex and holistic approach to optimize the quality and production costs of DTs, leveraging a new concept: the DTP. This disrupts traditional methods, providing

a reliable prototype to evaluate and optimize the building's performance with high accuracy across the lifecycle. This is valuable given the expected surge of DTs as the information structure development is optimized through a step-by-step approach based on the IRs needed. Decision-making improves, incorporating informed choices based on accurate data and addressing environmental concerns starting from the early design and tendering phase. Information protocols for suitable DTs can be provided, together with the truthful “as built” model. The methodology was tested starting from the semi-automated evaluation of waste quantities in a DB procedure for a new school. Considering waste generation from the early design phase is key to optimizing quantities and reducing the project environmental impact. The proposed approach showcases adaptability and significant impacts. It's undergoing experts' examination and, once validated, it could be extended to the other CAM criteria and the whole tender, providing the full GPP adoption and digitalization in tendering processes, with formalized links between the project's domains. This could provide a comprehensive prototype to easily and truthfully test different design choices, rather than evaluating isolated performances. It was compared with the traditional approach and another Information Management approach previously developed. The tendering process significantly improved thanks

to the digital and model-based evaluation system, reducing reliance on manual, time-consuming and error-prone tasks, and enabling simultaneous bids evaluation with streamlined procedures. Bids can be evaluated almost simultaneously with their submission, improving transparency thanks to open-source and fully accessible information, shared among stakeholders. Finally, analytical dashboards enabled the results visualization related to the single criterion, the overall bid, and the whole tender, providing an immediate comparison between the bids. Disruptive process innovation provides challenges as well, including current regulatory limitations on information models' exploitation. They should be updated, ensuring privacy, data ownership, traceability, and transparency. A change management strategy is needed to overcome the low propensity for innovation and the lack of digital and BIM skills among Public Clients. Another concern is the management of huge amounts of data, thus Machine Learning and Artificial Intelligence should be considered. Also, the limitations still posed by exporting through the IFC standard should be considered. Addressing these challenges is key for advancing the proposed PLM approach, this first proposal aims at filling the gap towards the definition of IRs for Sustainability DTs and digital, model-based approach for GPP enhancement.

EXPERIENCE- AND EVIDENCE-BASED DESIGN STRATEGIES FOR AUTISM-FRIENDLY HEALTHCARE FACILITIES

Alessandro Morganti – Supervisor: Prof. Stefano Capolongo

Co-Supervisor: Prof. Venanzio Arquilla – Tutor: Prof. Oscar Eugenio Bellini

Introduction: Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder, and the first manifestations can be observed during childhood. Some impairments arise later than others and affect verbal communication, social interactions, limited interest or activities, stereotyped behaviors, as well as self-injurious behaviors with different grades of severity: the concept of “Spectrum” gives a clue about the different nuances that this condition can take. The average worldwide prevalence of autism is 0.65% has grown a lot in the last two decades, also thanks to a stronger awareness of the disorder among healthcare staff and early detection of signs in the very first years of life. The American Center for Disease Control (CDC) estimates that 1 in 44 children at age 8 has autism, and the disorder is 4 times more represented in males than females. Earlier detection of autism allows for early interventions, significantly impacting the evolution of the disorder and the abilities that patients will develop in their life for communication, social interactions, and individual abilities. Interventions that proved to be effective include intensive,

early behavioral, cognitive, and psychoeducational therapies. Recent studies estimate that the cost of supporting an individual with ASD during his/her entire lifetime ranges between 1.4 to \$2.4 million, depending on associated intellectual disabilities. Individuals on the spectrum often suffer from sensory issues, experiencing hypo- or hyper-reactivity to sensory stimuli that would be perceived of normal intensity by neurotypical individuals, which can lead to strong discomfort. Lights, sounds, colors, shapes, tactile stimuli, smells, and thermal comfort in the built environment can strongly influence these users’ well-being, resulting in a sensory overload. Individuals with ASD attend healthcare facilities two to three times more than neurotypical individuals on average. However, there are still no official guidelines or regulations defining design standards to ensure that healthcare spaces meet their sensory needs and reduce their discomfort during diagnostic and therapeutic processes. **Research Objective:** The Ph.D. research aims at providing a set of design strategies for autism-friendly healthcare facilities,

serving as a guide for designers and decision-makers in the realization of new buildings or the adaptation of existing spaces. The definition of these strategies should be grounded on the analysis of the experience of large populations of individuals with autism and their caregivers in a co-design approach to provide evidence-based and experience-based design strategies. **Methodology:** The research has been developed through 8 different phases. After studying the sensory disorders of individuals with ASD, a systematic review of the scientific literature analyzed the existing studies that proposed design strategies and post-occupancy evaluation tools. Two web-based, multilingual surveys integrating items from clinical scales were created to investigate the experience that individuals on the spectrum had during their first and last visit to the spaces of the healthcare facility (e.g. hospital, clinic) they attend more frequently: caregivers were asked to report the experience of their children, while independent adults on the spectrum reported for themselves. The survey investigated specific indoor area of the building, such as the entrance area, the check-in

area (if present), connections (i.e. hallways, stairs, elevators), the waiting area, and the observation/therapy/consultation room. The close collaboration with the Stanford Medicine Autism Center allowed for the innovative integration in the surveys of revised clinical scales that detected the increase of Restricted and Repetitive Behaviors, proven to be a manifestation of the discomfort of users with ASD. To collect the insight of healthcare staff that attend to patients with ASD frequently –such as Medical Doctors, Therapists, Psychologists, Nurses, or Technicians – in-presence workshops and dedicated surveys have been conducted in Italy and in the United States. A first pilot survey was distributed in Italy. Improved and validated versions of the surveys were distributed in the US through the biggest national networks of caregivers and individuals with ASD: the Stanford Autism Registry, and the Simmons Powering Autism Research (SPARK) database. 1845 caregivers and 1035 independent adults with ASD across Italy and the US participated in the study. 73

healthcare staff professionals also contributed to the investigation. Data analysis provided validation of existing design strategies from the scientific literature and the definition of new ones, directly created from the first-hand user experience (UX) evidence that caregivers and independent adults with autism provided. Through statistical analysis, the research determined which spaces of healthcare facilities have a stronger impact on the discomfort of users on the spectrum. It was also possible to define and rank the space elements and sensory channels that are most impactful on the well-being of users with autism. The priorities of interventions are schematized in Figure 1 below.

The final set of design strategies has been validated by experts and applied to 8 healthcare facilities in Italy and the US. **Research outcomes:** The Ph.D. research resulted in a validated and tested toolkit composed of 73 design strategies. The strategies can be adopted to build new autism-friendly healthcare facilities, such as specialized clinics for neurodevelopmental disorders, children’s hospitals, or general hospitals, but they can also support the adaptation of existing spaces. The strategies’ flexibility allows for their future adoption for different spaces and building typologies as well.

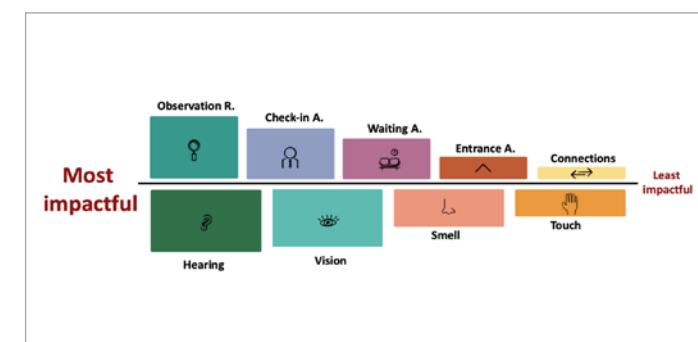


Fig. 1 - Ranking of the most and least impactful healthcare spaces and sensory channels on the well-being of users with autism.

MULTIDIMENSIONAL EXAMINATION OF VERTICAL GREEN STRUCTURES IN A CHANGING URBAN ENVIRONMENT

Ozge Ogut – Supervisor: Prof. Nerantzia Tzortzi

Co-Supervisor: Prof. Chiara Bertolin (NTNU) – Tutor: Prof. Laura Anna Pezzetti

As cities grow fast, there would not be space to build new parks and/or gardens in built environments. Hence building skins (i.e., green roofs and green walls) as part of green infrastructures (GI) network, allow increasing green density without spatial concerns. Both green walls and green roofs become therefore nature-based solutions (NbS) with high potential for increasing green density. The main motivation of this thesis is based on this inevitable space-related problem and to enhance the possibility of vertical green structures' (VGS) implementation as an adaptive NbS. Several studies have been made about green roofs, but more study needed on green walls since VGS is a relatively new technology in comparison to green roof. VGS are becoming of high interest in research and commercial areas. In comparison to green roofs, VGS contribute more to the enhancement of social wellbeing by providing stronger visual engagement of people with greenery and as being more easily implemented on existing buildings.

VGS can offer multi benefits on both new and existing buildings, which may help versatile and multi-scalar impacts in urban

areas. These simultaneous benefits of VGS could allow a more sustainable urban design and could compensate the lack of green spaces inside dense cities enhancing the wellbeing. Despite the awareness of environmental benefits and growing research on this topic, the acceptance of GI, including VGS mostly, still has challenges. The mentioned phenomenon of rapid urbanization has given rise to an array of challenges that accelerate a multitude of problem in urban areas. This merge of challenges encompasses a spectrum of concerns, spanning political, economic, social, technological, environmental, and legal (PESTEL) dimensions (see Figure 1), making sustainability an obligation, and NbS a pivotal approach. Among these solutions, VGS, a type of GI, have gained

prominence in the last decades. They hold the potential to effectively address requirements across these diverse dimensions. Within the landscape of urban areas, VGS play a significant role in tackling urban challenges, particularly in densely build and populated areas where limited horizontal space constrains the creation of additional green areas like parks and gardens. Anchored in this context, this Ph.D. thesis aims to examine the benefits and challenges of VGS within the spectrum of sustainability paradigms for resilient cities of the future. The PESTEL dimensions are considered as a network (see Figure 2), rather than individual items of a list. The priority of the PESTEL dimensions in the thesis is shown hierarchically, with the most important dimensions at

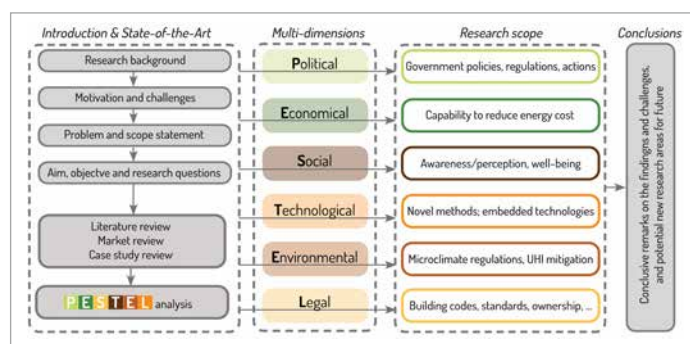


Fig.1 - Organisation of research modules and the contents.

the top and the least important dimensions at the bottom. The size of the boxes corresponds to the importance of the dimensions. Technologies and Environmental aspects are the primary focus, whereas the Economic and Social aspects are the secondary ones. Political and Legal are cross-dimensional aspects. The technological aspects feed the Environmental benefits since if the component (both living and non-living) selection is optimised, the Environmental benefits are maximised. In parallel, Technological developments can lead to legal consequences related to building codes, ownership, privacy, and liability. Environmental and Economic aspects contribute to the social awareness as the benefits become public knowledge. The aims and objectives of this

thesis can be classified under each studied dimension of PESTEL. On the **technological** front, novel methodologies are developed to assess the stress on vegetation, as well as the geometric deformation of vegetation to optimize the selection of species (i.e., living components) before the installation. Additionally, the critical review of the new trend of combining several technological tools into VGS, helped to estimate possible future challenges and opportunities. **Environmentally** speaking, deep comprehensive in-situ data analysis is conducted to assess the thermal regulation performance of VGS and their capacity to mitigate heat gain and the urban heat island (UHI) effect.

From an **economic** point, thanks to thermal regulatory benefits, it

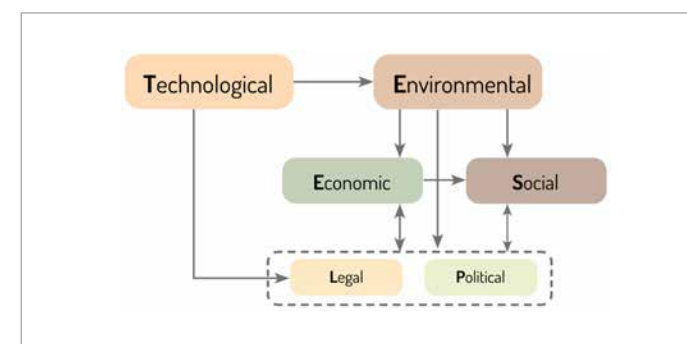


Fig.2 - The links between the six dimensions from PESTEL model for VGS cases.

contributes to reduce the energy cost for heating and cooling. Addressing **social** aspects, the thesis employs a questionnaire distributed among users of environments equipped with VGS to gauge the level of awareness and perception of these systems.

From a **political** perspective, the thesis acknowledges the influence of government policies, regulations, and political actions on the implementation of VGS. The **legal** dimension, despite not being the focus of the thesis, is always involved as the cross-dimensional aspect through building codes/standards, permission to install VGS, or ownership.

Concluding with insights drawn from the results, as well as the novel methodologies applied, the thesis underscores the complexity of VGS design, installation, and maintenance, proposing strategies to overcome associated challenges, and optimize the potential benefits. This interdisciplinary research enlightens VGS's pivotal role in the intricate landscape of urban sustainability and resilience.

TIMBER – CONCRETE COMPOSITE VENTILATED ENVELOPE SYSTEMS

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS FOR THERMAL PERFORMANCE CONTROL AND OPTIMIZATION

Sofia Pastori – Supervisor: Prof. Angelo Lucchini

Co-Supervisor: Prof. Enrico Sergio Mazzucchelli – Tutor: Prof. Laura Elisabetta Malighetti

In recent years, the building sector has been characterized by a rapid growth in the use of timber, thanks to the arise and spread of engineered wood products. The reasons are related to their great performances: the good seismic behaviour due to the high ratio between the mechanical resistance and the material weight, the good thermal insulation properties, environmental sustainability, behaviour under fire conditions (if designed in appropriate way), the strong attitude of timber towards prefabrication, the ease of systems integration in prefabricated timber components and the possibility of disassembly at the end of life. Research studies also demonstrate the well-being benefits of wood in living and working environments. But timber is also characterized by low durability if not properly protected and high hygroscopicity. Moreover, lightweight timber structures have low thermal inertia and acoustic insulation performance if compared to massive alternatives. For the optimization of timber-based construction systems, hybrid technologies might be used, combining different materials to take advantage of the best respective performances. Hybrid systems focus on the economy,

performance and ecology of the final product. The combination of timber with other materials, mainly reinforced concrete or steel, for building construction is quite spread nowadays. Materials hybridization is usually applied at two levels: at the building component scale, combining different materials within a single building element (e.g. a column, a beam, a floor panel, a wall panel, etc.), or at the building level, using different materials for different building components (i.e. the vertical structure, the horizontal structure, the envelope, etc.). Building components formed by timber and concrete or timber and steel are referred to, respectively, as Timber-Concrete Composite (TCC) and Steel-Timber Composite (STC) components. The present research work focuses on TCC components. The hybridization of timber and concrete allows to overcome some of the materials limits and achieve improved behaviour in terms of mechanical properties, acoustic performance, fire resistance and durability. Nowadays, TCC technology is well-known for floor systems. In fact, the very first applications of TCC components concerned the refurbishment of existing timber floors and, in the last fifty years, interest

in this building solution has increased, both for improving existing floor systems and for new constructions. On the other hand, only few and recent research works concern the use of TCC solutions for building facades. TCC facades are usually composed of an internal highly insulated timber-frame wall connected to an external concrete slab acting as shield against the weather agents. Generally, the timber wall and the concrete slab are separated by an air cavity. In case this last one is ventilated, the TCC envelope is comparable to a ventilated façade formed by internal lightweight wall and external massive cladding (i.e. the concrete slab). Such hybrid structure offers several advantages. First, the protection of the insulated timber structure from the outdoor weather agents, enhancing the façade durability, prolonging its service-life and, therefore, improving the sustainability. Also, the presence of an air cavity between the humid concrete slab and the dry insulated timber wall contributes to the duration of the envelope solution. The concrete slab helps increasing the facade resilience thanks to its high resistance against external impacts, also in consideration of the increasing number of extreme weather events (i.e. hailstorms,

windstorms) responsible for damaging the building envelopes. The solution is also characterised by a good airborne sound insulation, according to the mass-spring-mass principle, where the timber and concrete structures represent the masses, while the air is the spring. Considering the behaviour under fire, both timber and concrete have a good resistance, even though attention must be paid to the design of the air cavity. Another important advantage of TCC components is the possibility of entire prefabrication of the facade, just like for other timber-based systems, according to a wet-dry or dry-dry production process. One of the main limitations linked to off-site construction and prefabricated facades is building aesthetics. The most common finishing solution in case of precast timber façade panels is ETICS, which can be totally prefabricated – leading to the presence of visible joints between the panels on the façade – partially prefabricated or entirely made at the construction site. In case of TCC envelopes, the presence of the concrete slab as external finishing gives the possibility to reproduce unconventional aesthetics options, either traditional, such as mosaics or tiles, or innovative, such as 3D printed textures and patterns, photocatalytic or transparent concrete. Despite the mentioned advantages, there is limited knowledge regarding these systems and further research is needed to fully understand their properties, starting from the

hygrothermal behaviour. The present research aims at analysing TCC ventilated facades thermal behaviour, leading to a deep understanding of the potential as envelope solution for off-site timber-based construction. For this purpose, a prefabricated TCC ventilated envelope part of a real three-storey building, formed by an insulated timber-frame wall and a 50 mm thick concrete slab, separated by a naturally ventilated cavity, was monitored over one year considering opposite orientations (north and south) and different cavity depths (30 and 60 mm). The experimental data showed a good static and dynamic thermal behaviour, mainly due to the highly insulated timber-frame wall. The façade with smaller cavity performed slightly better in winter and summer, since the natural ventilation inside the cavity did not lead to appreciable façade cooling down, due the high radiative heat exchange between the cavity faces. The influence of the weather variables on the heat flux through the envelope was evaluated through a multiple linear regression model, showing that outdoor temperature and solar irradiation drive the façade thermal behaviour, while wind influence is negligible, but important for lowering the humidity value into the cavity, and consequently the risk for timber degradation. Since the TCC ventilated envelope object of the research is comparable to a ventilated façade with massive cladding, the heat flux through the envelope calculated experimentally was compared with the prevision by

ISO 6946. The results highlighted the Standard inaccuracy in describing and predicting the thermal performance of the TCC ventilated envelope. Other tools are therefore required to perform a detailed analysis, thus an optimised 2D CFD model of the façade was developed by using OpenFOAM. The final model, calibrated and validated against the experimental data collected, can describe and predict the envelope thermal behaviour with accuracy around 98% and up to 45 times faster than real time. The CFD model might be used to assess TCC ventilated facades thermal performance for different configurations, to find the optimal configuration for each specific project, avoiding expensive and time-consuming construction of mock-ups. The CFD model was developed and optimised for the specific envelope system but might be used also for different types of ventilated facades with internal lightweight wall and external massive cladding. Also, the study is an important step towards digital twins for TCC ventilated facades, since the calibrated CFD model can make predictions faster than real time. Accurate research in this respect might be interesting for the systems manufacturers, to further develop and optimise their products, and for designers, to better choose and specify the systems to be used.

«PROGETTO DI VITA» IN THE HOUSING DIMENSION: POSSIBLE AUTONOMY PATHWAYS IN IMPLEMENTATION OF LAW NO. 112/16 «DOPO DI NOI»

Cristiana Perego – Supervisor: Prof. Angela Silvia Pavesi

Co-Supervisor: Prof. Ilaria Oberti – Tutor: Prof. Monica Lavagna

Law no. 112/16 containing "Provisions on assistance for people with severe disabilities without family support", known as «Dopo di Noi» Law (*after us*), comes into force in Italy in 2016. The law, implementing the UN Convention on the Rights of Persons with Disabilities, introduces in the Italian legal system specific protections for people with disabilities from the moment they are left without family support, in the so-called «Dopo di Noi» (hereinafter "DdN"). The law defines measures aimed at the deinstitutionalisation of people with disabilities through a path of gradual detachment from the family, during the lifetime of parents and caregivers in the so-called «durante Noi» (*during us*) which is embodied in the realisation of «Progetto di Vita» (hereinafter "PdV"). The latter is built through a "holistic approach" since it is configured as a system in which all dimensions of the person's life are treated in close synergy with each other (health, housing, formation, school and work inclusion) and on the basis of a co-design model that sees the collaboration of a wide network of subjects (multidisciplinary *equipe*, Institutions and local authorities, Third Sector, representative organisations, family caregivers

and, where possible, the law beneficiaries themselves). PdV is defined from a multidimensional assessment of each person's needs in full respect of the own identity thus configuring itself as a "unique and unrepeatable" project for each person. The assessment identifies specific measures that can support the person's life path, which include, on the one hand, health, social and socio-health services, on the other hand, the activation of a series of interventions that can be financed through DdN Fund established by Law no. 112/16, which annually provides for the allocation of resources at regional level. In this way, the law promotes the realisation of new housing welfare infrastructure through co-design paths that systematise all dimensions for the realisation of PdV. The latter is thus configured as the pivot around which to build the quality of life of the person and through which to nurture the network of subjects and relationships ensuring the sustainability over time of projects for a future that can be experienced and trained in the present. The goal is to build a "social infrastructure" (composed of the physical residential infrastructure and of services of accompaniment to living)

that is essential to support the realisation of PdV over time. In this scenario, a PhD was activated by the Department of Architecture, Built Environment and Construction Engineering (DABC) of Politecnico di Milano in co-financing with the national Committee "Officina Dopo di Noi", within the project «Officina.net – Platform for dialogue and design», funded by Cariplo and Compagnia di San Paolo Foundations. Comitato Officina Dopo di Noi (hereinafter "CODDN") was established in 2017, due to the experimental nature of the law, at the initiative of On. Sen. Annamaria Parente, rapporteur to the Senate of Law no. 112/16, with the aim of monitoring and concretely supporting the implementation of the law throughout the country, in a network with Institutions, Third Sector Organisations and associations of family members of people with disabilities, pursuing the collective interest mission of spreading the culture of the law. The overall objective of the PhD thesis was to investigate the state of implementation of Law no. 112/16 on the national territory, focusing on the analysis of the characteristics and co-design processes that led to the realisation of housing welfare

projects financed by the law on regional territories. Starting with the "codification" of best practices for the deinstitutionalisation of people with disabilities emerged from the implementation of the norm, the objective of the thesis was substantiated in the realisation of a guiding tool for the proper law application, with a view to equal opportunities for beneficiaries, to enable research to act as a multiplier of projects for independent living of people with disabilities. The research was articulated in three macro phases declined with respect to three key elements for the implementation of Law no. 112/16. The first macro phase focused on the definition of PdV: the objective was to define the characteristics of PdV, strategies for its implementation and indicators that qualify it as an element of guarantee for the quality of life of people with disabilities. The goal was achieved through the participation in the interdisciplinary working group established in 2019 by Istituto Superiore di Sanità, within the Autism Fund project and on behalf of the Ministry of Health, for the definition of PdV of people with autism spectrum disorders oriented toward Quality of Life. The second macro phase focused on PdV declined in the path towards DdN: the objective was substantiated in the realisation of the monitoring of the state of implementation of Law no. 112/16 on the national territory, within «Officina.net» project, promoted by CODDN and carried

out in partnership among DABC of Politecnico di Milano (scientific partner), Istituto per la Ricerca Sociale (IRS), Fondazione per l'Innovazione del Terzo Settore – FITS! and BES Cooperativa Sociale, which deals with formation and work integration of people with disabilities. The third macro phase focused on PdV in the housing dimension: the objective was substantiated in the elaboration of a set of tools aimed at supporting co-design processes for the realisation of housing welfare interventions for «durante e DdN». The objective was achieved through the participation in a research project, subject of a collaboration agreement between the Office for policies in favour of people with disabilities of the Presidency of the Council of Ministers and DABC of Politecnico di Milano, aimed at identifying guiding principles to promote the replicability and scalability of the identified best practices. With a view to experimentation, research results were progressively applied within the project «Co-mix. Co-generare mixité inclusive nella città» funded by the Social Innovation Fund (D.P.C.M. 21st December 2018), which foresees the realisation of a housing welfare project for «durante e DdN» in Lucca city. The thesis led to the construction of a system infrastructure for analysing the implementation process of Law no. 112/16 and specifically to the elaboration of a set of tools for the co-design of housing welfare for «durante e DdN». These include a

series of recommendations for the realisation of housing interventions systematised in a checklist, as a tool for qualifying projects with respect to the adoption of recommendations that can be applied at any stage of the project development. In general, research results made it clear that design indications for the realisation of this type of intervention cannot be standardised regardless of the processes required to detect the person's needs. Rather, it is possible to work precisely on processes by developing tools based on the principles of Universal Design as expressed in Article 2 of the UN Convention to meet the needs of each person. In future developments, the set of tools elaborated in the thesis could be refined to elaborate, on the one hand, procedural guidelines for the realisation of housing welfare projects, on the other hand, a tool for evaluating projects quality with respect to the founding principles of Law no. 112/16. Research is proceeding through the research unit, "Officina Dopo di Noi" at BES Cooperativa Sociale (in partnership with DABC of Politecnico di Milano), aimed at establishing a permanent Observatory on the implementation of Law no. 112/16, through renewed support from the aforementioned banking foundations. Within the research unit, the set of tools will be refined in the directions identified as future research developments in order to make the Observatory's action systematic in an evolving scenario.

FIBER-REINFORCED ELASTOMERIC ISOLATORS (FREIS) WITH HIGH DAMPING FOR LOW RISE MASONRY BUILDINGS: NUMERICAL AND EXPERIMENTAL INSIGHT

Gaetano Pianese – Supervisor: Prof. Gabriele Milani

Co-Supervisor: Prof. Hamid Toopchi-Nezhad – Tutor: Prof. Tommaso D'Antino

Seismic base isolation is considered effective in reducing the vulnerability of structures, and it represents an optimal retrofit solution in terms of reliability and effectiveness. Steel-reinforced elastomeric isolator (SREI) is the method of seismic isolation that is used most frequently. It consists of several rubber pads interspersed with steel laminas for vertical reinforcement. Since these devices are generally too expensive due to the need to introduce thick connection steel plates and the high energy consumed for manufacturing, they are unsuitable for ordinary residential buildings, especially in developing countries. Fiber-reinforced elastomeric isolator (FREI) is a new type of elastomeric device. Instead of steel lamina, thin fiber layers are used. Compared with SREIs, FREIs have considerably lower weight and can be manufactured through cold vulcanization. They can be applied to the structure in several ways: bonded (traditional), unbonded, and partially bonded. In unbonded conditions (UFREI), the isolators can be installed between the upper structure and foundation without any bonding or fastening, reducing costs hugely. Furthermore, the dissipation

energy without steel supports improves thanks to the shear load transferred through the friction generated between the isolator and the structure surfaces during the rollover deformation (Figure 1). However, UFREIs cannot resist tensile forces, making them unsuitable for situations where overturning is of concern or where large vertical accelerations are anticipated. Moreover, the isolator could slip under certain loading conditions, resulting in permanent displacements. These concerns can be addressed by partially bonded applications (PBFREI), where only parts of the contact surfaces of the device are bonded to the connection steel plates. Many beneficial characteristics of the unbonded application, like dissipation energy improved, and of bonded one, like the

resistance to uplift forces and slip, are retained in partial bonding. Nonetheless, the costs associated with the production in terms of material are still high due to the presence of the connection steel plates. This can limit their implementation. So, the possibility of unbonded application remains a promising feature of the FREIs, especially for developing countries, because of their low cost and easy fabrication and installation. The technology of FREIs is steadily gaining recognition. However, despite ongoing technological advancements, their practical real-world applications remain limited at the current state of development. While FREIs have undergone thorough individual examination and characterization, their seismic performance has

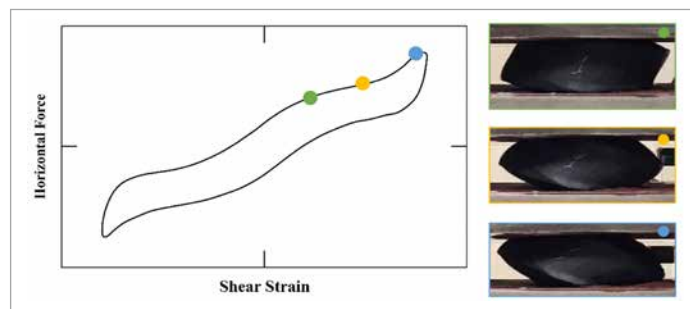


Fig. 1 - UFREI lateral displacement-force curve and typical shear deformation of the unbonded application.

primarily been assessed through numerical simulations. In theory, the use of these devices seems to offer a reliable, fast, and cost-effective solution. However, potential limitations, such as slip, damage of the devices, and buckling instability, may surface when applied. Additionally, the characterization of these devices and the materials used in their fabrication have often diverged from the recommended standards code.

This PhD study proposes FREIs made of alternating layers of high-damping rubber pads and glass fiber laminas for the seismic isolation of low-rise masonry buildings. The research aims to delve deeper into the dynamic and seismic performance of these devices while adhering to established worldwide standards codes. Furthermore, it seeks to explore practical applications, investigate the intricacies of large-scale production, and evaluate the feasibility and economic advantages of FREIs when compared to traditional SREIs. To achieve these goals, the following objectives have been identified.

- Proposal of new high-damping rubber compounds suitable for elastomeric seismic isolators: a comparative analysis of seven new high-performance rubber compositions for elastomeric seismic isolators is proposed. The compounds are made with unusual elastomer blends, different from the current market. The aim is to supersede common practices and, at the same time, comply with code recommendations.

- Development of a fabrication procedure for FREIs: this study aims to serve as a comprehensive guideline for the production and characterization of FREIs. In particular, a standard protocol is proposed that can be followed for the complete production and characterization of the device.
- Investigation into the influence of the shape factors on the final lateral response of FREIs: the geometrical design process is crucial to correctly define a device with an overall stable lateral response. This study introduces three distinct models of FREIs, each characterized by varying shape factors and aspect ratios while maintaining a consistent amount of rubber material. The objective is to investigate the influence of shape factors on the final behavior of the devices.
- Proposal of an optimal design procedure: the study underscores an in-depth exploration of fiber-reinforced elastomeric isolators, combining numerical and experimental approaches. The objective is to optimize the design of the devices in terms of seismic isolation properties based on preliminary numerical results.
- Experimental characterization of the devices in bonded, unbonded, and partially bonded applications: a pioneering comparative experimental analysis of the same FREI in all the boundary conditions is introduced. Particular emphasis is placed on the PBFREIs, proposed in a circular shape

and also characterized with the uplift test for evaluating the quality of the reduced bonding adhesion area.

- Investigation of the seismic performances of UFREIs with shake table tests: the seismic performance of the device is investigated with unidirectional shake table tests of a concrete block isolated with two unbonded devices subjected to several ground motions. The final aims are to assess the effectiveness of UFREIs in reducing the seismic demand, examine the response of UFREIs under unidirectional ground-motion excitation, verify the capacity of these bearings to resist major unidirectional excitation without damage and investigate the limits of this isolation system in the face of major seismic inputs.

In conclusion, this study markedly enhances the comprehension of FREIs, providing new perspectives on behavioral characterization and manufacturing methodologies. Based on the results obtained, there is a significant potential for FREIs to be considered as a practically viable solution to the mitigation of seismic damage in ordinary low-rise masonry buildings.

IN-USE OFFICES AND ECOLOGICAL FOOTPRINT: A CALCULATION MODEL TO MEASURE THE EFFECTS OF HUMAN OCCUPATION AND BEHAVIOUR ON ENVIRONMENTAL SUSTAINABILITY

Alice Paola Pomè – Supervisor: Prof. Gianandrea Ciaramella

Co-Supervisor: Prof. Chiara Tagliaro – Tutor: Prof. Andrea Antonio Caragliu

The Earth, the biophysical system where humankind operates, is intricate and self-organized. The complexity leads to a significant time delay between economic actions and their ecological consequences, hindering the progress of world economies towards sustainable development. Such delays set the risk of ecological instability, posing a threat to both the overall economy and society. In this transition, the Architecture, Engineering, Construction and Operation industry (AECO) plays a key role in mitigating the impact of human activities on Earth. Widely acknowledged as a major contributor to greenhouse gas emissions and resource consumption, the built environment also serves as the primary setting where individuals spend approximately 90% of their lives.

Once the industry recognized the environmental impact of buildings, international and national standards focused on the design and construction phases of the building life cycle. However, buildings consume the highest amount of resources during the operational and maintenance phase (O&M), which is also influenced by user behaviours. The social effect of buildings confirms

that users, rather than building systems, are primarily responsible for the environmental impact of buildings in use.

In this context, offices emerge as crucial assets, due to the significant changes in their usage and occupancy introduced by the Covid-19 pandemic. With the growing flexibility in employees' ways of working, the field of facility management (FM) must grasp the potential for reducing the environmental impact of in-use offices and harness user behaviours to align with organizational sustainability strategies. Thus, this field has the ability to aid the industry in its journey towards the sustainable development. To facilitate the implementation of strategies aimed at mitigating the environmental impact of buildings, FM requires suitable

tools to measure and manage not only the building system (e.g., envelope and plants), but also user behaviours. With the aim to overcome the absence of an effective environmental impact tool, this research develops a model to measure the environmental impact of in-use offices, highlighting the effects of user behaviours by adopting a methodology divided into three main steps.

The preliminary investigation focuses on analysing sustainability applications in FM. This comparison identifies the Ecological Footprint (EF) as the most suitable indicator to reveal the effects of user behaviours in the measurement of buildings' environmental impact. Especially, EF ability to educate individuals on their environmental impact represents an opportunity for

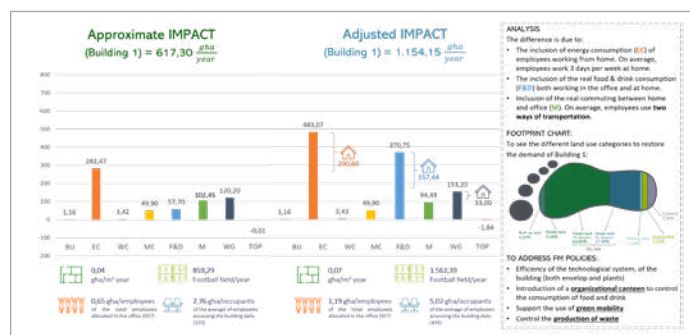


Fig. 1-Building 1 Approximate VS. Adjusted WIEFA sheet – elaboration of the author.

more effective FM's policies. By using a holistic approach, the EF offers a comprehensive assessment based on the comparison between the demand of resources/emissions and the Earth's capacity to regenerate those resources and absorb waste. This methodology adopts conversion factors, set internationally, to convert impact sources (demand) into a standard unit of measurement, the global hectares, which facilitates the comparison with the equivalence productive lands (supply). The development step employs an action-research methodology (Participatory Action Research – PAR) to elaborate the structure of the calculation model, called Workplace Integrated Ecological Footprint Assessment (WIEFA). By combining quantitative and qualitative approaches, PAR engages different stakeholders in refining the model, improving its structure, and testing its calculation through nine case study buildings. The iteration of PAR steps together with the integration of environmental impact assessments standards support the definition of boundaries and the standard calculation process. With the objective to compare different ways of working and users behaviours (such as, working from home and working in the office), the model evaluates the environmental impact of the workplace by assessing losses and gains (representing the EF impact sources) across three categories: site, building, and users. WIEFA identifies several losses, that include material consumptions

resulting from maintenance and cleaning activities, water and energy consumption from building operation, as well as mobility and dietary habits of users. With the gains, WIEFA assess the workplace's ability to reuse resources, such as the electricity generated by photovoltaic panels. The algebraic sum of these sources is converted into global hectares and compared with the land use categories, following the EF methodology. The testing step verifies WIEFA. The model effectiveness is demonstrated by comparing the results of the Approximate WIEFA, obtained from the development test, and the Adjusted WIEFA, which collects real data of user behaviours through a survey (Figure 1). While the model reliability is assessed by comparing the results of Adjusted WIEFA with the building energy model, plotted with Design Builder. In addition, a sensitivity analysis is performed to understand the influences of two design parameters (space occupation and space configuration) on the environmental impact of in-use offices. Revealing the major influence of space occupation, the test confirms the importance of considering users' behaviours in the measurement of building environmental impact during O&M. The research advances the promotion of more sustainable FM practices, by influencing the ongoing debate on AECO sustainable development. WIEFA represents a guide for professionals, including facility managers and real estate operators, in making decisions and

taking actions across the entire building life cycle. Additionally, it has an educational effect by addressing building users towards more sustainable behaviours. WIEFA is a quantitative model, capable of testing the effectiveness of policies and strategies over time by performing iterative calculations. It also offers a dynamic framework to measure and manage offices over time and compare environmental impacts across territories. This has the potential to reshape the industry standards by promoting more sustainable directions. Despite the above mentioned enhancements, the research presents some limitations. A first constraint arises in the measurement of sustainability performance of in-use offices, as only the environmental dimension of sustainability is evaluated. Further improvements will consider to integrate impact sources to encompass social, economic, and governance impacts. A second limitation emerges in the comparison of results. The application on nine case study buildings prevent to establish a benchmarking analysis. Addressing this limitation will be a primary focus of future implementations. Finally, the introduction of digital technologies in the industry will enhance the application and effects of WIEFA, that has the potential to foster the technological innovation by acting as an overarching structure to collect, elaborate, report, and address more sustainable use of the built environment

THE MEMORY OF ANTIQUITY IN CHINA: THEORIES AND PRINCIPLES BETWEEN REWRITING AND PRESERVATION

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Tutor: Prof. Stefano Della Torre

The research aims to investigate the role of antiquity in Chinese culture to understand the role of the past in shaping Chinese cities, the past and present theories of heritage protection, and to detect their possible evolution.

Some key concepts, therefore, need to be first investigated and clarified to give an account of the peculiar development of Chinese cities and the specific relationship between the old and the new, such as the idea of antiquity, memory, the past, tradition, and finally preservation. Time is perceived as a circular concept, accepting the destiny of buildings to become ruins. The appreciation and the pursuit of material evidence also existed in Chinese culture. This gave the basis for the preservation of archaeological sites and monuments.

At the same time, the concept of “Time” was merged into space through the instrument of Capital City planning; the cultural meaning behind the urban structure is very rich, and even a smaller site is related to a greater urban design idea. This gives the basis for the protection of the morphological aspects of historical areas. Thus, a more comprehensive Chinese cultural position for conservation is proposed as a kind of “integrated preservation and

rewriting process”. This rewriting process would include both cultural continuity (the preservation of the forms and functions of the past in the present) and cultural modification (the projection of the present onto the past’s forms and functions). If modification needs to be included, how to intervene in the historic site appropriately? Could the Chinese context and current practices assume a concept of rewriting?

The research intends to verify what kind of nature has the memory in the Chinese city and in what specific form we can shape a tradition of modern architecture capable of retaining past urban features, protecting fabrics, and retaining traces while allowing a sustainable degree of development. Therefore, a continuous search for a dialogue between the past and the present is necessary to root a new kind of modernity into an awareness of our traditions. In this way of thinking, protecting historic areas should look at the uniqueness of each cultural context in in-depth research that includes getting to know the thing that needs to be protected better and coming up with a way to combine modern design with conservation measures.

From the theoretical aspect,

the dissertation deepens the comparison of critical contemporary keywords such as antiquity and authenticity in different Chinese cultural theories compared with the Western ones.

In Chapter 3, the research on urban conservation in China is studied in the international theoretical development context. It shows that the Chinese conservation movement also follows a similar development path with international trends. The key principle in the “Integrated Preservation and Rewriting Process” is still “authenticity”, meanwhile the understanding of “authenticity”, is also evolved gradually from a quite exclusive “material-based authenticity” to a “knowledge-based authenticity” after the 1990s when charters from the Asia Pacific region were proposed.

Then, digging from the traditional cultural position, a “living experience-oriented” authenticity is proposed, with all respect to the preservation theory. It intended to include also more interaction between the present life and the memory of the past. This implies a living past hounded with the present, not one exotically different or obsolete.

The inclusion of urban form

research in urban conservation is also another trend in China, as we can see clearly after the study of laws and regulations. The inclusion of urban morphological research in the “Integrated Preservation and Rewriting Process” will bring a clearer research route.

Such keywords are examined in the state of the art by both reviewing the theoretical background and several cases in China, as well as analysing conservation plans and the frequently occurring problems derived from the simplification of their analytical tools, the lack of in-depth surveys, the disregard for material aspects of culture, and the lack of proper tools for balancing the contradiction between protection and development.

How are these basic principles, such as authenticity, minimal intervention, integrity, and “not alternating the original state” applied in the operational phase when architects are doing projects? Chapter 4 is about new architectural design in historic tissues. Those architectural practices mainly reflect several points that concern the protection of historic urban landscapes.

- 1) The first is about respect for the historic layout. The historical plan is the environment of monuments, so their morphological features should be respected.
- 2) The second point is about traditional construction knowledge. and how to make minimal interventions based on a structural reason.
- 3) The third is about symbolic meaning; some archaeological

shelters are designed in a specific style by early-generation architects. The imitation of traditional building elements reminds us of works by Paolo Marconi. On the other hand, others are trying to make urban interpretations by using modern language. In this way, modern projects would be encapsulated in tradition and realized with awareness of tradition.

Through a deep analysis of selected case studies in China, the research intends to clarify the issues in the concrete reality of a given context and look for meaningful comparisons with Italian cases.

In Chapter 5, the comparison of the three groups of Chinese architects demonstrates that there are various methods of architectural practice in the historical environment of China. The new design’s stylish reconstruction lacks the innovation of the original text. It shows a misunderstanding of the Chinese cultural position, which is more innovative than just copying and imitating. Re-coding without solid morphological study, on the other hand, lacks awareness of preserving the existing text. Instead of reaching architectural language autonomy, the prototype research in China has not yet developed a new language; it is still influenced by the original style and image. Through a comparison of Chinese and Italian masters who have contributed to the protection of historical cities, it is obvious that, although they belong to different cultural bodies, the two countries

have many similar viewpoints in the research of historical cities. As the research made by Pane, Feng, and Samonà indicated, cities as “organic organisms” have their “intrinsic formal unity”. The new intervention should “join the past” of the city but build “the new” to keep the continuity between the past and the present. Based on a deep survey of existing sites or texts, rewriting should be a process to enhance the site’s morphological features and cultural meaning while the existing site is well preserved. Only by keeping the balance between preservation and rewriting could architects build a prosperous future rooted in the past and present.

Finally, the research proposes principles for urban and architectural design in the historical texture (1- Respect the context. 2- Objectivity for Deciphering the site. 3-The integrity of all the historical layers. 4-Recognizability of the Rewritten elements), as well as a methodology of cooperation between experts from different disciplines, envisioning a combined approach of conservation and enhancement and tracing some meaningful guidelines for historical and morphological analysis.

DIGITALIZATION OF THE CONSTRUCTION SECTOR (AEC) - THE CASE OF SMALL AND MEDIUM-SIZED CONTRACTORS

Hooman Sadeh - Supervisor: Prof. Alberto Pavan

Tutor: Prof. Andrea Tartaglia

The digitalization of the construction sector is a new trend that has gained interest from both industry and academia. There have been numerous efforts to evaluate the factors that hinder the digital transformation of construction contractors, particularly small and medium-sized enterprises (SMEs). Given that digitalization and its prolonged processes pose significant challenges for SMEs in the construction industry, it has become an area of concern for academic researchers who aim to find solutions or formulate theories to enable technological innovation with minimum restrictive drawbacks for the industry.

To achieve this research goal, relevant hypotheses were constructed to analyze the efficiency of information sharing, innovation capabilities, and the feasibility of Building Information Modeling (BIM) implementation for small and medium-sized contractors. Relevant information was collected through a structured online questionnaire, and 70 responses were analyzed. Based on the analysis results, it was observed that additional information was necessary to

evaluate the overall digitalization of the industry and to further develop the formulation as a theory of digitalization. As a result, a survey research design and Questionnaire 2 were created as proper research methodology, which was distributed online among the target population of architects, engineers, designers, owners, contractors, subcontractors, and others. Out of all the received responses, 55 cases were deemed appropriate. Several inferential statistical techniques were used to analyze the collected data, including factor analysis, path analysis, multiple regression analysis, and analysis of variance. The results showed that information-sharing efficiency was at a medium level among SMEs, while innovation capabilities and BIM usage were minimal. Additionally, strategic partnerships among firms had the highest negative impact on BIM feasibility, while information-sharing efficiency had the highest positive effect. A certain number of hypothetically most important factors were selected among tens of impacting variables such as construction site, human resources in terms of specialty, marketing, data management,

planning, firm size, firm culture toward digitalization, partnership, productivity, and information sharing. The construction firms had an overall intermediate digitalization level, with planning having the least score and data management having the highest score among those digital dimensions. Furthermore, the correlation among all dimensions was found to be significant. Moreover, the association of firms' specialty and size was tested with respect to digitalization score, revealing that micro and large firms differ in terms of digitalization levels, and small and medium-sized firms also differ in that regard. Additionally, it was observed that there was no statistically significant relationship between firms' specialty and firms' degrees of digitalization. Accordingly, all firms were taxonomized into two typical conventional and oven-guard construction companies toward a fitting and significant theory of digitalization. The findings show that the owners of the conventional firms have an illusion of digitalization as a disconcerting process in terms of high cost, loss of earnings, and loss of authority in all aspects of firms'

activities and productivities.

To address such an illusion, a practical resolution was presented by means of the above theory through which conventional firms have some ultimate options toward either reconsidering digitalization as a suitable alteration and transformation or expect firm breakdown in an unequal market competition.

Lastly, a digital data sharing platform was developed to assist the needs of SMEs towards information-sharing, where the information flows were redefined, providing a suitable environment for those firms lacking advanced technological capabilities.

EXPERIMENTAL TESTING METHODS FOR THE PERFORMANCE CONTROL OF STANDING SEAM ROOFING SYSTEMS FOR LARGE-ROOF APPLICATIONS AND PHOTOVOLTAIC SYSTEMS INTEGRATION

Giacomo Scrinzi – Supervisor: Prof. Angelo Lucchini

Tutor: Prof. Marco Vincenzo Valente

The use of metal systems for roofing has become more and more common over the years for buildings of any kind and size. Several different technologies are nowadays commonly used, among which the most, referred to as standing seam metal sheet, are made of panels with the same length of the slope, in various geometries and shapes, highly versatile to adapt to different cases and scopes of use. Such systems are also suitable to support various devices – the most common case is represented by photovoltaic modules, but they can potentially be other lightweight structures to be integrated on the surface – connected to the metal panels by special anchor clamps. The in-service behaviour of such systems in standard conditions is generally investigated by manufacturers in terms of load bearing capacity, wind uplift resistance and water tightness using methods widely discussed in the literature. In order to achieve the full performance control, special configurations and large geometries must be considered. Particularly, thermal expansion behaviour and friction issues together with wind loads transferred to fixed-point clips

in the case of roof-attached tilted PV strings are capable to significantly affect the service life expectancy of roofing systems and their components. In this respect, several experimental testing methods, both on-site and in laboratory, are proposed to assess system's performance. In particular, thermal expansion behaviour is investigated through a series of monitoring campaigns on a reference case-study that highlight the influence of clips and anchor clamps on the roof behaviour (Fig. 1). Moreover, wind loads acting on roof-attached tilted PV string, and therefore transferred to fixed-point clips, are assessed through a set of boundary layer wind tunnel tests on a representative scale model (Fig. 2). Eventually, a full set of mechanical tests on system specimen and components is proposed for each system characterisation and commissioning purposes (Fig. 3). The testing methodologies are suitable to be extended to other similar products. Design loads, monitoring, and testing protocols are meant to be a reference for systems manufacturers, in order to further develop their products and materials characteristics

to easily comply with different projects requirements, and designers, to better choose and specify the systems to be used.



Fig. 1 - Experimental setup to monitor standing seam panels' longitudinal thermal expansion using wire displacement transducers and surface temperature sensor.

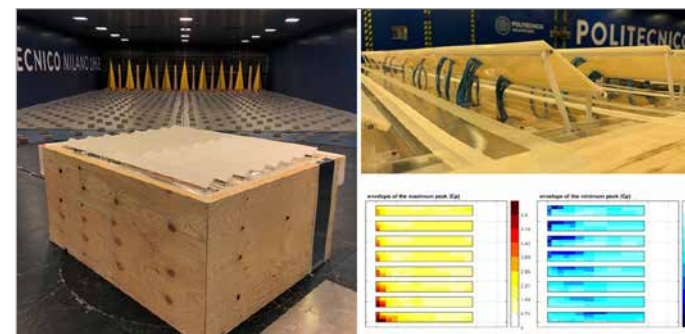


Fig. 2 - Scaled model of a flat-roof building provided with roof-top PV strings tested in Politecnico di Milano's boundary layer wind tunnel and qualitative positive/negative envelope of pressure coefficients distribution over the strings.

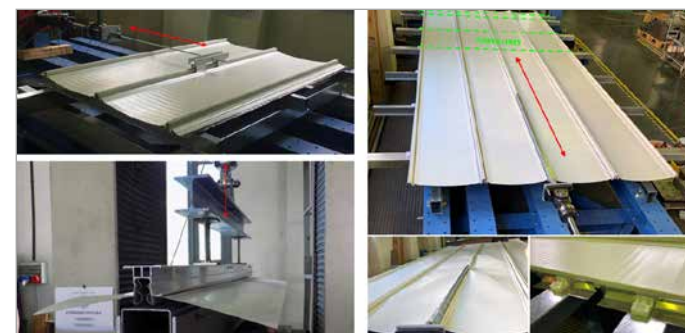


Fig. 3 - Mechanical testing setups developed to assess standing seam roofing systems' performance: anchor clamps shear stress tests (top-left); uplift tests (bottom-left); slope-axial static loading tests (top-right) and ways of failure (bottom-right).

A DIGITAL TWIN-ENABLED BUILDING LOGBOOKS IMPLEMENTATION. A FRAMEWORK TO ENHANCE DATA ACCESS AND KNOWLEDGE EXTRACTION SUPPORTING INFORMATION MANAGEMENT IN THE BUILT ENVIRONMENT

Martina Signorini – Supervisor: Prof. Bruno Daniotti

Co-Supervisor: Prof. Cecilia Maria Bolognesi – Tutor: Prof. Fulvio Re Cecconi

The research has been carried on within the context of Architecture, Engineering, Construction and Operation (AECO) sector's digital uptake and building management. According to the background analysis, the building operation and maintenance (O&M) are instrumental to maintaining buildings' regular functionality, ensuring the level of performance, efficiency and service life, and minimising unplanned failures in the connected asset (e.g. HVAC shutdown due to a lack of proper maintenance to the equipment). The investigation of the International Energy Agency analysis shows the role of AECO sector in energy consumption and related CO2 emissions. According to the analysis, building operation accounts for 30% of worldwide energy consumption and 27% of total energy AECO sector emissions. Therefore, this highlights the need for effective building management, which results in developing strategies for the O&M phase. Indeed, how a building is operated and maintained influences building performance and as a consequence, it represents a challenge to environmental sustainability. When managing a building, other issues such as a great amount and variety of

data occur. As a result, a lot of information needs to be managed. Building operations data is mostly not updated, incomplete, and in low interoperable formats. This causes a lack of knowledge about building systems and components' performance, impacting the effective development of operation, maintenance, and refurbishment strategies. Despite the existence of this large amount of data in buildings, there are few solutions to efficiently manage and correlate them, and this point has seldom been addressed. Ensuring the connection between data collected through various systems within a building and with the surrounding environment is crucial. Focusing on these issues, the research explores digital technologies and connected tools to help enhance information management. Especially, it concentrates primarily on the in-use phase of the building lifecycle, the moment when a greater variety of information enriches the building. From the use of Building Information Modelling (BIM), AECO industry started to adopt technological strategies to organise and digitalise information about construction works, and consequently, data embedded into a 3D model can be shared more

easily. By using a digital approach, information exchange (including communication and sharing) can be enhanced. Moreover, the industry's greater adoption of digital technology improves the condition and performance of the building. For example, sensors allow to monitor temperature, humidity, and occupancy to guarantee that the right levels are maintained for interior comfort levels while preventing energy waste. Thanks to Internet of Things, the advent of Digital Twin (DT) makes its way into the construction sector allowing for some benefits, including the ability to monitor the as-is conditions, detect anomalies before they occur, make diagnosis, and give an added value compared to BIM. The State of the Art makes it evident that the Digital Twin is still in its infancy and a standard definition is still missing. It is developed by different research groups and companies most of the time as an interactive platform that displays the real-time performance of the building. It is generally represented as constituted by several technologies, as the literature indicates, through which it is possible to fulfil specific needs. Making data-driven decisions in operations, engineering construction, and architecture is

now feasible thanks to the Digital Twin concept and makes Digital Twin a key enabling technology. However, in addition to not having a standard definition, within the literature that shows case study developments, there is a lack of description of how the exchange of different data takes place. The fundamental definitions, data dictionaries, and relations that support DT-based applications are rarely explicitly stated, and the information and process requirements for data sharing in Digital Twin implementations are hardly addressed. Furthermore, the building industry is perceived as being fragmented since information is generated along the whole building lifecycle. This makes the process of gathering, storing, exchanging, and updating information challenging. By providing a space for the industry to store and share building data, the establishment of a common data repository would solve the problem. In this regard, the Digital Building Logbook results in a collector of building-related information. The study of literature review helped in outlining the key indicators required by logbook proposals and consequently, to define which are the main indicators that should be included in a Digital Building Logbook. None of the examined logbooks propose strategies for automatically gathering, storing, and disseminating data. Given the aforementioned scenario, this study focuses on two "data-centric" technologies: Digital Twin and Digital Building Logbook. On one side a technology that helps in data-driven decisions

and on the other a tool that serves the purpose of gathering building-related data. The first is an instrument that addresses specific requirements such as building monitoring that enables predictive maintenance analysis, which in turn improves the efficiency of decisions; the second provides more transparent information about the building features and condition. Finally, the research presents a Digital Twin-enabled Digital Building Logbook implementation. It outlines the methodology adopted to develop a framework as flexible as possible to accommodate different scenarios and address various service requirements with the main objective of enhancing data access and information extraction for Digital Twin applications, thereby contributing to better building management and knowledge. Because of the interoperability issue and the complexity of the built environment, different ontologies have been studied relying on a federation approach to connect several contexts. Therefore, the Digital Twin implemented is developed by examining the data modelling part and using a federation approach, exploiting available data within their domain, while maintaining the capabilities of each selected data model. By concentrating on the in-use phase of the building and looking at buildings subjected to interventions, the developed Digital Twin-based data model, which has as a fundamental element the Digital Building Logbook, can be used for improved maintenance

decision-making as support for Facility Managers. It offers a multidisciplinary knowledge connecting several areas such as space, assets, sensing systems, and maintenance. The presented approach has been tested on a case study to verify the effectiveness of the Digital Building Logbook implementation, as a collector of building models, systems, and maintenance-related data and as a gateway space to connect disparate domains. The test specifically focused on the in-use phase of the building, looking at how the decision-making process could be managed efficiently with available data – without the creation of others –, and support the building and information management. The framework enables the collection of diverse building-related data, the generation of interdisciplinary knowledge, and more informed decisions during the in-use phase when the built asset is or has to be the object of interventions. The outcomes of the framework development contribute to improving building management towards better data access and knowledge extraction for Digital Twin applications in the Facilities Management domain, and solving the interoperability issue when data arise from different domains.

RESILIENCE MANAGEMENT OF BUILT HERITAGE STRUCTURES: BRIDGES

Zehra Irem Turksezer Sagir – Supervisor: Prof. Maria Giuseppina Limongelli

Co-Supervisor: Prof. Michael Havbro Nielsen – Tutor: Prof. Andrea Antonio Caragliu

Several natural and anthropogenic hazards in the last decades caused cascading failures across systems. The Christchurch earthquake in 2011 triggered a rockfall on electric utilities, which caused a loss of communication and provoked a delay in emergency services. Another example is the failure of the Polcevera Bridge in Italy which started as the collapse of a bridge. In a short time, severe economic losses were experienced in trade in the region.

In complex systems such as transportation, electric, or communication networks, such failures may be associated with catastrophic consequences in terms of service provision losses. Substantial research has been undertaken in order to identify how the risks associated with service disturbances related to such extreme events may be managed optimally. To this end, the concept of resilience has been introduced to enhance decisions on the management of systems and to minimize the risk associated with service disturbances over systems' service lives. Very substantial efforts are presently being invested into research on the modeling and assessment of the resilience of socio-technical systems.

Resilience includes the short-term

ability to quickly recover from a disturbance event, which can mitigate the impact of the disruption, and the long-term capacity generation for efficient reorganization and recovery after disturbance events, which is crucial for adaptation. This capacity must be valid for the lifetime management of the system. The general body of knowledge on the various system characteristics affecting resilience is increasing, and so is the capability to model and analyze systems.

Despite the vast volume of research on the resilience of infrastructures, so far, only very little attention has been directed on how to manage the resilience of built heritage structures, i.e., structures providing services beyond those which are directly related to structural functionality, through their cultural, historic, and social values. Furthermore, after events of disturbances such as major earthquakes or floods, the prompt recovery of the social and cultural functions of the built heritage structures may leverage the resilience of the communities by maintaining societal cohesion around the shared historical legacy represented by the structures themselves. This cultural element of social capacity adds

a new dimension to resilience management compared to ordinary structures and gives a different nuance to the concept of the resilience of built heritage structures, compared to ordinary structures. On one side, built heritage structures may be particularly vulnerable to natural hazards due to the accumulated effects of degradation during their lifetime, and on the other side, recovery and maintenance works can be more difficult and expensive due to the several constraints related to the historic value of the asset that limits the range of decision alternatives. In the literature, there are some attempts to define the resilience of built heritage structures; however, a systematic approach to their resilient management is still lacking. This Ph.D. thesis aims to contribute to filling this gap by proposing a decision analysis tool

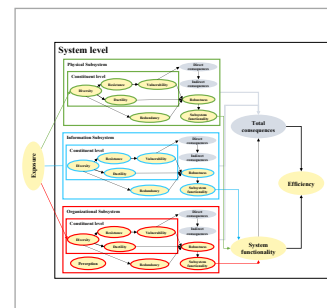


Fig. 1

based on the identification and the interplay of resilience indicators. The latter conveys information about the system characteristics which contribute to the resilience of the built heritage system, thereby supporting the ranking of decision alternatives for managing the system resilience.

The proposed approach is illustrated through two case studies addressing two built heritage systems: an ordinary bridge (i.e., Borgoforte Bridge in Italy) subject to scour due to flash flood events and a deteriorating built heritage bridge (i.e., Uzunkopru Bridge in Turkey). To this end, the system is modeled using Bayesian Probabilistic Nets (BPN), whereby the flow of entropy between systems states and indicators and, not least, the hierarchical dependencies between them become explicit. The two case studies include

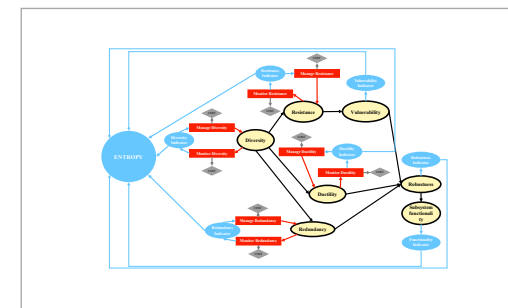


Fig. 2

a number of different decision alternatives on how to manage the system characteristics. The influence of diverse decision alternatives on the system performance of two different bridges is investigated and compared.

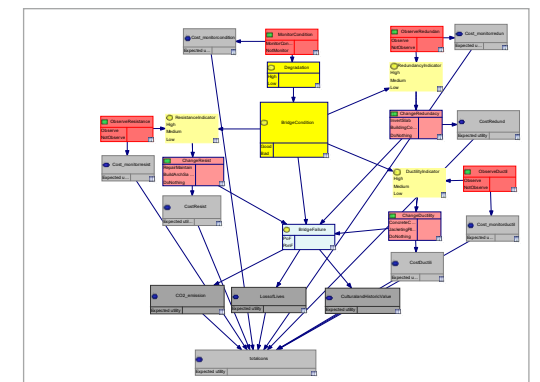


Fig. 3

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.

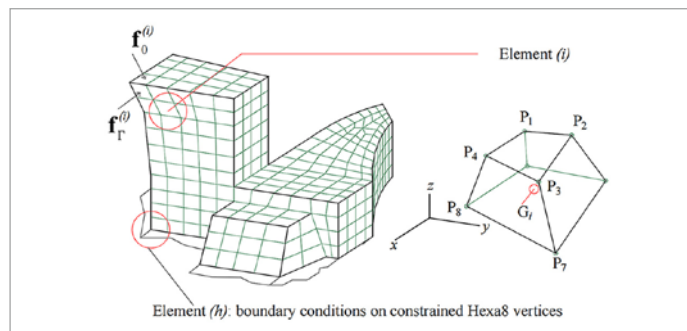


Fig. 1 - Generic DEM discretization of a structure with 3D Hexa8 rigid elements for the pagoda.

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.

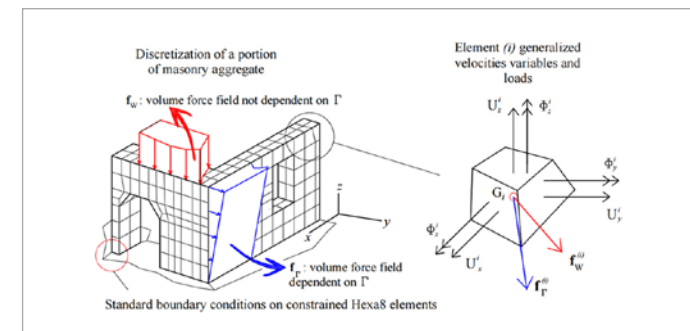


Fig. 2 - Generic DEM discretization of a structure with 3D Hexa8 rigid elements for aggregates.

SMART CITY APPROACH FOR NEIGHBORHOOD SOCIAL HOUSING

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Co-Supervisors: Prof. Giuliano Dall'O', Prof. Giancarlo Paganin

Tutor: Prof. Monica Lavagna

Given the rapid trend of technological advancement, the concept of a smart sustainable city has emerged to offer smart solutions to the efforts and activities designated to ensure ESG and sustainability achievement. Although several rating systems have been proposed to assess the performance of different projects at different scales, there is still no comprehensive framework to support and measure the level of smartness in the neighborhood building stock, with specific reference to the social housing context, in which all measures and policies can be effectively realized without any managerial challenges, being in charge by just one unique entity.

To bridge this gap, this research project aims to propose an assessment framework to measure the level of smartness in the neighborhood. This framework is developed using a mixed method approach that encompasses three qualitative and quantitative phases, including, i) creating the comprehensive taxonomy of smartness KPIs; ii) formulating determinant indexes to assign

weights to KPIs; iii) using an output-based measurement method to control and measure the level of smartness within a set of checklists of required technologies, at five levels of smartness, for each single KPI. The novelty of this thesis is also reflected in these three phases, in which, a comprehensive list of smart solutions that can be applied in the neighborhood context is collected; a new set of indexes that reflects the main goals of smartening is developed to assign weights to the smartness KPIs; and a new checklist of smart technologies that are required to deliver the expected smart services are solidified. In the end, the applicability of the final framework is tested on a case study, through three scenarios that reflect the current status of the neighborhood, the needs of residents, and the priorities of the community's managers.

This framework empowers policymakers, engineers, and community managers to clarify the objective level of potential smartness through different elements of the neighborhood. Moreover, this pioneering framework can be leveraged

to quantitatively evaluate the smartness of neighborhoods and distinguish the critical difference between the definition of smart and smarter neighborhood building stocks. As this research is committed to the social housing context, the last section evaluates the applicability of smartness KPIs in the context of Italy, by using qualitative methods, such as a focus group approach and SWOT analysis.

Keywords: smart neighborhood, social housing, smartening KPIs, building system automation, sustainability, ESG