VOL. 9, NO. 2 (2023)

KNOWLEDGE AND SCIENCE ON BUILDING TECHNOLOGIES. MEANS, INSTRUMENTS AND MODELS

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
DOI: 10.30682/tema0902

Cover illustration: Stereotomic helical staircase in Villa D'Este, Tivoli, Italy.

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e-ISSN 2421-4574
ISBN online 979-12-5477-367-3
DOI: 10.30682/tema0902
Vol. 9, No. 2 (2023)
Year 2023 (Issues per year: 2)

Publisher:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l'Edilizia
c/o DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica - Politecnico di Bari
Via Edoardo Orabona, 4
70125 Bari - Italy
Phone: +39 080 5963564
E-mail: info@artecweb.org - tema@artecweb.org

Publisher Partner:
Fondazione Bologna University Press
Via Saragozza 10
40123 Bologna - Italy
Phone: +39 051 232882
www.buponline.com

TEMA: Technologies Engineering Materials Architecture
Vol. 9, No. 2 (2023)
e-ISSN 2421-4574

EDITORIAL

KNOWLEDGE AND SCIENCE ON BUILDING TECHNOLOGIES MEANS, INSTRUMENTS AND MODELS

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Technologies
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e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

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DOI: 10.30682/tema090013

This contribution has been peer-reviewed.

The increasing influence wielded by *Technique* in defining the frameworks of contemporary social and productive life urges a revision, or perhaps better, an adaptation, in the cultural and educational maturity of the various professionals working in the field of architectural design and building construction, both on the scientific research and professional practice fronts.

"Making" was"art" in that pre-technological condition in which the maker-craftsman was mirrored in the work that reproduced its specific "quality" while "making", in the technologically evolved stage, has become "production." In this context, the shift from "qualitative" to "quantitative" properties is evidenced by dissecting the "making" into partial tasks that the technical structure reconnects until they are combined into the final product. Thus, the progressive slide from the condition of artist-craftsman to that of technician-specialist is revealed.

Thus, the contemporary condition of *Technique* is embedded in this domain in its correlation with the various human activities. This theme also highlights the need to open a new space for reflections based on a different theoretical and cognitive approach to the topic itself.

In fact, the traditional concept of *Technique* as a tool is nowadays associated with the notion of an entity provided with decision-making significance. The transition from the dimension of a medium, thus lacking the ability to choose, to that of goal, with its well-defined evaluative property, is seen as the epilogue of the technologically evolved condition. This latter condition, the contemporary one, is now far away from the instances that guided, until the second half of the 20th century, the entry of mechanized processes into the dynamics of production.

Above all, the endemic influence provided by the Information Technology revolution of the 21st century has progressively broken down the traditional boundaries on which the disciplinary patterns of knowledge had been consolidated, both as tools and methods of research but also as predictive potentialities for models based on the processing of large amounts of data.

Recent developments in the application of Artificial Intelligence are the most explicit expression of the potential of this contemporary evolved condition of *Technique*, which requires a constant confrontation with the ethical dimension of the heterogenesis of goals, paralleling what happened in the last twenty years in the field of Biotechnology.

COMPRESSED-AIR FOUNDATIONS IN ITALY: HBIM-AIDED STUDY OF THE TIBER RIVER EMBANKMENTS (1876-1900)

TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

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DOI: 10.30682/tema090005
This contribution has been peer-reviewed.

Abstract

The paper focuses on using compressed-air foundations technology in Italy in the last three decades of the 19th century. The case study of the Tiber River embankments in Rome (1876-1900) reveals the significant application of the technique to construct retaining walls, exploiting iron caissons as excavation chambers. Furthermore, the case study discloses the transfer of knowledge in Italy and the innovative contribution of Italian construction companies and engineers to the international development of the technique. In this framework, applying the so-called 'demountable caissons' marked a significant step in perfecting the attempts conducted since the late 1850s to recover the iron used for constructing the caissons for future use. The study exploits the original design documents of the foundations of the Tiber retaining wall, conserved in the Archive of the Genio Civile of Rome, and an HBIM, functioning as an investigation tool and digital archive for educational purposes.

Keywords

Construction History, HBIM, Pneumatic foundations, Iron construction, Archival research.

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1. INTRODUCTION

In the 19th century, the rapid development of the railway network and the improvement of urban river infrastructures brought widespread progress in foundation techniques. Using air pressure has been considered an efficient method for excavation below the groundwater level.

In the backward Italian building industry, the use of compressed air for foundations was introduced in the 1860s by French and English construction companies and further developed in the 1870s by Italian engineers and local contractors [1].

The national evolutions of air pressure-based foundation methods in the second half of the 19th century are still poorly addressed in the construction history literature [2, 3]. The topic can be significantly improved by analyzing the work site micro-histories via literature of the time and archival research. Furthermore, considering the complexity of the technique in terms of both the construction process and building details of the excavation devices, the use of digital tools for knowledge and graphic representation, such as HBIM, can support the investigations, providing a powered visual framework [4, 5].

Under these premises, the scope of the present paper is an insight into the application of the technology in Italy – via the case study of the design and construction of the Tiber River embankments (1876-1900) – combining archival surveys and philological HBIM approach, based on historical documents [6, 7]. Archival surveys were mainly conducted on the design documentation produced by the *Ufficio Speciale per la Sistemazione del Tevere* – "Special Office for the Tiber's settlement" –, today kept in the Archive of the Genio Civile of Rome [8]. The Special Office was the institution charged with the execution design and the direction of works of the river embankments since 1876: the archive, thus, collected execution drawings, technical reports, work site agendas, and construction site pictures, providing crucial data for insight on the excavation compressed air processes. The case study was framed in the coeval experimentation at the national and international level via the analysis of the technical literature of the time – manuals and journal papers – addressing the subject. The HBIM was first used as an investigation tool to acquire a robust knowledge of the construction details and the building processes and, thus, developed in terms of a digital archive for educational purposes [4–7].

The contribution presents the following contents: a general overview of the development of the use of air pressure for excavation works in the 19th is provided in Paragraph 2, retracing the introduction of the *pneumatic foundations* in Italy; in Paragraph 3, the historical analysis of the case study is presented, while the HBIM process and its outcomes are presented in Paragraph 4; conclusions, concerning knowledge increasing and methodological consideration, are given in Paragraph 5.

2. PIONEERING ON THE *VACUUM* AND *PLENUM* METHODS (1840-1850)

In addition to daring methods known from as far back as the 13th century [9], the first technological solution was the *diving bell*, comprised of a small chamber, open at the bottom and isolated from the water by overpressure.

The English engineer John Smeaton (1724-1792) was the first to use the diving bell for excavations below the groundwater level. Dry digging was only possible for a short time before oxygen was depleted, whereas the bell could reach a limited depth [9].

Between the 1840s and the 1850s, French and English engineers would excavate below groundwater level for mining and digging deep bridge piers' foundations [3]. Two alternative methods were developed: the so-called *vacuum* method based on the depressurization process for sinking hollow piles [10], and the so-called *plenum* method based on the overpressure of an excavation chamber [11]. Initially applied to mining shafts, the latter affirmed compressed-air caisson technology for excavating foundations.

In 1841, the French mining engineer Jacques Triger (1801-1867) submitted to the *Académie des Sciences* an account of using compressed air to successfully sink a colliery shaft through the alluvial deposits of the Loire [11]. In 1848, Triger proposed extending the use of the system, at first for shaft sinking and particularly for the foundations of bridge piers [3].

In the meantime, the experiments with excavation techniques based on air pressure advanced through an invention by the English physicist Laurence Holker Potts (1789-1850). In 1843, Potts filed a patent listing "certain improvements in the construction of piers, embankments, breakwaters, and other similar structures" [10]. The invention comprised the sinking of iron hollow piles, open at the lower end and closed at the top by a cap. Reversing the Triger process, a partial *vacuum* was formed within the tube by means of air pumps. Shingle and sand would flow upwards through the pile due to atmospheric pressure, and the rush of water from below would break up the soil and undermine the lower edges of the stack. Gravity enabled the pile to descend, assisted by the pressure of the air on its closed end, and when it was filled, the contents would be discharged by a pump. As Potts wrote in 1848, «In practice, a very partial *vacuum* is required; the descent of the tube is simultaneous with the commencement of the extraction of the air» [8].

That system soon gained the backing of the great engineers and companies of the time and was used for railway bridges (Tab. 1), such as the Black Potts Bridge over the Thames River (1849) and the Britannia Bridge (1849).

In 1850, Potts' pneumatic piles were adopted for the foundations of a bridge across the River Medway at

Year	Bridge Name	System	Engineer
1849	Britannia bridge	vacuum piles	Stephenson
1849	Conwy bridge	vacuum piles	Stephenson
1849	Black Potts bridge	vacuum piles	Brunel
1849	Benha bridge	vacuum piles	Stephenson
1849	Neuville-sur-Sarthe bridge	vacuum piles	Fox
1850	Rochester bridge	water inflow	Huges

Tab. 1. *Main bridges with vacuum piles based on Potts' system (1849-50).*

Year	Bridge Name	System	Engineer
1850	Rochester bridge	pneumatic piles	Hughes
1855	Torino-Novara bridges	pneumatic piles	Murray
1859	Royal Albert bridge, Saltash	pneumatic piles	Brunel
1859	Kowno bridge	pneumatic piles	Cézanne
1859	Khel bridge	pneumatic caissons	Fleur Saint-Denis
1861	Argenteuil bridge	pneumatic piles	Castor
1863	Piacenza bridge	pneumatic caissons	Biadego
1864	Mezzanacorti bridge	pneumatic caissons	Cottrau

Tab. 2. *Main bridges with compressed air foundations based on Trigers' system (1850-65).*

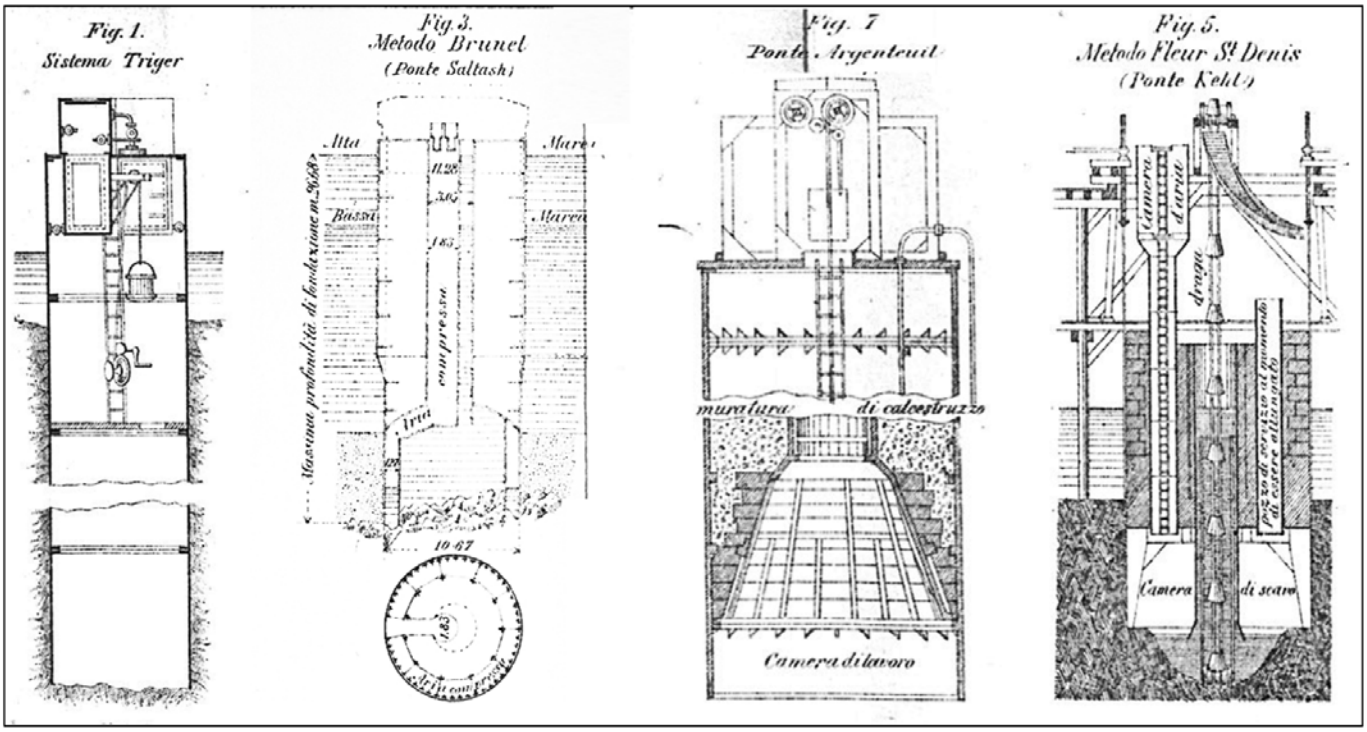


Fig. 1. *Triger's plenum system: main modifications of the excavation chamber (1850-70), reported in [10].*

Rochester, Kent, which the Fox & Henderson Company managed. The method proved to be a failure because it was found to be impossible to sink cylinders through the compact mass of Kentish ragstone, which encumbered the riverbed [3]. The contractor's engineer, John D'Urban Hughes (1807-1874), reversed the process to be very similar to that of Triger by giving each pile the characteristic of an overpressured excavation chamber. The Triger method, perfected by Hughes [12], was soon adopted as the standard for excavating the foundations of deep bridge piers (Tab. 2), while that of Potts, not suitable for excavation in consistent soils, was progressively abandoned [3]. In the 1850s, the Triger method was perfected through subsequent modifications concerning mainly the enlargement of the excavation chamber, using iron caissons: iron caissons were first used in 1859 by the engineer Fleur Saint Denis and, thus, became the standard solution in the 1860s and 1870s [13].

2.1. THE INTRODUCTION OF COMPRESSED AIR METHODS IN ITALY

In Italy, the technique was introduced by English and French contractors operating in the country since the 1850s; the first national treatise on the topic was published late, reporting on the knowledge transfer process to the local engineers and contractors [1, 3, 14–16].

The first applications were developed for railway viaducts in the early 1850s. These included the foundation of four railway bridges (1848-1853) – over the Stura, Orco, Malone, and Agogna Rivers – between Turin and Novara, managed by the English contractor Fox & Henderson Company [3]. In the early 1860s, the technique was first applied with the contribution of Italian engineers: the construction of the pneumatic foundation of the viaduct over the Po River in Piacenza was directed by the Italian engineer Giovanni Battista Biadego (1850-1925), exploiting the design of wrought-iron caissons [1]. In the following years, the *Impresa Industriale Italiana Costruzioni Metalliche* (IIICM), directed by the engineer Alfredo Cottrau (1839-1898), led the national development of compressed air foundations, becoming the national dealer of the technique [3].

3. THE TIBER RIVER EMBANKMENTS (1876-1900)

In the last three decades of the 19th century, the urban path of the Tiber River in Rome was channelized with new embankment structures featuring high retaining walls [17].

Since the very first work sites in the late 1870s, the ordinary excavation methods below groundwater level were considered unsuitable to reach the foundation depth required for the stability of the structures: the use of compressed air processes gradually established itself as the standard solution.

3.1. EXPERIMENTATION OF THE TECHNIQUE FOR DEEP FOUNDATIONS OF BRIDGES

The very first application of the system on the Tiber River was dated 1864: compressed air was used for the foundations of the two cylindric bridge piers in the riverbed of the railway bridge on the Rome-Civitavecchia line; works were led by foreign construction companies under the direction of the Italian engineer Romolo Burri [18].

In 1877, a system of tubular piers was applied for the foundation in the riverbed for the pedestrian Ripetta bridge, involving, for the first time, a local contractor: the Italian construction firm IIICM.

On 25 September 1876, the IIICM presented a memorandum, signed by Cottrau, that illustrated the advantages of an iron structure as an alternative to the wooden truss bridge project already approved by the local authorities [19]. The proposed solution guaranteed a smaller footprint in the riverbed and improved the structure's resistance against the impact of the river's flow. The iron truss bridge, with a total length of 94 m, presented four spans, three of which were 27 m long and 8 m wide. The two main girders, also to serve as parapets, rested on coupled cylindrical piers with an average height of 15-16 m and a diameter of 1.80 m. When proposing the iron structure, IIICM suggested using compressed air tubular foundations for the piers in the riverbed [19]. The tubular foundation system consisted of cylindrical piers functioning like excavation chambers: piers were formed by piling wrought-iron rings with a wall thickness of 8 mm; once sunk to the specified depth, they were filled by

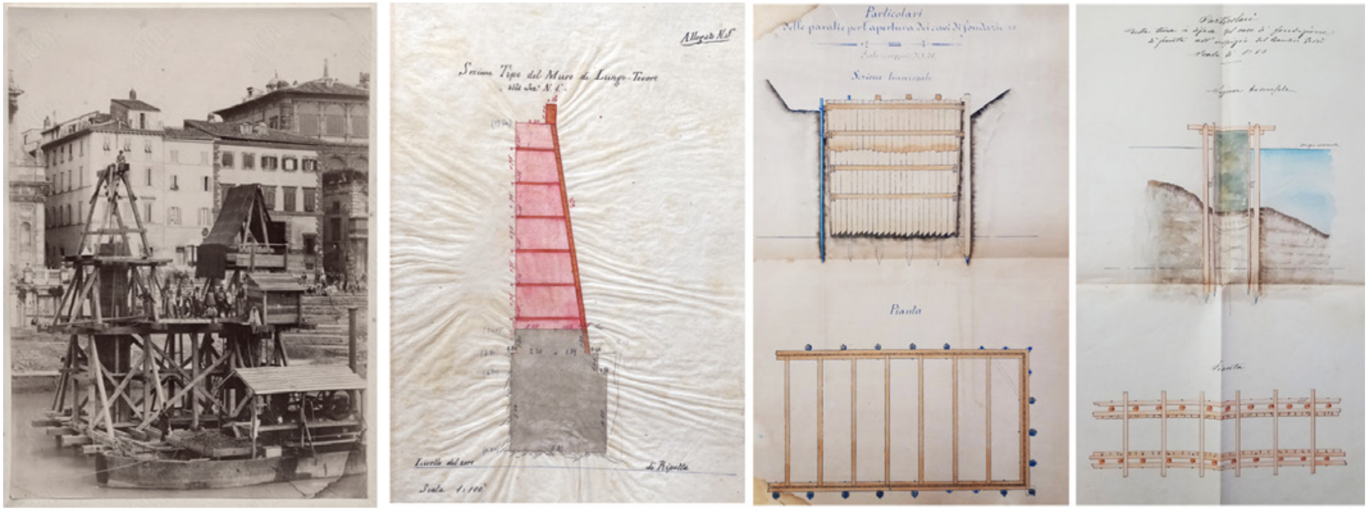


Fig. 2. *The compressed air tubular piles of the Ripetta bridge foundations: picture of the sinking of the tubular piles [14]; Special Office of the Tiber's settlement, execution drawing of the retaining wall and traditional excavation device for excavation below groundwater level, 1876 (courtesy of Rome State Archive, USTRA collection).*

a concrete cast. A wooden castle equipped with winches was designed to sink the piles (Fig. 2).

3.2. THE RETAINING WALLS FOUNDATIONS: COMPRESSED AIR CAISSONS

The design of retaining walls featured sub-vertical masonry structures and concrete foundation blocks (Fig. 2). The construction site started in 1876. Conventional excavation methods below groundwater level – wooden cofferdam (Fig. 2) – didn't allow to reach the design foundation depth, 6-9 m below the low water level, affecting the planned works in costs and times.

In 1878, the engineers of the Special Office considered the conventional excavation processes unsuitable, suggesting the application of compressed air methods. In particular, the use of pneumatic iron caissons, as excavation chambers, was proposed for the foundations of the retaining walls, in the Regola lot of land, assigned to the Campos construction firm [20]. The proposal relied on subcontracting the construction of the wrought iron caissons to IIICM, which had already been entrusted with the Ripetta bridge [20].

The technology was firstly applied to the foundations of a 200 m long wall section (Fig. 3), with four rectangular masonry piers (6x6.50 m in plan), exploiting wrought-iron caissons with a constant depth of 6.60 m from the river level. The caissons were 3 m in height and featured the same plan dimensions as the piers. Each caisson, made of a wrought iron sheet joined by a flat

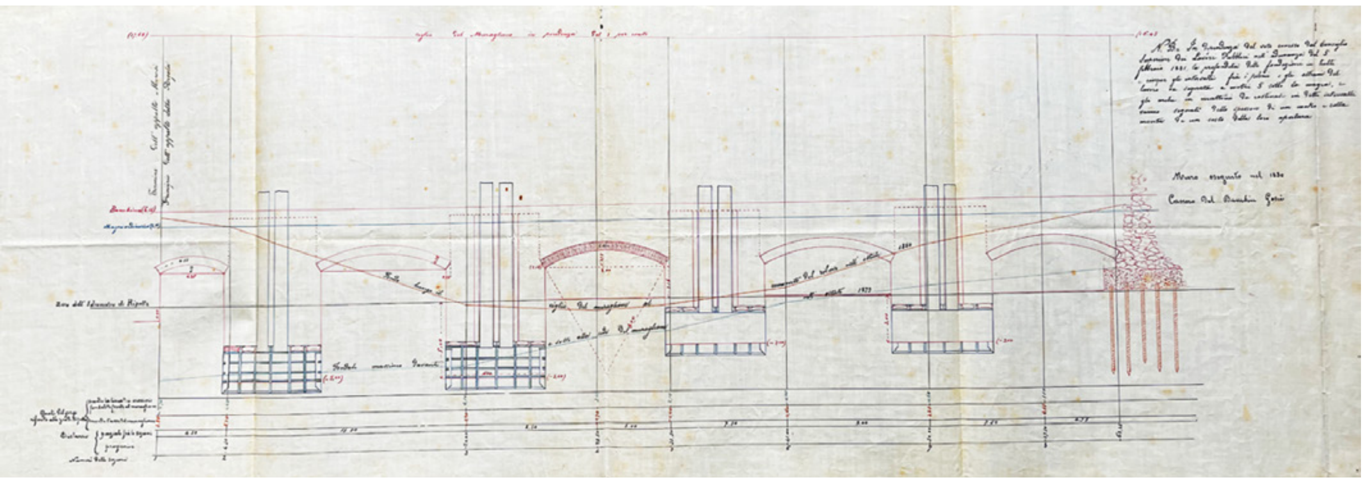


Fig. 3. *IIICM, wrought-iron caissons for the retaining walls' foundations, 1882 (courtesy of Rome State Archive, USTRA collection).*

iron, was equipped with a pair of iron tubes 90 cm in diameter, connecting the excavation chamber at the bottom to the airlocks and the outside.

At the design stage, the proposed building procedure consisted of excavation works in the caisson chamber to obtain the progressive sinking of the caisson and masonry works over the caisson's ceiling for the piers' elevation. The masonry piers, in tuff and pozzolanic mortar, were thus built in free air, functioning as an additional load for the sinking of the caisson.

The construction site opened in 1882 [21]. As reported in the technical treatizes of the time, the proposed building process was improved with the pioneering application of the so-called demountable caissons aiming to «minimize the considerable amount of iron that remains lost in the foundations» [1]. The caissons, designed by the IIICM, featured a demountable wrought-iron sheets elevation wall (in Italian *camicia*) for supporting the masonry built over the ceiling (Fig. 4).

The excavation chamber (20x4.80 m in plan and 3 m high) was comprised of wrought-iron sheets, strengthened and stabilized by vertical and horizontal elements in flat irons (Fig. 4): the ceiling was strengthened by a grid of truss in flat irons, while the vertical walls, composed of 7 mm-thick wrought-iron sheets, were reinforced with triangular-shape ribs; a set of tie rod was added at the base. The caissons were equipped with a pair of iron tubes, 90 cm in diameter (in Italian *camini*), which would connect the excavation chambers to the airlocks and the outside.

The elevation wall for supporting the masonry built over the excavation chamber ceiling (*camicia*) was composed of 7 mm-thick wrought-iron sheets jointed with flat irons that functioned as coulisses (sliding joints) (Fig. 4). During construction, the latter were weakly fixed to the wrought-iron sheets by only four small spikes. Once the masonry works were completed, the wrought-iron sheets were removed.

In 1882, the adoption of compressed air caissons became mandatory for constructing the foundation of the retaining walls, with a minimum depth of 6 m below the mean river level. As a direct consequence, the building details of the retaining wall section were updated by the Special Office (Fig. 5). The possibility of assigning a broad building lot to a single construction company – featuring technological skills and economic robustness to guarantee the extensive adoption of the compressed air foundation technology – was envisaged by the Special Office and approved by the national authorities (*Consiglio Superiore dei Lavori Pubblici*): Italian contractors didn't fit both the economic and technological requirements; thus, the Swiss firm Zschokke & Terrier was appointed for the works [21].

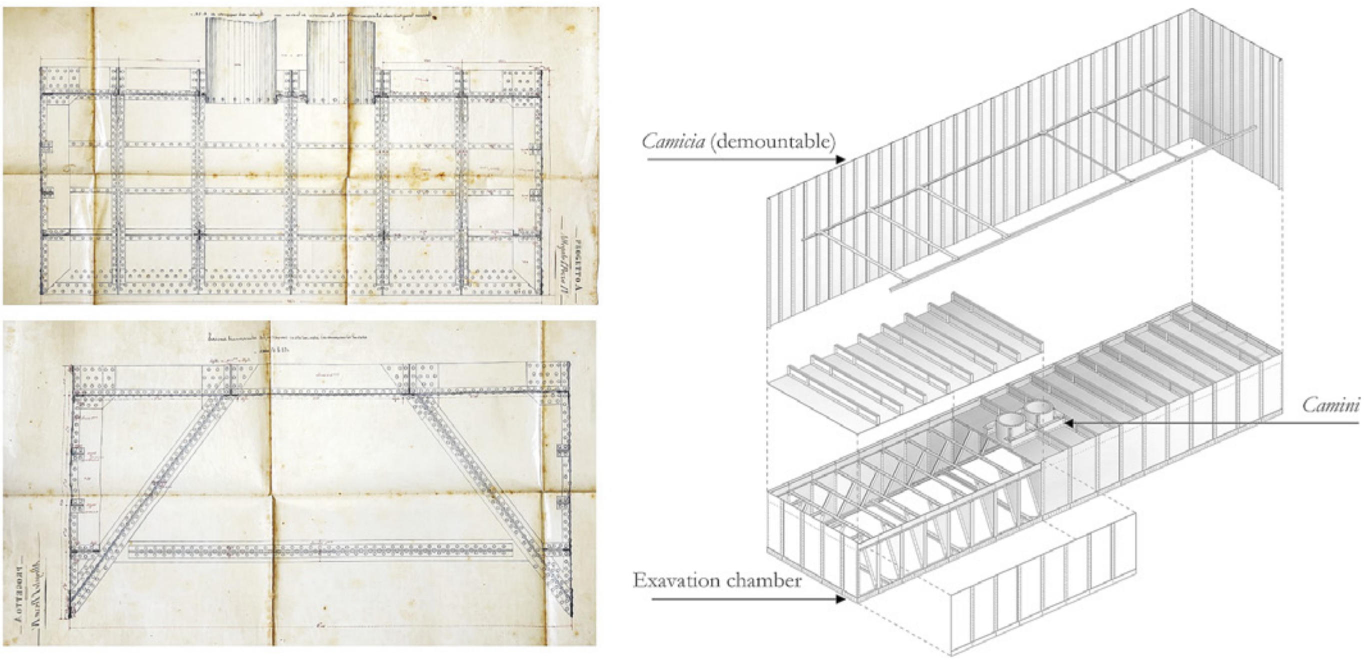


Fig. 4. *IIICM, construction details of the cassion, 1881 (courtesy of Rome State Archive, USTRA collection); 3D reconstruction of the caisson.*

Fig. 5. *Special Office for the Tiber's settlement, construction drawings of the retaining walls with wrought-iron caissons, 1885 (courtesy of Rome State Archive, USTRA collection).*

The foundations designed by Zschokke were approved in June 1884, and the construction sites opened in January 1885. While the Zschokke & Terrier established novel production plants in Rome, the Special Office for the Tiber's settlement soon standardized the technology, as proved by a new set of execution drawings of the caisson structures, signed in 1885 (Fig. 6).

The caissons were enlarged, with a maximal length of 30 m, a maximal width of 6 m, and a mean height of 3 m; the construction details were perfected with the new

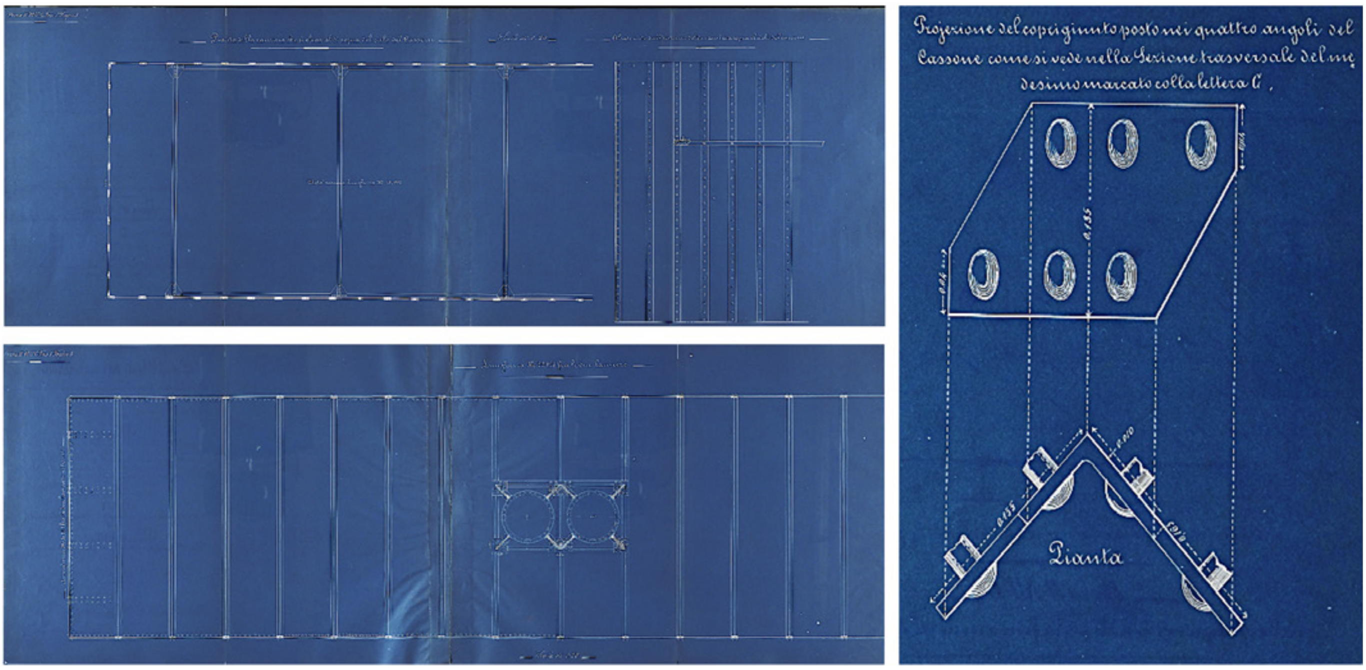


Fig. 6. *Special Office for the Tiber's settlement, construction drawings of the wrought-iron caissons, 1885 (courtesy of Rome State Archive, USTRA collection).*

Fig. 7. *Pneumatic foundations works on the Tiber's banks, picture by G. Primoli, 1888-90 (courtesy of Fondazione Primoli).*

design of the structural elements and the joints in flat irons. The execution drawing of the demountable *camicia* assumed the same building details of the 1881 project, standardizing the solution proposed by the IIICM (Fig. 6).

Two additional tubes were added for the concrete filling. The caisson walls were built from 8 mm thick wrought-iron sheets and strengthened by a series of triangular-shaped vertical ribs with a 1.10 m step. The airlocks were 4 m high cylinders of 2.20 m in diameter that featured an additional smaller chamber of 2.20 m in height and 1.40 m in diameter and two conical appendixes to allow the extraction of excavation materials with buckets and winches (Fig. 7). Once the caisson reached the foundation's depth, the excavation chamber was entirely filled with concrete. The concrete cast was composed of superimposed layers by the workers in the chamber; the cast even filled the 40 cm space between two adjacent caissons, creating a monolithic foundation block.

Winches set up the entire caisson on a wooden castle, then used to demount and retrieve the wrought-iron sheet elevation wall (Fig. 7).

The Zschokke company remained the main contractor entrusted with the use of the technology until 1900 [22]. The complex risk of the technology due to the use of compressed air, in terms of workers' health, arose since the first application. In this regard, the 1882 contract, stipulated with the Zschokke company, introduced the mandatory presence of the doctor on the excavation work site and obliged the contractor to refund workers and their families in case of accidents [23].

4. THE WROUGHT-IRON CAISSONS HBIM

A document-based HBIM [4–7] was developed to verify the anatomy and building details of the caissons, exploiting a "Key set" of original design documents, ranging from execution drawings to technical reports.

4.1. METHODOLOGY AND PHASES

The HBIM processes featured five steps (Fig. 8): i) set up of a customized Common Data Environment (CDE); ii) crossing analysis of the historical documents to provide

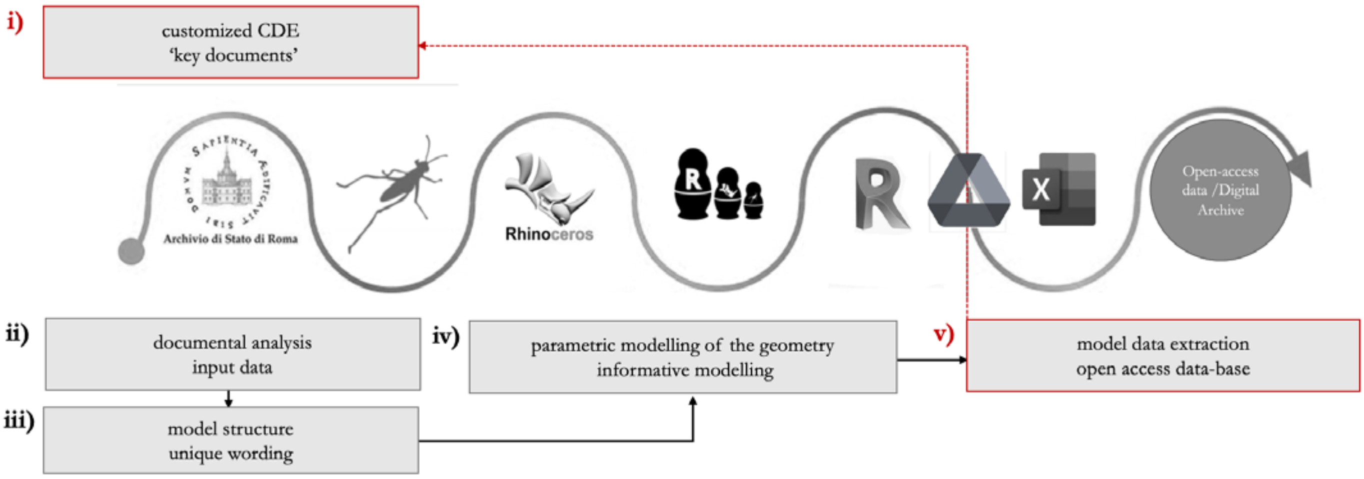


Fig. 8. *Workflow of the HBIM process.*

geometrical and informative input data of the model; iii) design of the model structure and wording of the model items (unique ID); iv) fully parametric geometric modeling, exploiting the data derived from historical documents; v) extraction of the graphic and informative data of the model in the open-access database.

The procedure's first step (step i) focuses on defining a customized CDE to support the subsequent modeling phases and assure data conservation. The standard areas of the CDE [24] were customized as follows: "Input" area, containing the listed and organized historical document and the input data tables (step ii); "Work in Progress" area, containing the models (step iii, iv); "Published" area, containing the open access database (step v), embedding hyperlink to the historical documents stored in the "Input" area.

Step ii) focused on categorizing information derived from the historical analysis and preparing the model input data (informative and geometric), referring to each building element of the caisson. A sample of the data workflow, known as the "Triangular-shape rib", is reported in Tab. 3.

Buiding Element	ID	Document Typology	Information Typology	Geometric Input Data	Informative Input Data
Triangular-shape rib	M-A_B -nXnY-0	Execution drawing	Geometric data	• Shape • Dimensions • Positioning	
			Data on building materials	• Connection systems • Industrialized elements dimensional standards	• Materials Typology
		Technical Reports	Construction system data	• Positioning (structural grids)	• Structural Typology
			Construction History		• Date
			Geometric data	• Shape • Dimensions • Position	
			Data on building materials	• Connection systems • Industrialized elements dimensional standards	• Materials Typology • Materials Properties

Tab. 3. *Modeling procedure step i): sample of the data workflow from the historical analysis to the input data.*

Step iii) focuses on defining the model structure, consistent with the anatomy of the caissons and the wording of the model objects. The unique ID of each model object was composed by combining the following: the building element "category" indicated with a letter; the building element "type" marked with a letter; and an alphanumeric code to identify the position of each element. The latter was composed of a numeric value corresponding to the position of each element on the X and Y axis of the structural grid of the caisson, followed by the numeric index of the two main levels of the caisson ("0" for the working chamber and "1" for the so-called *camicia* respectively). For example, for the triangular triangular-shaped vertical ribs, the standard ID code was composed of matching: "category" (indicated by the letter "M", "type" (indicated by the letter "A" or "B", numeric value, ranging from "0" to "n" of the position on the X and the Y axis respectively, numeric index of the working chamber level, "0" the resulting standard ID is "M-A-nXnY-0".

After defining the structure, the geometric and informative modeling was performed in step iv), within two subsequent actions. First, the fully parametric geometrical modeling of the building elements of the caissons, referring to "category" and "type" (Fig. 9), was performed via a Grasshopper algorithmic code for Rhinoceros [25]. Second, the set up of "custom families" referring to the "category" and "type" of the building elements, and the association of informative data to each digital item of the model was conducted by exploiting the BIM software Revit 2022 [26] via the plug-in Rhino Inside Revit [27].

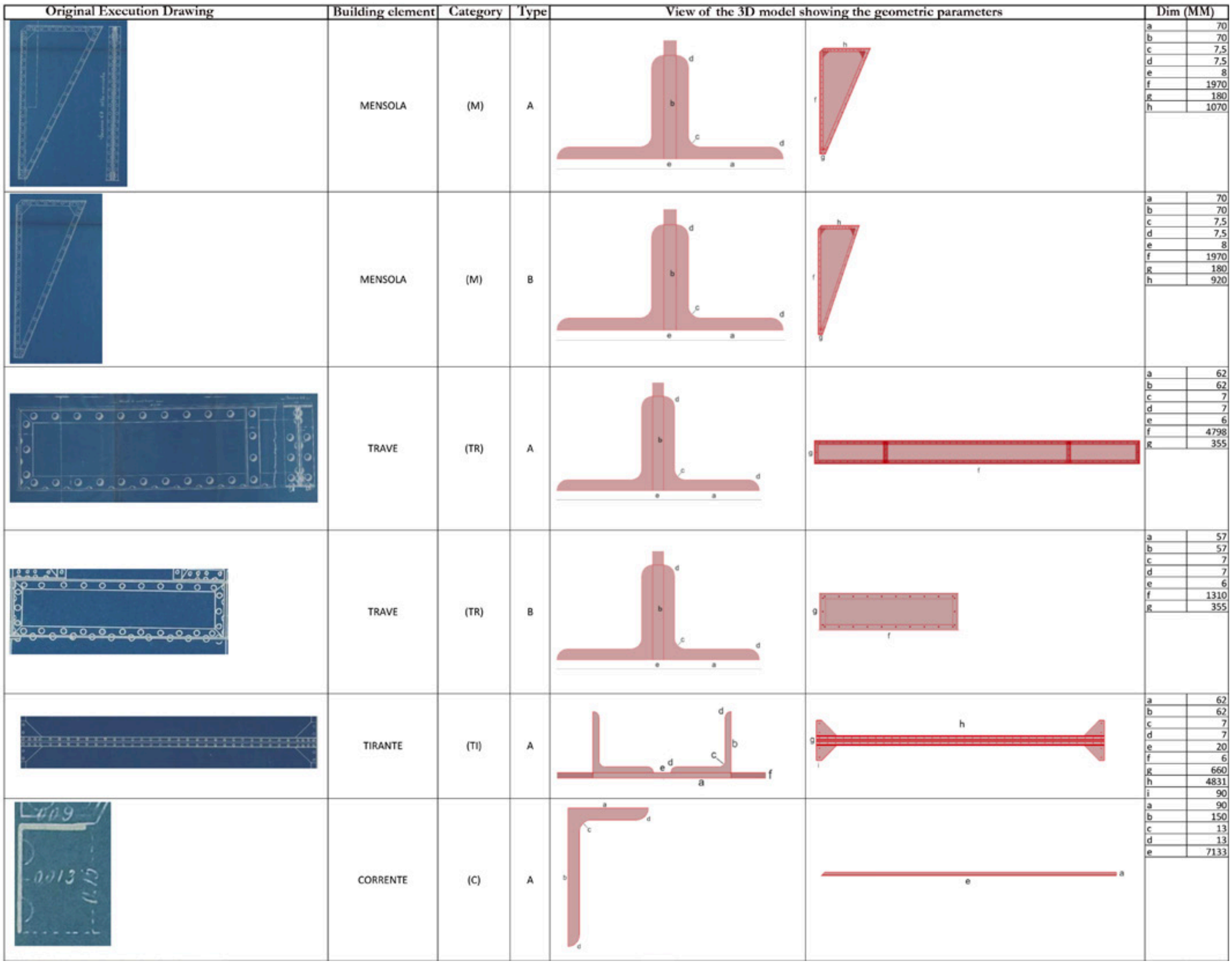
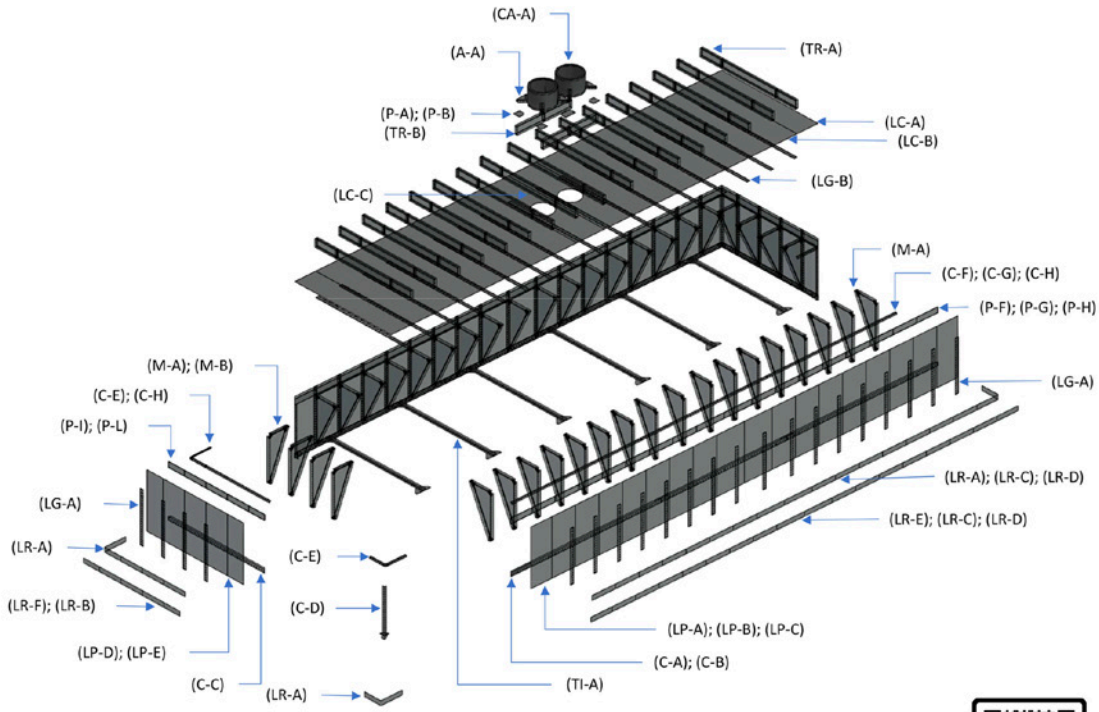


Fig. 9. *Modelling procedure step iv): the parametric model of the building elements geometry, based on the historical documents data and referred to as "categories" and "types".*

Lastly, step v) focused on the extraction of geometric and informative data of the model in an open-access database, exploiting the automatically generated tables function in Revit 2022 [28]: the buildings elements (model items marked with ID) were listed in textual tables, accompanied by descriptions fields – e.g. main geometrical dimensions, building materials, year of construction –, and by the hyperlink to historical documentation and graphic representation, stored in the Google Drive-based CDE (Fig. 10).

Wording of the model objects (ID)

Category	Type
Mensola (M)	M-A M-B
Trave (TR)	TR-A TR-B
Tirante (TI)	TI-A
Corrente (C)	C-A C-B C-C C-D C-E C-F C-H
Lamiera di parete (LP)	LP-A LP-B LP-C LP-D LP-E
Lamiera di rinforzo (LR)	LR-A LR-B LR-C LR-D LR-E LR-F
Lamiera del cielo (LC)	LC-A LC-B LC-C
Lamiera di giunzione (LG)	LG-A LG-B
Piastra (P)	P-A P-B P-C P-D P-E P-F P-G P-H P-I P-F
Angolare dei camini (A)	A-A
Camino (CA)	CA-A

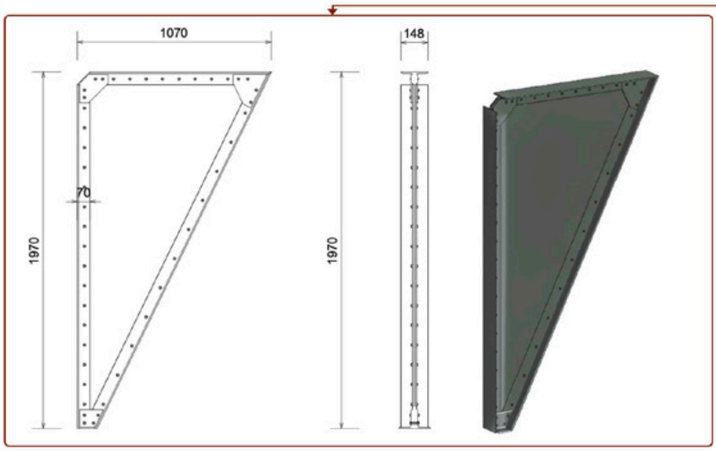


SCAN ME

Access to the full data-base

Open-access database of the model objects (caisson building elements) and digital archive of historical documents

Object ID	Category	Type	b (mm)	h (mm)	s (mm)	material	Technical drawing	Historical document (input source)
MA-1x3y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-1x4y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-2x1y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-2x6y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-3x1y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-3x6y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif
MA-4x1y	M-A	M-A	1070	1970	148	Ferro, duttile	VEDI TAVOLA N.1	CASSONE-SEZIONE_TRASVERSALE.tif



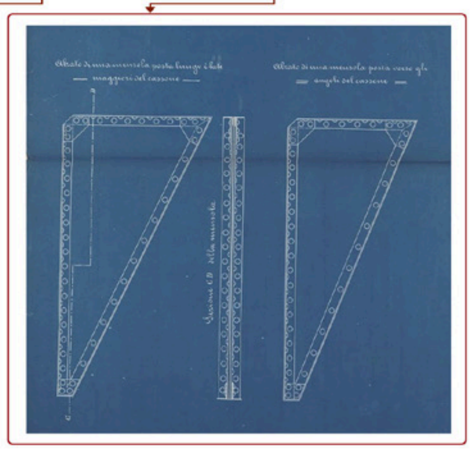


Fig. 10. *3D view of the model items and access link to the open-access database (Google Drive).*

4.2. DISCUSSION

Steps iii) and iv) – the heaviest actions of the process, in terms of conceptual design and geometrical modeling times – allowed us to achieve the crucial goals of the proposed methodology: the scalability of the modeling procedure and the interoperability of the model data, via the production of an open-access database.

The fully parametric modeling of the geometry, performed in step iv), exploiting algorithmic code, allowed, from the one hand, to adapt the 3D model to minimal dimensional variation (e.g., the different dimensions of the foundations of each retaining walls sector); from the other hand, to fill the lack of standardized digital object libraries, concerning historical building elements, with customized digital "families" of iron building elements, to be used in further models [7].

In step iii), the setup of a robust hierarchic structure of the model supported by a detailed wording of the model objects allowed the production of an open-access database featured by a strong connection with the anatomy of the represented structure. The categorization of the building elements and the unique wording of each "item" supported the production of easy-to-read tables, embedding informative and geometric data of each model object at the same time. Tables are, thus, enriched by the direct association (hyperlink) between the historical document and the model object, providing at the same a "proof" of the philological modeling approach and a tool to simplify the consultation of the historical records (i.g. execution drawings), exploiting the direct relation with the building elements data. A diagram of the organization and the functionality of the open-access database is shown in Fig. 10; the QR code provides access to the complete database of the building elements of the caisson as an insight into the cited functionality, even in terms of a digital archive of the historical documents.

5. CONCLUSIONS

The contribution focused on the use of compressed-air caisson foundations technology in Italy in the last three decades of the 19th century. From a methodological point of view, the study was supported by a historical-document-based HBIM, functioning as the same as both research and digital archives.

In the second half of the 19th century, alongside the main application of deep foundations for bridges, the deployment of pneumatic foundations was crucial in designing and constructing river embankments, especially in densely inhabited urban areas. The historical-documents-based analysis of the Tiber River embankment construction disclosed the fruitful knowledge transfer of the compressed-air foundations methods to Italian engineers and contractors, highlighting their innovative contribution to the international evolution of the technique. In this perspective, the study remarked on the following issues: the crucial role of the application of the pneumatic foundations for the construction of the Tiber River embankments; the innovative contributions in the standardization of the design of iron caissons, introducing demountable parts – the so-called *demountable caissons* which marked a significant step in perfecting the attempts, conducted since the late 1850s, to recover the iron and had a beneficial impact on the construction costs.

From a methodological point of view, the conjunction of the archival investigation and the HBIM supported both the investigation phase of the construction history analysis and the dissemination of the results. On the one hand, the document-based HBIM provided a powerful visual framework to understand the geometry, building details, and construction process of the analyzed structures and supported the cataloging of historical documents, facilitating their analysis in the digital environment. On the other hand, the production of the HBIM-related open-access database, embedding the digital collection of historical documents, expands the capacity of the model in terms of an open-access digital archive, providing an effective educational tool to disseminate knowledge of historical structures.

Acknowledgments

Research is supported by the *Tiber'S geotechnical analysis, satellite monitoring, historical investigation* project A0375-2020-36632, Research Groups 2020, Lazio Innova. Archival investigations are carried out within the research agreement between the *Archivio di Stato di Roma* (ACS) and the University of Rome Tor Vergata -DICII. The authors express their gratitude to Dr. Vincenzo De Meo (ACS). Digital models are elaborated by the student Daniele Bove for the master thesis in *Ingegneria e*

Tecniche del Costruire titled *I muraglioni del Tevere a Roma: ricerca documentale e modellazione HBIM* (tutors: I. Giannetti and E. Eramo), University of Rome Tor Vergata, a.a. 2021-22.

Authors contribution

The Authors contribute in equal parts to the present paper.

Funding

The research is supported by the project 'Tiber'S: geotechnical analysis, satellite monitoring, historical investigation, A0375-2020-36632, Research Groups 2020, Lazio Innova.

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AUTARKY METAL ROOFING AT THE MECENATE PAPER MILL IN TIVOLI: AN UNSEEN APPLICATION OF GINO COVRE'S PATENTS

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DOI: 10.30682/tema090007

TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

Abstract

In 1887, the Papermill Mecenate settled at the Sanctuary of Hercules the Victor in Tivoli, thanks to the construction of the Canevari Canal. The papermill represented, for decades, the largest industrial plant placed on the former religious site, which had already housed various manufacturing functions. The phases of greatest overlap occurred in the 1930s and 1950s by engineer Emo Salvati, who designed many reinforced concrete structures. In 1938, he and Marco Segrè, the factory owner, approached Gino Covre to make lightweight metal roofing. Arrived in Rome in 1935, Covre was already working steadily with the Antonio Badoni firm in Lecco. In Rome, he registered many patents, including the one for "Vaulted arch, composed or constituted with frame elements" (1936). The paper presents the historical-constructional investigation, supported by digital information modeling, of two unpublished applications made by Covre that were lost in the late 20th century. Covre's Rome period is under-explored, and the case study raises important questions about those early years. The loss of vaults gives greater emphasis to existing traces-photographic, documentary-that can provide insights into the lost built object. Gino Covre's experimentation in the autarkic phase with metal structures by means of a significantly reduced use of material appears to be an exceptional issue, and the application of Tivoli tests the system later used at the Palace of Congress at E42 designed by Adalberto Libera.

Keywords

Metal vaults, Metal structure, Lost Heritage, Autarchy, Industrial archaeology.

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1. INTRODUCTION

This contribution represents an excerpt of a broad program of investigations on the ancient industrial area in the monumental complex of the Sanctuary of Hercules the Victor of Tivoli (Fig. 1). The specific thematic areas of research concern the knowledge of the prolonged production vicissitudes, the related architectural bod-

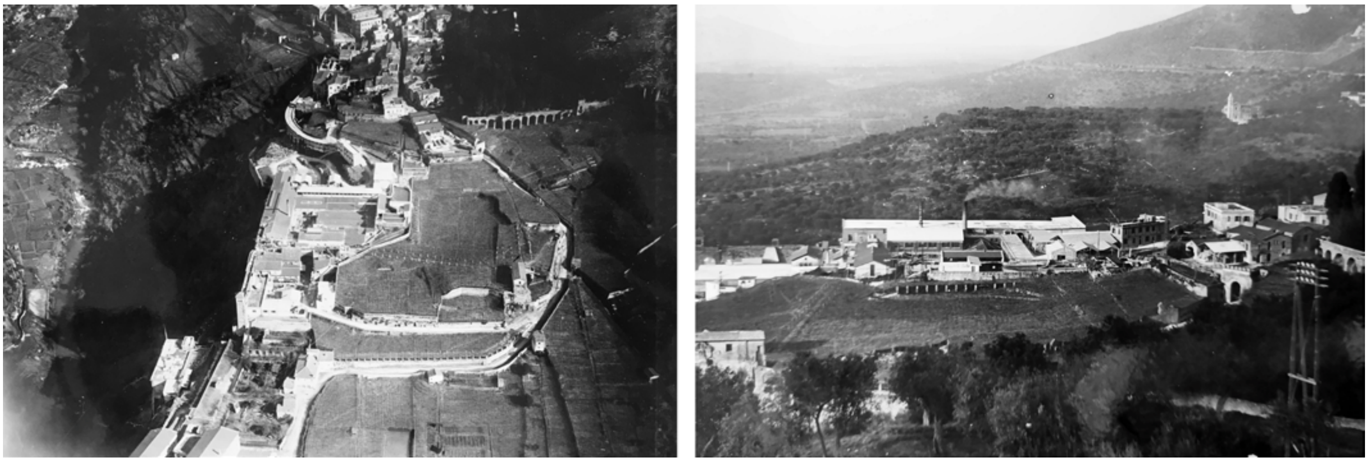


Fig. 1. *Two aerial views of the Segré Paper Mill before and after the interventions coordinated by Emo Salvati. 1926, left, and late 1930s, right © ASR.*

ies and the urban outcome, as well as the identification of design tools for the management and enhancement of the archaeological-industrial palimpsest. The latter, in Tivoli, particularly at the Sanctuary site, consists of evidence of at least five centuries of productive activity, from manufacturing to industry [1–3]. It confirms Tivoli as an exemplary case of the Italian way toward industrial heritage [4, 5]. In a rich sequence of uses, the industrial production of paper and electricity began in the late 19th century, as well as, among many others, a pasta factory, thanks mainly to the opening of the canal, known as Canevari, through the sanctuary structures in 1886. The aims of the research are broad, and therefore, they ask for different disciplinary competencies, from the architectural area to the historical and economic ones. The activities of the main research unit in Rome, skilled in historical-architectural engineering, have been devoted to the survey of historic building organism and architectural restoration tools. In parallel, the research groups at the universities of Evora and Seville deal more specifically with community awareness and intangible heritage. An early sharing of results took place at the Second General States of the Industrial Heritage of Rome in 2022, in the specific session held in Tivoli at the Antiquarium of the Sanctuary [6–8].

The paper focuses on the story of the Mecenate – or Segrè – Paper Mill of the Tiburtine Paper Mill Society [9] at a significant historical moment: autarky. Due to the sanctions imposed by the League of Nations after the invasion of Abyssinia by Italy (1935), the fascist regime encouraged policies aimed at self-sufficiency, imposing the use of local products with specific laws (i.e., RDL n. 216 of 01/07/1926, Law n. 189 of 01/09/1939, RDL n. 1326 of 10/07/1939). In this context, the use of metallic materials in building construction was rigorously limited, influencing both reinforced concrete and iron construction processes.

The research brought to light that engineer Gino Covre worked for the paper mill in the construction of several metal roofs and that in one of them, in particular, he pioneered his first patent for the construction of metal vaults with a very low use of material [10]. This patent, recalled by scholars in the few publications to date, is the basis of the construction solutions adopted by Covre the following year for the realization of the large cross vault wanted by Adalberto Libera in his project for the E42 Palace of Congresses. Thus, the Tivoli case proved worthy of attention, although limited to a functional use and related to a demolished building. The presence of many reuses, especially productive reuses, at a religious site and the subsequent, intentional loss of the material object have raised more than one question and forced extensive research both on the theoretical front, addressed by colleagues at the Universities of Evora, Seville, and Rome with the working group "De Ora a Labora" (from "Pray" to "Work"), and on the technological front, aimed at the application of digital tools for the representation, fruition, and data sharing of now an intangible heritage.

2. METHODOLOGY

The methodology integrates current investigation tools typical of construction history and industrial archaeology with the opportunities offered by the approach of ArchaeoHBIM [11].

As early as the first Congress of Construction History in Madrid in 2003 was an opportunity to take stock of the purpose, method, and field of studies. Among the many participants, Werner Lorenz pointed out that one of the main motivations for pursuing these studies is the invaluable resource they could offer to face the crisis in engineering [12]. The case presented in this paper offers an opportunity to define the outlines of the missing part of a building organism, rediscovering it as objectively as possible through the support of the plans and the evidence of building site photographs, archive documents, and architectural-constructional survey of the remaining building. The systematization of the documentation was done through the support of digital tools in the BIM environment, and an essential role is played by the restitutive survey of the original state, according to Poretti [13]. Thanks to the potential of a 4-dimensional HBIM, the survey of the original state could be complemented by the reconstructions of multiple states of the configuration of the work: before, during, and after the life cycle of the studied work (Fig. 2).

Thus, the research took up the challenge of declining the ArchaeoHBIM, of which it captures the experiences of applying it to the legacies of antiquity for objects and systems of industrial archaeology. As reported in a previous methodological contribution, digital tools enable the organization of the complexity of layered data in a system characterized by multiple archaeologies to increase the possibility of cognitive synthesis for the various disciplines involved [14]. Documentary, archival, and architectural survey research has been associated with the generation of an information model that, on the one hand, has the standard elements of cultural heritage applications (integrated surveys, scan-to-BIM process, multi-scalarity and automation of semantic recognition processes of geometric elements), while on the other hand, it has experimented with those specifically characterizing industrial heritage: sanitary and environmental engineering; presence-absence of machines; industrial construction experimentation; and the links between production organization, functional layout, and spatial form.

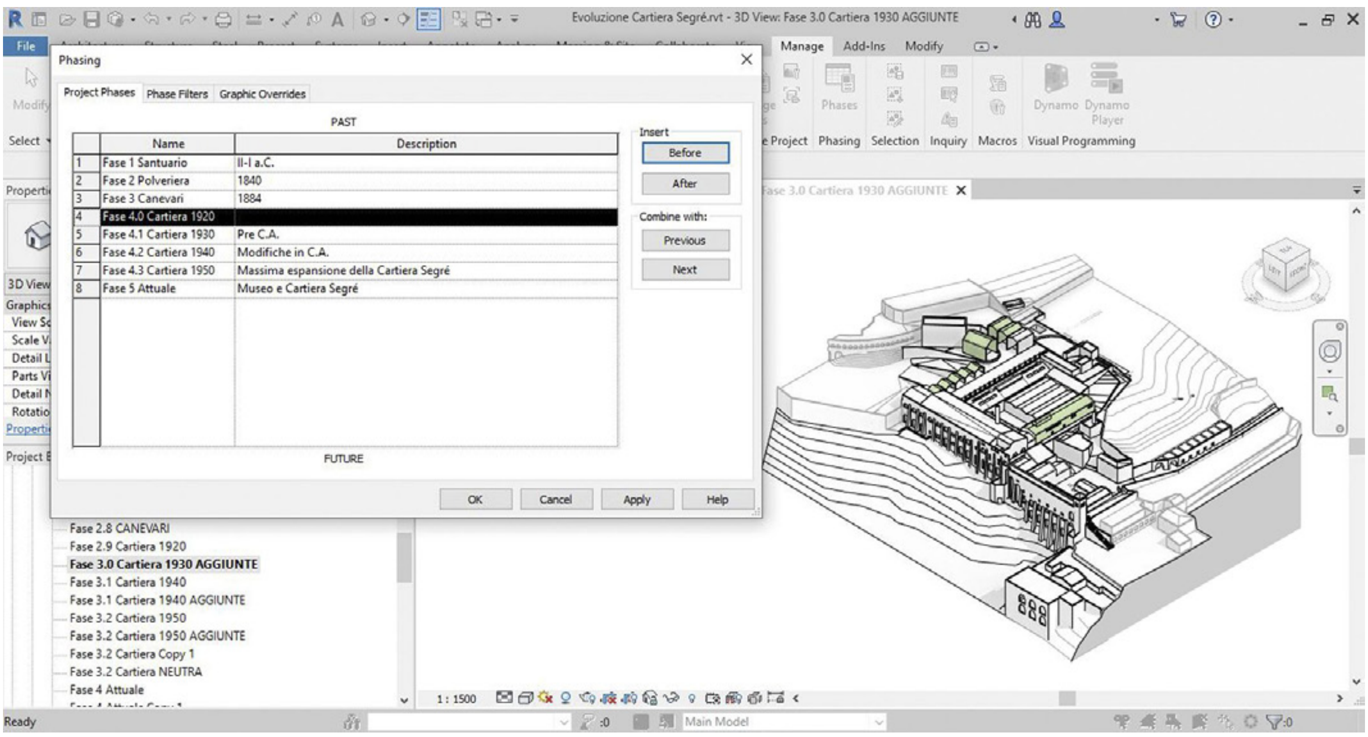
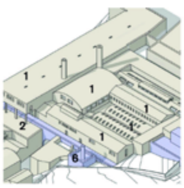
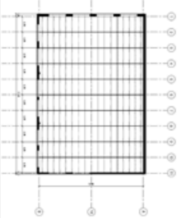
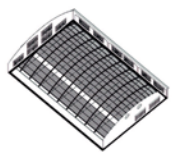
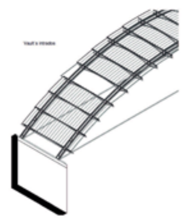
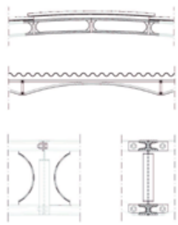


Fig. 2. *Definition of the phases for the diachronic BIM of the former Segrè Papermill within the BIM Authoring Autodesk Revit - AR.*

The Cartesian and temporal referencing on the component of a digital model was also very useful because of the breadth of archives consulted (Fig. 3). Among the main ones were the State Archives of Rome, the Municipal Historical Archives of Tivoli, and the Badoni Archives at the Politecnico di Milano. The representation of the case study through a BIM exploited the typical construction potential by families and instances. In fact, the use of industrialized components, found in components manufactured off-site in the mechanical workshops, matches the construction logic of BIM models and the standardization of components. However, this is a favorable case because experimental technical solutions, such as the one found, may often lack comprehensive historical-documentary information.

The information modeling aspects of the BIM process are entrusted to the definition of the LOD (Level of Detail). Although discordant in formalization in different countries' standards, the LOD is defined by progressively more detailed stage scales and by the subdivision of two concepts: the geometric component (in Italy defined LOG, Level of Geometry) and the information component (in Italy defined LOI, Level of Information). The applications of the BIM process to industrial heritage share the same principle with those of archaeological heritage, particularly for production machines that are often in a state of severe degradation or are even completely absent. This complexity is also reflected in the definition of LOD for lost elements [REF Paper sustainability] and for construction elements referred to specific patents, far from large-scale standardization logics such as industrialized constructions, and for which it is complex to frame the elements of the BIM model in an exact LOD scale, such as that of the analyzed case study. Nonetheless, the issue required a specification elaborated in Tab. 1, where the authors linked the horizontal elements (HE) modeled and the Italian LOD scale, specifying where they are reconstructions of the original configurations.

Finally, a further aspect is gratified by the realization of the information/model and concerns the spatial configuration of the buildings in relation to the production layout. The definition of the complete information model of the previous stages effectively supported an understanding of the geometric complexity and the reconstruction of the production process that defined its

LOD A	LOD B	LOD C	LOD D	LOD E	LOD F	LOD G
						
Geometry Representative 3D volume **Object** 3D solid, barrel vault **Characteristic** Rough dimensions of the building	**Geometry** Generic 3D model **Object** 3D solid of walls, roof and openings **Characteristic** Rough dimensions of the building and approximate position in its contest	**Geometry** 3D model with definite grid and proportions **Object** correct 3D geometry of vertical and horizontal elements **Characteristic** Floor plan with correct dimensions and thickness of walls, openings and roof	**Geometry** 3D model of structural and architectural elements **Object** 3D geometry of the construction system **Characteristic** Primary and secundary structural elements, building skin	**Geometry** Detailed 3D model of structural elements **Object** 3D geometry of the forming parts of the curved trusses and the secundary joists **Characteristic** Primary and secundary components	**Geometry** Detailed 3D model of structural elements and structural connections **Object** 3D geometry of the main structural connections **Characteristic** Correct size of composite truss elements	**Geometry** Detailed 3D model of structural components and connections **Object** 3D geometry of all the components **Characteristic** Correct size of composite truss elements, material properties

Tab. 1. *Definition of the constructive detail of the lost light metal vault to the deepest possible LOD.*

On the other hand, concerning the surviving ancient archaeological structures, it was necessary to proceed by integrating the methods of laser photogrammetry and imaging methods. In the lost metal vaults, the original presence of modular components has been an advantage in modeling and defining parametric elements for various properties, including virtual reconstruction of what is lost, as in the present case. Furthermore, preserving building components also permits defining performance characteristics or assigning a decay status [15]. For example, in reinforced concrete structures built with lightweight technologies to cover large factory spaces, such as for the vaults of the halls for the Hollander machines, it is methodologically possible to combine geometric surveying with automatic identification of major pathologies.

shape and space. Therefore, the paper focuses on the integrated result of the historical-documentary research, construction survey, restitutive drawing, and 4D modeling of the lost metal elements of the Segrè paper mill. Then follows the detailed description to which it is associated, as a complement, also the considerations on the impact that such loss due to voluntary demolition has not only on the understanding of the factory but of the same ancient sacred building in its millennial history.

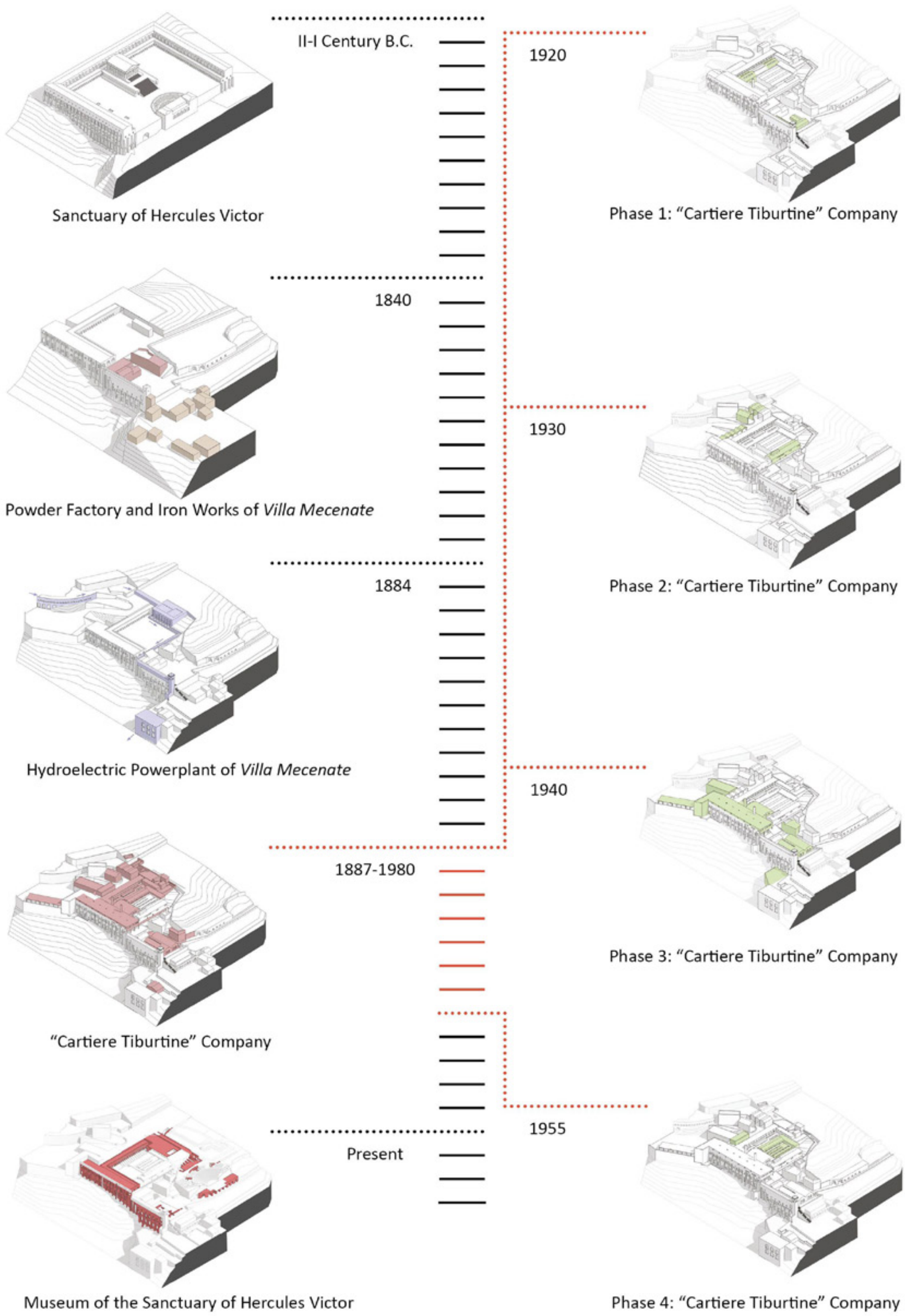


Fig. 3. *Case study evolution stages in contemporary age in the BIM model - AR.*

3. THE MODERNIZATION OF THE MECENATE PAPER MILL IN THE THIRTIES OF THE TWENTIETH CENTURY

From its founding in 1887, the mill had many expansions required by the evolution of production techniques, the use of different forms of energy within the mill, and the need to quantitatively increase production. Thus, it would be going to occupy more space in the Sanctuary and overlap with growing new structures. At the peak of autarky, the Segrè family's paper mills in Tivoli went through a season of crucial industrial renewal and growth in the quality and quantity of production. The fortune of the Segrè, in particular, is related to their main production site, the Cartiera Tiburtina, also known as the Mecenate or Segrè paper mill, located in the ancient structures of the Sanctuary of Hercules the Vintor. The latter site was historically traversed by water, enriched in the 16th century by the significant amounts of water diverted for the monumental fountain system of Villa d'Este, designed by Pirro Ligorio. As written above, the city has a long tradition of productive activities, including paper and woolen mills, ironworks, and oil presses propelled by many conduits derived from the river Aniene. In the structures of the Sanctuary, productive uses can be traced at least from the beginning of the seventeenth century with the installation of ironworks [1] by the Camera Apostolica and precisely for the exploitation of those flows conducted for the pleasure of the cardinal Este [8]. The sequence of subsequent uses is only partially defined. Starting in 1887, with the construction of the Canevari Canal, the site was at the center of the city's rapid industrialization. Taking advantage of the energy produced thanks to the power plant fed by the canal, the Tiburtina Paper Mill was installed, which at the turn of the century: «is lit by electric light, has 2 steam boilers for heating, of the total strength of 45 horsepower, and 2 rotating autoclaves for boiling rags and straw. It produces paper of various qualities, including very thin paper for letter copying, citrus wrapping, and similar, also making large exports of it». It is the most advanced of the 7 plants operating in Tivoli, employing a total of 381 workers, 5 paper machines, and 9 drum machines [17].

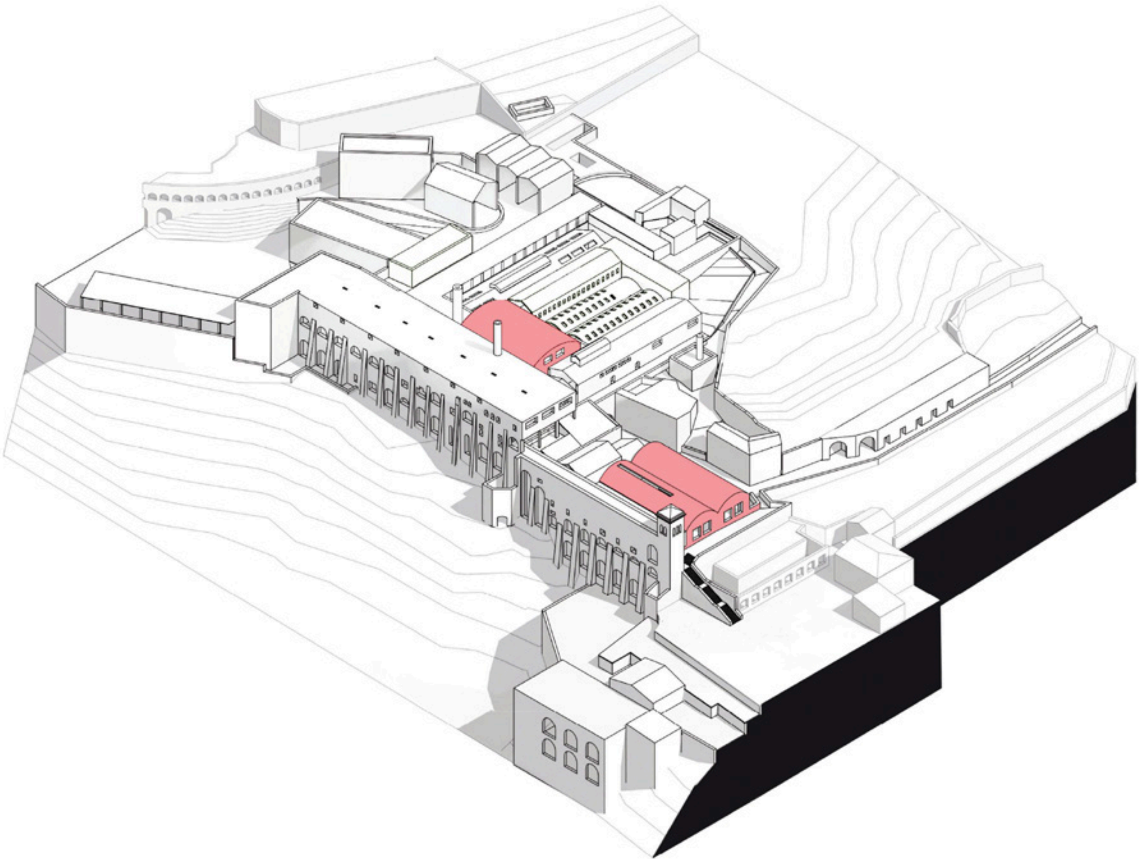


Fig. 4. *Configuration phase of the paper mill in late 1938. In pink are Gino Covre's metal vaults - AR.*

Later, when the company is about to celebrate its 50th anniversary, the site is affected by a massive building activity supervised and coordinated by engineer Emo Salvati on a commission from Marco Segrè. Production is rationalized, new and powerful machines are installed, a small power plant is built, and a new thermal power plant provides steam for the turbo alternators that power the three paper machines, numerous Hollander beaters, and refiners. In 1937, the work was completed in time to celebrate the factory's 50th anniversary in the largely renovated paper mill in the presence of the authorities, workers, technicians, and their respective families. The interventions of the 1930s are, therefore those that make the maximum overlap between the factory and the ancient site, covering with elevations every extension of the ancient artifact, and also using as much as possible the outdoor or underground spaces of the "Via Tecta".

Notably, the main structures built by Salvati, starting in 1936, all in reinforced concrete, were: the new paper sorting department, in the courtyard of the third continuous machine, corresponding to the old sacred area of the Sanctuary; the new warehouse for outgoing paper and wastepaper, adjacent to the north side of the triporticus; he also renovated the north building of the rag shop, inserting reinforced concrete frames; and he rebuilt the west room of the rag shop, located on the last level of the substructures and now gone. As part of these works, Salvati and Segrè turned to lightweight metal vaulting for some large-scale roofs. They, therefore, first approached the firm Anonima Costruzioni Italiana, which, on March 25, 1938, proposed a metal solution based on Cametti's patent for metal lamellar vaults, and, only later, contacted Gino Covre, who had arrived in Rome in 1935 when his professional relationship with the Badoni firm of Lecco [18], a historic mechanical company, was already well established. The sequence of operations carried out in this epoch, referenced in the BIM model, is shown in the figure (Fig. 4).

4. METAL VAULTS OF GINO COVRE

4.1. THE LOST VAULTS AT THE MECENATE PAPER MILL

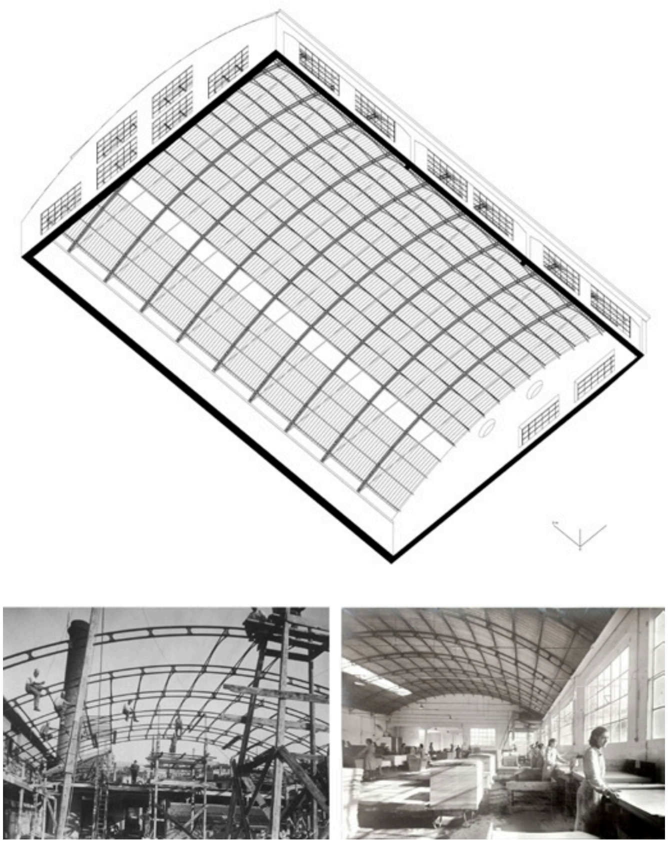


Fig. 5. *Left: Restitutive model of the original configuration of the metal vault of the Paper Selection Room.*

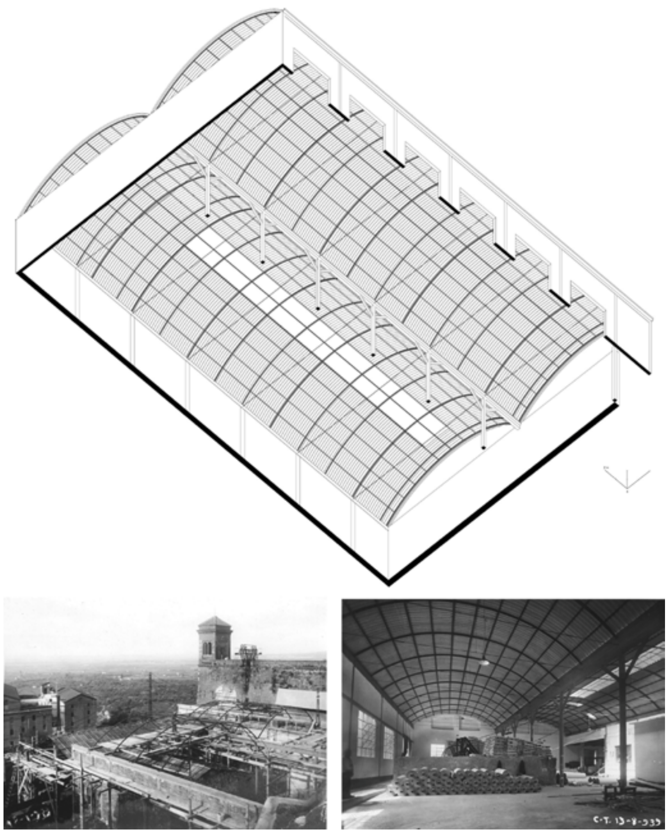


Fig. 6. *Right: Restitutive model of the original configuration of the metal vaults of the Courtyard First Paper Machine.*

Following a conversation with Marco Segrè and Emo Salvati on May 16, 1938, Covre proceeded to design the roofing of two halls with wide vaults of metal components. On July 5, 1938, he delivered the executive design for the whole thing. The first roof consists of a vault with plan dimensions of 18.40x27.40 m, made to cover the upper floor of the new concrete slab in what was the courtyard of the third continuous machine adjacent to the triporticus, in the west sacred area (Fig. 5). The room is intended for paper selection and served by a freight elevator that connects it with the floor of continuous machine, of the finish hall, and further down directly with the "Via Tecta". The need for a light and non-pushing roof is understandable since the elevation structures intended to support it consist of: on the east side by the masonry wall of the west rag house, built as a superelevation of the entablature and attic of the east triporticus, and on the west side by a reinforced concrete frame made partially embedded in the masonry of the pre-existing Hollander Beaters Hall (Fig. 7). Covre devised a solution consisting of ribs and transoms that applied what he had registered in Patent No. 343079 of September 10, 1936, "Vaulted arch, composed or constituted with frame elements" (Fig. 9). Ribs and transoms form a curved frame in which the elements cooperate with each other for the stability of the whole. The ribs have a height of 290 mm and consist of the upper and lower wings, given by pairs of "U NP 4"-normal 40-mm profile-welded with a pitch of 115.5 cm to uprights made from 200-mm-wide, 4-mm-thick plates (Fig. 8). The pitch of the struts is halved near the supports to provide greater resistance to shear stress. The struts are composed and stiffened at the transverse warp by the incision of two crescents to which are welded calendered plates sect. mm 40x4. The individual struts, which constitute for discrete pieces the core of the rib, are welded to the profiles of the ribs, both on the outside (with a bead at the intrados and extrados of the rib on the edges of the "U NP 4"), and on the inside, again on the edges of the "U NP 4". Therefore, searching for maximum optimization of the amount of steel Covre does not follow the usual strategy of the lattice beam but rather that of lightened arch beams.

With a view to greater stability, the secondary joists are designed not to rest on the structure but to be solidified to both rib wings. They are made of 40-mm "T NP 4" profiles bolted in situ by means of plates previously welded into the core of the "U NP 4" bridges of the ribs. The upper chord is straight; the lower one is arched calendered; the joists are therefore configured as arched beams, a fact that later will be easy to find in Covre's works. The nodes between ribs and the chords of the secondary joists, as they are configured, are similar to a hinge behavior, which can ensure the absence of additional stresses generated, for example, by the thermal deformations of large arches. The vault is very low, with a radius of curvature of about 16 meters, and the ratio of rise to span is 2.95/18.40, which is less than 1 to 6, and this, combined with the nature of the constraints, makes the presence for each rib of tied rods intended to unload the thrust essential completely. In the design phase, two Φ 24 mm are provided for each rib, while in the construction phase, only one of greater diameter was placed. The use of material, therefore, is kept to a minimum, compensated by great care in increasing the strengths by shape as far as in the individual components, such as in the stiffened crescents of the struts or the arched lower chords of the joists. The ribs were not assembled or welded in place, as they were from the design intended to be joined in situ by bolting in two sections. A valid supposition may lead to believe that they were made by the firm Antonio Badoni, since on July 6, 1938, Covre, as soon as the project was delivered, wrote to engineer Giuseppe Riccardo Badoni inviting him to carry out the work even though he feared that: «the small amount of workmanship makes you a little perplexed or may affect prices», but insisting that the «Cartiere Tiburtine are planning other works […] far more important than this one». A search for confirmation of Covre's wishes is still underway at the Badoni Archives and the Segrè Fund.

The second intervention consists of two metal vaults to cover the courtyard of the 1st paper machine (Fig. 6). The purpose is to make a new newsprint depot. It is unique how the solution proposed by Covre is for this building completely different, in the view of an approach, which can be called tailoring, to the design conditions. The courtyard has a plan dimension of m 22.60x33.10 and is divided into two bays by a reinforced concrete frame with six pillars of sect. 20x20 cm, parallel to the existing boundary walls. The individual bays, therefore, measure 11.30x33.10 m and are covered with a low-arched metal vault. A modest span is thus obtained for which he proposes a much simpler metalwork than the one adopted for the chosen paper room. The two vaults are made with ribs and joists based on the use of U-shaped metal elements in the section of just 58x32x4 mm.

With this extreme simplification, the rib is made with a double "U" juxtaposed on the core side with a plate of 4 mm thickness in between, while the secondary joists are made with a single "U". The ribs are composed by welding into a single component, while the joists are bolted in place to the ribs with hinge constraint. The presence of constrained tie rods eliminates horizontal trust, plunged into the concrete beams of the edge. Tied rods are provided by design for each joist every 5 meters, but during construction, twice as many are laid in place, fixing them at all the ribs, located with an axial distance of 2.5 meters. For the sake of completeness, we report that before turning to Covre, Salvati had drawn up a design hypothesis delivered in August 1937, which was later canceled (it is not known whether Salvati had also drawn up a roofing hypothesis for the chosen paper hall, but it is likely to be considered consistent with his mandate on all the works of the paper mill). Salvati's design for the paper newspaper room already presents the elevation structures that were later built and would support the Covre vaults. However, metal roofing was preferred to the initially planned wooden roofing. Before Covre's proposal, an outline design and estimate were requested from the company ACI - Anonima Costruzioni Industriali, which had, for this purpose, sent its offer with a solution based on the CAM patent of engineer Cametti and brought as a curricular example the steel "lamellar" vaults and canopies made in only 29 days for the new Ostiense Station. On a comparative analysis, the structures proposed by ACI presented more joists (+35%) made with "U" profiles about 150 mm high. Probably, given the prohibitive cost of steel during the autarky, the offer of the ACI company was not approved and we turned to engineer Covre to have a solution, thanks to his patent, with a significantly lower use of material (for the ribs alone there is the use of less than half of the steel).

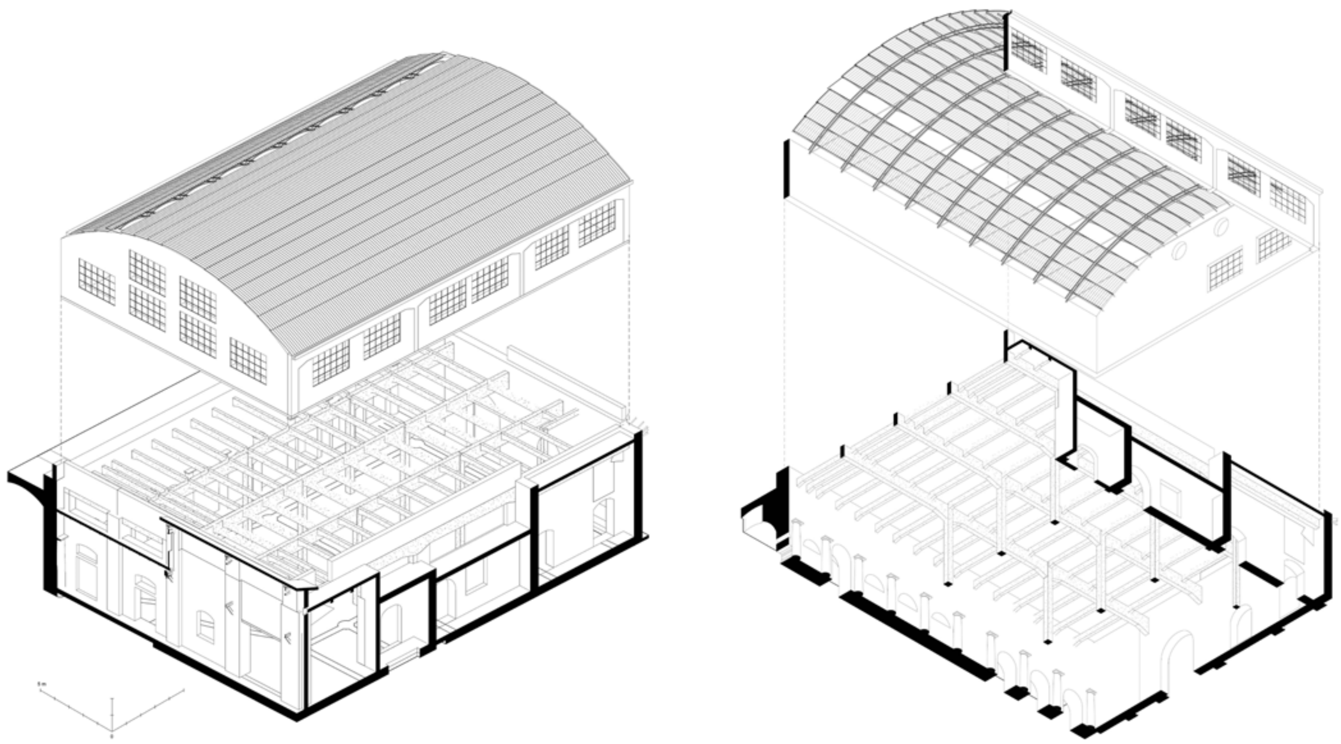


Fig. 7. *Exploded axonometric view of the paper selection room and the processed paper store in the sanctuary structures.*

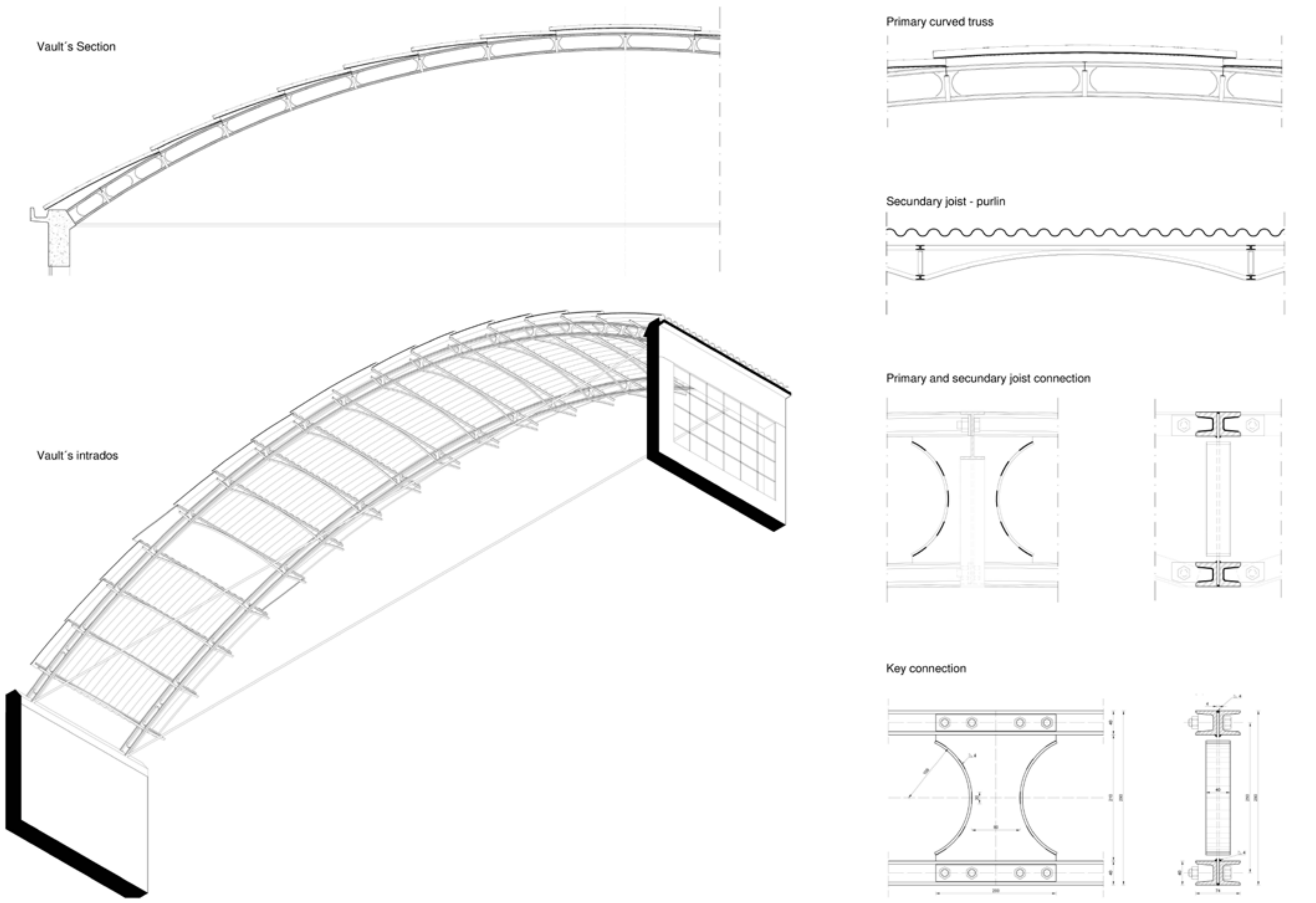


Fig. 8. *Construction details of the metal vault of the paper selection room.*

4.2. APPLICATION AND DISSEMINATION OF THE BUILDING SYSTEM

Behind such successes is the enduring partnership between engineer Badoni and the designer. It was from 1930 that the latter worked steadily with the historic Antonio Badoni firm, which was headed by Giuseppe Riccardo Badoni. For the Badoni firm in 1934-37, he dealt, among other things, with the metal structures to be built for the Feltrinelli House designed by Lodovico and Alberico Barbiano, confronting more closely with the themes of the new architecture to which he would later make his notable contribution [19]. In addition, Badoni had established «permanent connections with Rome, where his correspondent is Eng. Adelchi Cirella, who takes care of relations with the various ministries». It was to Cirella that Covre was addressed when, in 1935, he moved to Rome [20]. The association strengthened over the years, so much so that «in 1946, an office of the Badoni Company was established at the office of Eng. Gino Covre to coordinate and develop the technical-commercial work resulting from Eng. Covre's expertise and the use of his patent for the welding of steels applied to large infrastructures» [18]. Giovannardi also notes that Covre's biography [21] is still far from complete, and this small case study can contribute, with the questions it raises, to open a window on the early years of the Roman period, which, with good reason, can be considered those of the designer's establishment in great engineering and thanks to which the fruitful and lasting association with Pierluigi Nervi and many other engineers less familiar with metal construction will also be born. It is worth mentioning at least one other outstanding example, the metal solution for the arch of E42 worked out by Covre with Badoni, for which full-scale samples were also built.

As the Badoni firm itself stated a few years later, the works for light industries, or exhibitions, «are the prac-

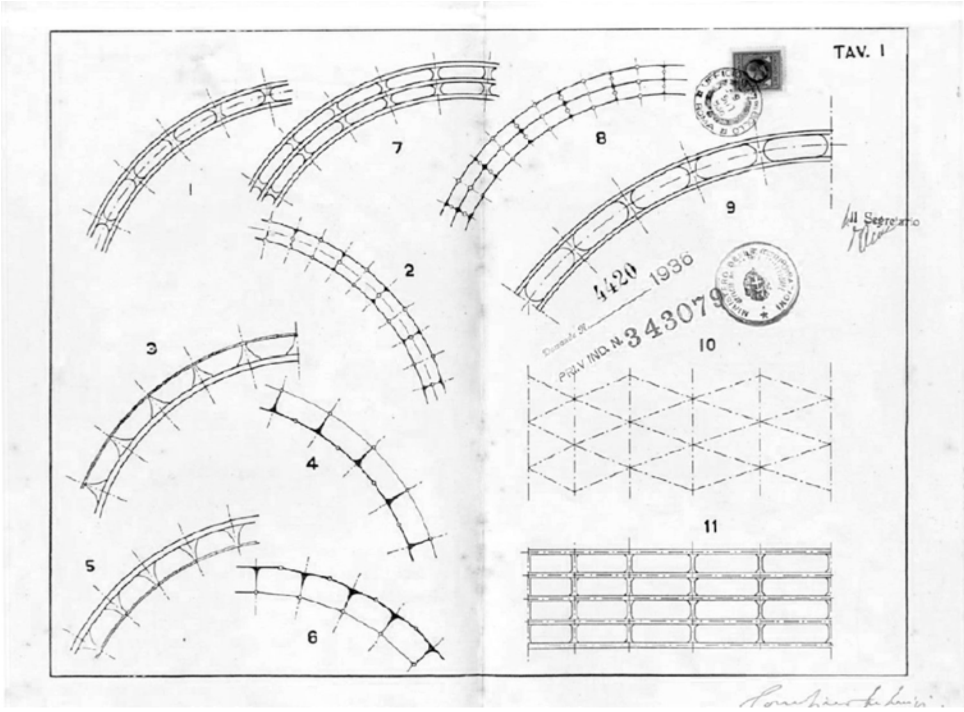


Fig. 9. *Patent n. 343079 / September 10. 1936 «Vaulted arch, composed or constituted with framed components» by Gino Covre, son of Luigi © ACS.*

tical application of the brilliant results obtained from a profound study of engineer Gino Covre on the theory of solid-element structures […]. The Covre-type structures are all electrically welded and bolted together at assembly […] these structures, given their characteristics, are easily assembled and disassembled, allowing the integral recovery of the structure itself and its subsequent reuse» [18].

The construction solutions of the original patent are finally applied in the construction of the great cross vault of the Palace of Congress at E42. They were not only an initial start of later design research; when convenient, the designer adopted them again for many years. They are found, for example, used in the construction of three pavilions for the 1951 Milan Expo, each measuring 20x72 m in plan, plus a projecting canopy of 3 m. For a total covered area of each pavilion of 1,600 square meters, a quantity of only 36 tons of steel was used, and the three halls were also built in only 50 days (Fig. 10).

Fig. 10. *Left: the cross vault of the Palace of Congresses and Banquets of Rome E42 under construction © 1939 ACS. Right: the Agriculture Pavilion, Milan International Exhibition © 1951 Badoni Archive - Polimi.*

5. SACRED PLACE AND SUBSEQUENT REUSES: DEMOLITION AS LOSS OF HISTORY AND IDENTITY

The research also compels some further considerations. With the secularization of religious property in the Napoleonic era and following the Unification of Italy, many new productive functions came to settle in many sacred places, churches, and convents, among other reuses. After the requisitions, many examples of religious typologies were subject to major changes in use, and all of this is an emerging theme of relevant interest for understanding our built environment and the relationships that innervate the historic territory. The presented case study comes from a longer historical event in time, but in its palimpsest, there are traces of numerous transitions through productive uses and religious centralities. Originally settled as a sanctuary, it provided countless functions inside it, making it a territorial centrality [22]. With decadence, it had several processes of reuse, parceling, reduction of the area used, and partial renaturalization. It housed monastic communities and churches, an important part of the sacred area became a fine vineyard, and, within it, more and more productive and industrial initiatives took place, thanks to the waters that never stopped flowing through it and, indeed, from the construction of Villa d'Este onwards increased considerably.

It is also undeniable that the Sanctuary's structures, especially the ornamental ones and those in elevation above the imposing substructures, are now lost, and the remaining ones are significantly compromised by the many events. In this condition, they have formed an organism with the items of the various structures that have been superimposed on it that have opened up new meanings, paths, and relationships with people, the city, and the land. Today, the area is fenced as an archaeological site of cultural interest, scientific research, and public enjoyment. The co-presence of the signs of ancient and modern sacred events, as well as of ancient and modern productive ones, requires the utmost caution with respect to the removal of non-antique elements; indeed, it demands a careful reading of them, on a par with those of the Roman age, as only from this can arise an understanding of the processes that have taken place and the changes in the original organism. The alternative is a cultural and social impoverishment of the "city of water, electricity, paper, and landscape". Such impoverishment would, however, be associated with the objective difficulty of understanding the archaeological ruin if entirely stripped of the traces of its successive uses. Moreover, the presence of an industrial and architectural history made up of firsts and excellences is in itself a reason for cultural recognition, and the comprehensiveness of different values can only make the site even more unique.

6. CONCLUSIONS

The specific study, which emerged as part of an all-round investigation of the archaeological-industrial object, required the involvement of many skills. The whole activities, research, architectural survey, construction investigation, and HBIM process (which allowed the systematization of archival data, literature, history, and direct comparison with material data) made it possible, in general, to place the lost Covre's works in Tivoli, in the broader unfolding of the local or global architectural and construction issues [23]. This is a case of heritage loss due to a choice made at the end of the 20th century because of a value selection based on principles that do not respect the different eras of the landscape and industrial objects. In fact, the pavilion's roof survived until the late twentieth century; the Superintendence authority demolished it as part of a larger demolition plan that affected many vestiges of the factory. The study was also an opportunity to see how Covre's patent was used as an alternative to another relevant, little-investigated autarchy patent for lamellar vaults, the Cametti. This one, used, for example, for the vaults of the Ostiense station in Rome, is based on metal-slat/lamellae, in direct reference with Hugo Junkers' patent used from the hall of his 1929 Kaloriferwerk.

Unfortunately, the haste of demolition of Covre's works was not accompanied by an industrial archaeological or construction history study, resulting in two levels of misunderstanding. On the one hand, the non-disclosure of the general value of the phases of construction and use makes places like this sacred and productive, a special reservoir of information about the centuries-old history of the community, the settlement, and the site. On the other, the value of the object itself [14]. Research and modeling tools make it possible to bridge part of this historical gap and carry forward a cultural memory of dual value that would otherwise be completely lost. The absence gives new importance to all the existing traces – photographic, documentary, construction site – that could provide, in an investigation at this point focused on a lost heritage, the valuable elements to understand the built object and place it in what appears to be an exceptional affair: Gino Covre's experimentation in the autarkic phase with vaulted metal structures for large spans, by means of a significantly reduced use of material [20]. From what has emerged, the work deserves such a study, as it does not appear in the studies so far [20, 21, 24]. At the same time, it seems to constitute a pioneering use of the system patented by Covre in 1936, and, finally, because it was precisely on the basis of the same system that he proceeded to design some large works in metal construction just a year later, such as the roofs for the new pavilions of the Innocenti company, but especially the roof of the E42 congress building by Adalberto Libera (1939-41). Perhaps also belonging to this group of works, to what may constitute a "heritage series", there is a hangar built for the Littorio airport also in 1938, currently under study by the authors.

A distinctive trait of the most influential events in the history of construction is precisely that of starting from the experimentation of a new insight found in individual cases, completed works and research, and then arriving, after many and repeated trials, at the elaboration of an overall vision to be subjected to the scrutiny of the present and future times. Thanks in part to the work conducted on the occasion of the "Archivio in-vita" exhibition, desired by the heirs, the Milan Polytechnic, and the Municipality of Lecco, on the Antonio Badoni archive, the time is ripe for a widespread investigation of Covre's works, for whom questions are opening up about a prolific and brilliant career as a designer-inventor attentive to the needs of industry and architecture, from the Milanese season to that of Rome, to that of the postwar period, from his association with Badoni to his collaborations with Nervi, and with many other architects of his time [25]. Issues not only of the science and technique of building but of architectural authorship as a whole and of a major contribution to the renewal of the spatial qualities of his time.

Acknowledgments

Scientific collaboration agreement on "Industrial Archaeologies of Tivoli" between Dicea-Sapienza University of Rome, Aipai-Italian Association for Industrial Archaeological Heritage, and Institute of Villa Adriana - Villa d'Este Ministry of Culture. P.I.: E. Currà, S. Del Ferro, L. Bernardi.

Authors contribution

Conceptualization, E.C..; methodology, E.C.; historical research, E.C., A.D.P., R.R., general supervision, E.C.; survey, A.D.P., R.R., M.A., E.C.; digital model supervision, M.A., A.D.A., M.R.; digital model elaboration, A.D.P., R.R.; drawings, A.D.P., R.R.; writing, E.C. § 1,2,3,4,5,6; A.C.D., V.S.S. § 5, 6; A.D.P., R.R., M.R., A.D.A. § 6; reviewing, M.R., A.D.A.

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DIGITAL REPRESENTATION STRATEGIES TO REVEAL THE CULTURAL SIGNIFICANCE OF CANADIAN POST-WAR ARCHITECTURE

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

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DOI: 10.30682/tema090002

This contribution has been peer-reviewed.

Abstract

Considering the growing attention on the architecture of the second half of the 20th century and the rising issue of its documentation and interpretation, an operative methodology is presented to support knowledge production activities and conservation. Post-war architectural lexicon materialized spatial narratives from the '50s up to the present. These spatial narratives can be visualized through analogic or digital drawing to gain in-depth knowledge and support interpretation and analysis.
The proposed documentation strategy emphasizes the opportunities for digital representation in revealing and interpreting the post-war architectural lexicon. The potential advantages of employing digital survey and representation techniques for information visualization and management are being discussed in relation to the Strutt House, designed by Canadian architect James W. Strutt between 1951 and 1957.
The study encompassed a thorough examination of primary and secondary sources, a comprehensive survey, and the experimentation with various modeling approaches in the SCAN to BIM procedure, with the final aim of comprehending the significance, purpose, and cultural value of documented characteristics. The adopted approach exploits the opportunities of geometric 3D modeling to visualize complex structures and semantic enrichment in an HBIM environment to support the knowledge, interpretation, and preservation of this outstanding example of Canadian Post-war architecture.

Keywords

Digital documentation, Visualization, HBIM, Canadian architecture, 3D modeling.

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1. INTRODUCTION

The second half of the 20th century generated unprecedented typologies and an incredible variety of architectural languages. Heterogeneous examples range from the Sydney Opera House by Jørn Utzon to the architectures by Lissoni, Quaroni, Passanti, Giò Ponti, Portoghesi, Rossi, Bottoni in Italy or to the building by Victor A. Lundy, Paolo Soleri, Frank Gehry and several others in the States. However, the role of this architectural production as a representative example of collective memory has only been recognized and studied recently. Its protection poses the question of the values of recent memory whose survival depends on two elements: protection by the law and the sensitivity of the designers called to intervene [1].

Recent policies grounded on an ecological and economic vision put this tangible and intangible heritage even more at risk. These risks include several types of building interventions, such as the loss of constructive details and solutions (once thought consistently with the quality and specificity of the single materials); the adoption of invasive recladding systems that deeply alters facades and their architectural language; the variation of windows' profile, the replacement of entire facades; the addition of volumes and other kinds of retrofitting intervention (such as the installation of photovoltaic systems) that distort buildings' image.

Unfortunately, a summary redevelopment and retrofitting of the built heritage, from 1945 until nowadays, has already shown its results. A study conducted in 2018 about the outcomes of the energy requalification process resulting from the low carbon policy showed the reduction of the architectural quality and the negative social implications of this kind of redevelopment [2]. In this framework, several researchers, such as Franz Graf, are looking for new and more adherent models for the redevelopment project of residential buildings in the second half of the 20th century that require accurate knowledge of pre-existing structures.

Considering this common set of problems with a worldwide dimension, the present contribution illustrates an operative methodology to support the understanding and dissemination of the defining features of architecture through digital representation tools. The proposed workflow is further implemented on a representative example of Canadian architecture built in the '50s. The article focuses on the documentation, visual understanding, and interpretation of the house architect James W. Strutt designed, exploiting the opportunities of digital representation and 3D modeling in fostering a coordinated and comprehensive knowledge base of the constructive system. The research opens several application pipelines that are illustrated and debated, paying particular attention to the replicability of the adopted approach.

The research stems from a collaboration between public and private institutions, including the Fondation Strutt Foundation (FSF), the National Capital Commission (NCC), and the Carleton Immersive Media Studio (CIMS) lab.

2. THE METHODOLOGY

The goal of this contribution is to propose a documentation strategy to support the transmission of knowledge about post-war architecture and the nature of its significance. The final aim is to raise awareness about the importance of conserving these architectural structures, store and transmit knowledge about their evolution and significance to society, and support their preservation. Considering previous concerns, an inductive approach was adopted to ensure that the developed framework is tailored to the particularities of the object under study.

The case study of the Strutt House, built in the '50s by the architect J. Strutt for his family, has been studied. Data collection activities included site visits, *in situ* studies, a literature review, and multiple interviews with a selection of specialists to verify, complete and expand the existing knowledge base. A global framework was established to guide the documentation of the case study and the definition of representation strategies to reveal the fabric's significance [3]. The proposed method can be implemented in other contexts to identify replicable strategies for disseminating knowledge about post-war architecture.

3. THE SIGNIFICANCE OF THE CASE STUDY: THE STUTT HOUSE, AN ICONIC CANADIAN ARCHITECTURE

The Strutt House is a Recognized Federal Heritage Building and a significant example of Canadian architecture located in the city of Gatineau, in the Canadian province of Québec [4] (Fig. 1). The house is one of the most iconic masterpieces of James Strutt, an influential architect in post-war Canada. One of the most outstanding qualities of this design lies in its modularity, which is omnipresent in all dimensions [5].

The design of the house enhances the building's structural efficiency, spatial organization, and the expression of its aesthetic qualities. Also, the expression of the building's structure through its materiality allows the visitor to perceive the intelligence and rationality of the design from all indoor and outdoor spaces. The use of experimental building materials and assemblies, the

Fig. 1. *Strutt house location and its relationship with the topography of the surrounding natural context. Processing by authors.*

integration of technologies, and the implementation of new constructive techniques for the wooden hyperbolic paraboloids are all evidence of the architect's innovative attitude.

The Strutt House is a representative example of the architect's research on non-orthogonal and naturally structural geometries and weight efficiency ratios. Concerning Strutt's experimental attitude, his research in non-orthogonal geometries was driven by several intentions. On the one hand, he intended to offer spatial qualities that can be found in the natural environment, such as caves. He wanted to create stimulating and inspiring spaces regardless of how he worked with orthogonal compositions. Wide and narrow angles, inclined roofs, Hyperbolic paraboloids, also referred to as hypars, and other features of his Architecture give an organic dimension to his houses indeed. On the other hand, his research in geometry followed functional purposes. For instance, in the Strutt House, the Canadian architect took advantage of every single corner, optimizing the use of space. If the house spaces seem very small when looking at their square meters, the architectural qualities and the functionality of the place give the visitor the impression of a very spacious building (Fig. 2). These explorations allowed him to improve his constructions' cost-effectiveness as it optimized the use of both labor and building materials. Further, the importance of the relief and surrounding nature in the house's design and location demonstrates the architect's sensitivity to the preservation of natural landscapes and the permanent dialogue he establishes between his designs and their context. The perception of the qualities of this architecture is intimately linked to the natural beauty of the site on which it was built (Fig. 3).

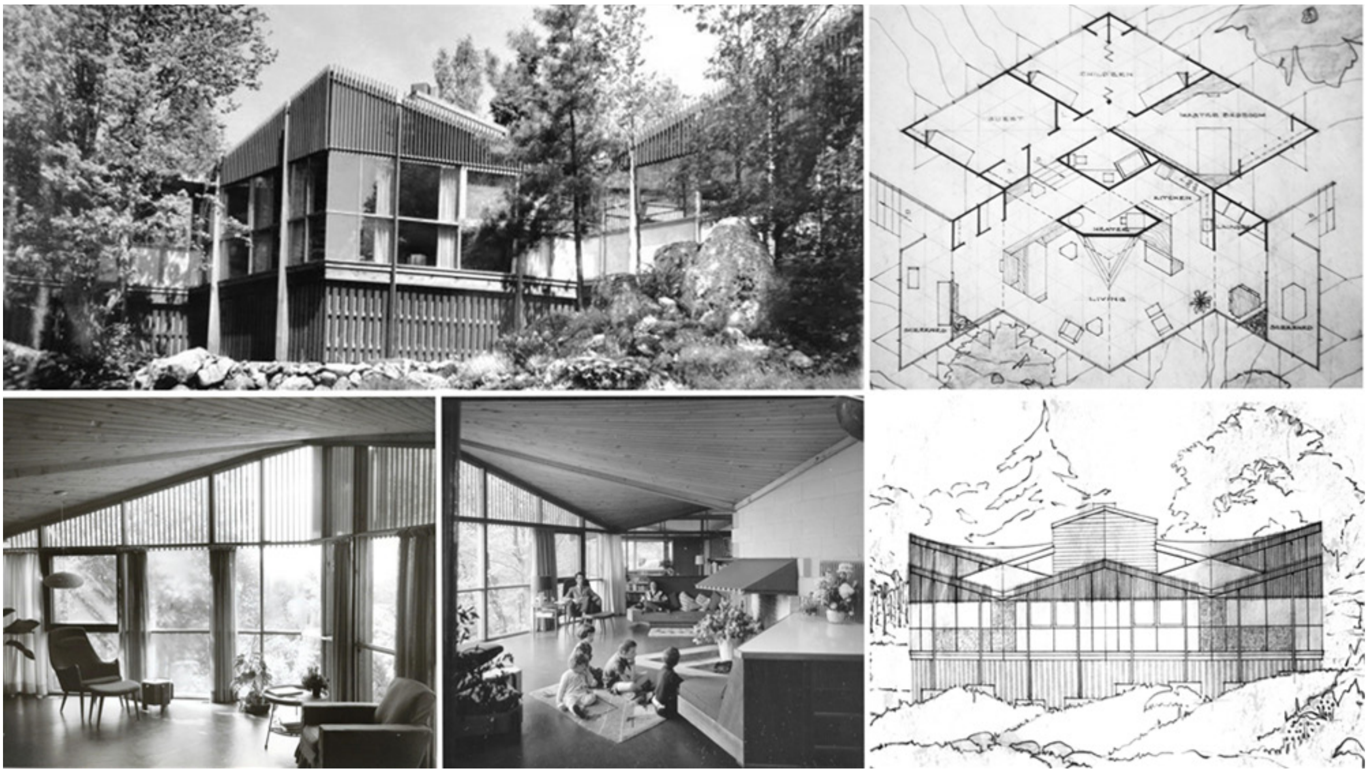

Fig. 2. *The original design of the Strutt House. Source: Fondation Strutt Foundation. Image processing by authors.*

Fig. 3. *The relationship of the Strutt house with the surrounding context. Source: photo 3 was shot by Kristen Balogh, photo 2 by "L'Institut royal d'architecture du Canada". Image editing by the authors.*

3.1. UNDERSTANDING AND INTERPRETING JAMES W. STRUTT'S ARCHITECTURAL LEXICON

For an in-depth understanding of the architectural language adopted in the Strutt house, a brief introduction to the personality of James W. Strutt is needed. Indeed, apart from his studies in Architecture, his experience as a pilot of the Royal Canadian Air Force during WWII strongly influenced his design. The influences of his education and training as a pilot are evident in the structure and the parsimonious quality of the aircraft frame of the Strutt House.

Additionally, during his fifty-six years of work, James W. Strutt showed particular interest and attention in exploring different aspects of architectural design such as weight-efficiency, wooden hypars, the relation between the built and surrounding nature, non-orthogonal geometries, use of wider angles than 90° and a meticulous balance between form and function [6]. He did not limit his Architecture to a single vocabulary, style, or expression. Rather, he always explored different materials and spatial configurations.

In the elaboration of the project of the house (and more generally in most of his works), James W. Strutt defined his concept from the intrinsic qualities and values of the site on one side and the requirements of a project on the other. Then, he gradually applied the most appropriate geometries that would be naturally structural, allowing economical and rational use of materials.

Concerning the influences on his architectural language, the architect was amazed by Frank Lloyd Wright's work and the architectural qualities of the Prairie Style, by Buckminster Fuller for weight-efficiency structure, and by Eduardo Catalano's experimental "Hypars". As reported by Truesdale, «James W. Strutt […] has looked to the master architects of his time and studied what has come before to create a synthesis with, and of, his own understanding of the world around him» [6].

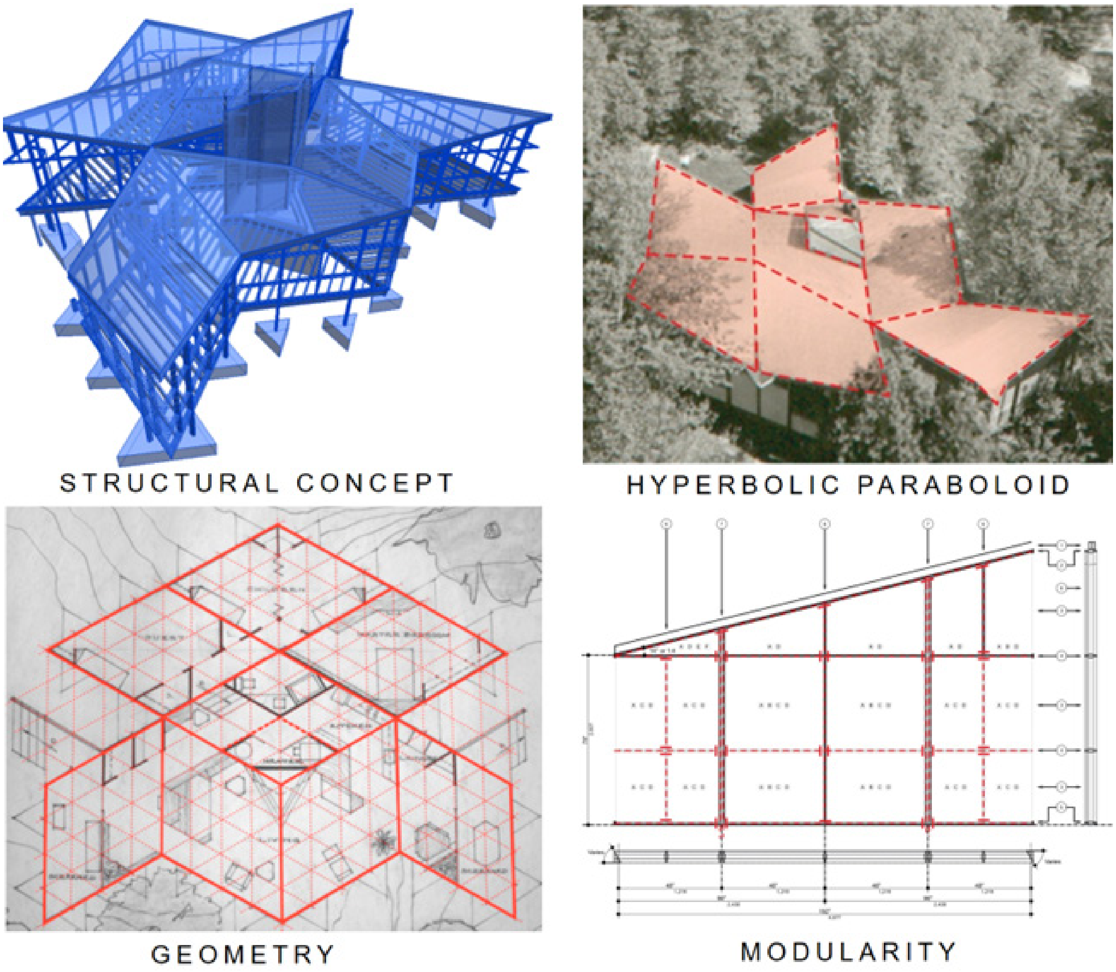

Fig. 4. *Key identified features of the design of the Strutt house that have been interpreted and analyzed using digital 2D and 3D representations. Image editing by the authors.*

Aware of this layered and cultured architectural language, digital 2D and 3D representations supported the analysis and interpretation of the drawn and built project of James W. Strutt, outlining some of the key features of his work, including but not limited to structural concept, hyperbolic paraboloid, modularity and geometry, the latter observable, for instance, in the rhombus grid and the façade walls (Fig. 4).

4. DIGITAL DOCUMENTATION WORKFLOWS FOR THE KNOWLEDGE AND INTERPRETATION OF POST-WAR ARCHITECTURE: THE CASE OF STRUTT HOUSE

Before elaborating on the documentation strategy, significant information about the Strutt House was first collected, analyzed, and interpreted [7]. Several types of sources were mobilized to enrich the knowledge base related to the case study [8]. The following sections describe the adopted documentation workflow (Fig. 5), including the geometric and semantic information modeling in the BIM environment [9]. Finally, a reflection on the opportunities offered by the adopted approach in terms of knowledge transmission and virtual representation is also provided [10].

4.1. THE RECORDING STRATEGY

Considering the functional, evidentiary, associative, and sensory aspects of value related to the spatiality, functionality, materiality, and structure of the place, 3D modeling was considered the most suitable for generating virtual representations [11]. A complete point cloud of the house and its setting was captured with a coherent density to enable the 3D modeling of building components in BIM software. Multiple sensors were implemented to capture the entire point cloud. Terrestrial Laser Scanning (TLS) was used for the topography, the façades, and the indoor spaces thanks to the FARO Focus 3D X330 Laser Scanner. Individual scans were registered and combined in Scene software. Considering the importance of the hypars in the overall significance of the building, the point cloud of the roof was captured through aerial photogrammetry

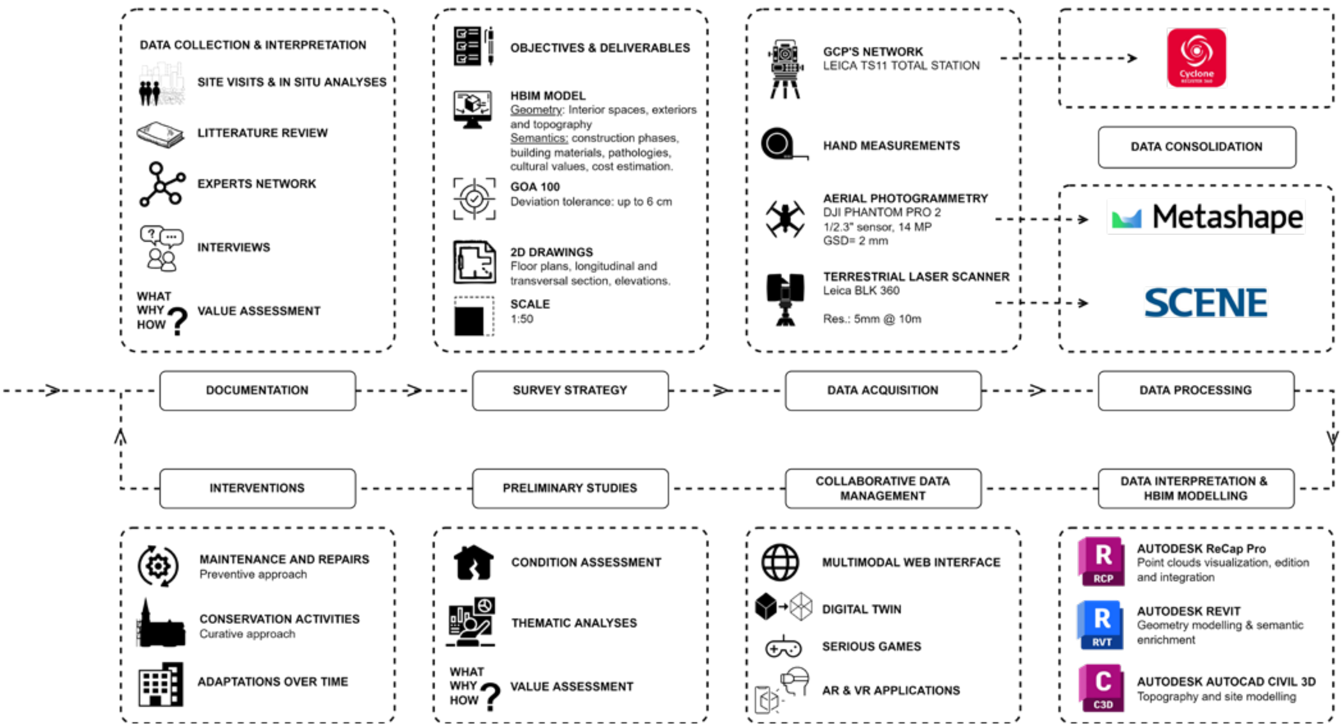

Fig. 5. *The diagram displays the comprehensive method for recording, modeling, and managing data related to the case study. The survey strategy is based on key findings of the documentation phase and particularly on the most important cultural values associated with the site. The figure also depicts the documentation techniques and technology used to capture the 3D point cloud and the software to combine and consolidate individual datasets in a common coordinate system. The following step illustrates the Scan to BIM process, the collaborative management of heritage information, and the dissemination of related knowledge based on the generated HBIM models and other deliverables. Image source: authors.*

with the DJI Phantom 2 pro drone. The data processing was achieved in Metashape. A Ground Control Points network (GCPs) was created to facilitate the registration of individual scans in Scene and to consolidate the datasets in a single coordinate system. The coordinates of the GCPs have been acquired with Refletorless Electronic Distance Measurement (REDM) using the LEICA TS11 Total Station (TS). The result was a consolidated dense 3D point cloud with RGB data (and intensity values for TLS data) of the whole house and the hill's topography.

In addition, hand measurements had to be taken for the accurate documentation of built-in furniture and the survey of key structural elements repeated all over the building (like the 2" by 6" wooden post, for instance). The idea was to enable the comparison of on-site measurements and the captured point cloud with the blueprints of the original design. For the generation of plans, sections, and elevation, we opted for the scale 1:50, considering the absence of interior decoration and details. Regarding the level of accuracy of the 3D model, a grade of accuracy GOA100 [12] was adopted (consequently, the representation of geometries has a deviation tolerance of 4-6 cm).

4.2. THE SCAN-TO-BIM PROCESS

In the Scan-to-BIM process, several workflows for geometry modeling have been considered, ranging from fully manual to more assisted-automated operations. Based on point cloud data, the manual approach implies the direct modeling of buildings components' geometry in the BIM environment as parametric objects. Repetitive elements can be modeled individually if the deviation exceeds the initial tolerance. If not, the parametric object can simply be snapped, orientated, and scaled onto the point cloud until it fits the exact object size and position. Another method lies in the use of a dedicated plug-in that creates multiple sections, either at regular intervals or targeting key geometric primitives, of a portion of the point cloud to enable more accurate modeling of object deformations [13]. It is a relevant alternative for accurate and fast 3D modeling of components. Besides, the "automated" or "assisted" modeling technique lies in the detection of building elements based on the analysis of point cloud data in third-party software, such as Edgewise, through face detection to identify horizontal (floors, slabs) or vertical (walls, doors, windows) building elements for instance. Although this approach is promising for Scan-to-BIM for very recent constructions with standardized components, modeling unique architectural works and their constitutive elements requires a more cautious approach to interpreting survey data. Indeed, it is very likely that important adaptations occurred over time, and it cannot be assumed that everything is as it seems to the eye. The usefulness of this method in this context is also to be questioned, as building elements and related data are often not documented in available libraries. Finally, another possibility is to create a solid mesh of a particular object from point cloud data in a 3D modeling solution like Rhinoceros 3D, for example, to further import it in the BIM environment and attribute it to the appropriate IFC Class.

Given the aims defined for the Strutt House's 3D model, the fully manual approach (Fig. 6) was chosen

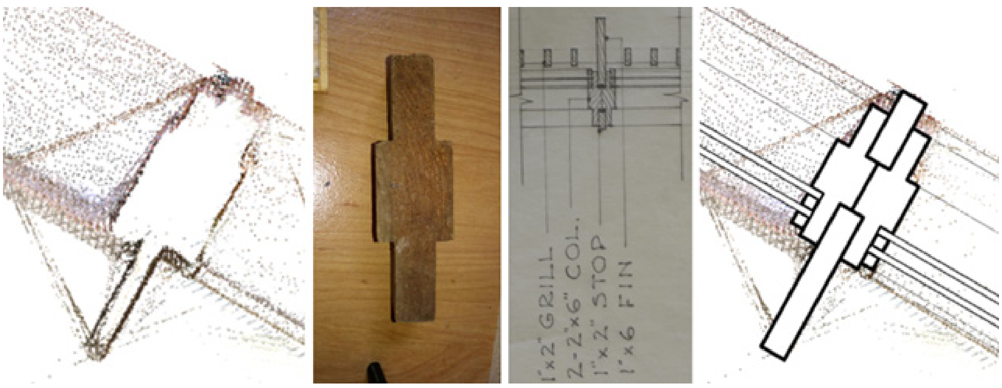

Fig. 6. *Parametric objects have been created as Revit families (right) based on a comparison between hand measurements (center left), point cloud data (left), and archival documents (center right, Canada's National Archives). The significant amount of missing data for complex wooden assemblies led to using the point cloud as a base to locate, orient, and scale parametric objects. The deformations of building features were not represented as they felt under the defined deviation tolerance (4-6 cm). Image edited by the authors.*

Fig. 7. *This image illustrates the modeling workflow with the mapping of parametric objects onto the point cloud and the superposition of the point cloud with the HBIM model of the house (left); an overview of the final model with a section perspective showing the lower and upper level of the house (right). Image source: authors.*

as it allowed for reaching a satisfying Level of Accuracy (LOA) while enhancing the modeling process' efficiency (Fig. 7). Regarding the topography, the terrain model was built based on point cloud data in AutoCAD Civil 3D using Kriging interpolation.

The semantic enrichment of the Strutt House HBIM model was achieved in the BIM environment using the object's attributes [14]. Data about the construction period of components, the pathologies, the associated cultural values, the cost estimation for conservation actions, the order of assembly and dismantling, as well as building materials have been integrated to enable performing condition assessment, thematic mapping on the 3D model, cost estimation for interventions and to evaluate the ability of the model to assist stakeholders in the execution of conservation activities.

4.3. THE OPPORTUNITIES OF THE HBIM MODEL FOR INTERPRETATION AND ANALYSIS

This section explores the possibilities semantically enriched HBIM models offer to support documentation and knowledge. Among the topics explored, the ability of HBIM models to constitute a knowledge base for the archival and transmission of heritage information and to centralize diverse sources of information is questioned. Then, the potential of this approach to facilitate the understanding and interpretation of multiple aspects of post-war architecture in Canada is analyzed.

4.3.1. HBIM AS A KNOWLEDGE BASE

HBIM models allow the storage and classification of geometric data about features of the built heritage and related semantics and, therefore, offer the opportunity to create a digital archive for posterity [15]. In the case of the Strutt House, some information collected during the preliminary study has been associated with objects of the HBIM models. For instance, all building materials used in the construction of this building were inventoried and added to the software library with basic properties. Some experimental materials, such as the asbestos-cement panels used for the façades, no longer meet the requirements of certain standards in the construction industry. In the event of their complete or partial replacement, HBIM models preserve and centralize the necessary data to inform future stakeholders about past states of existence and give them a rapid insight into the site's evolution over time. Although the management of multiple temporal states of an object in Revit is thought to support the planning of construction sites for new buildings, this application can also be used to represent past states and, therefore, inform about the most important development phases along an object's lifecycle.

4.3.2. UNDERSTANDING & INTERPRETATION

Initially, the aim of implementing HBIM in the documentation approach was to create a comprehensive 3D model of the building components and their assemblies to facilitate the understanding and interpretation of complex and irregular elements. The case study of the Strutt House demonstrates HBIM's capacity to enhance the communication of architectural details, concepts, and structural designs. The combined use of 2D orthographic projections & 3D views allows the user to adapt data visualization according to his digital models and drawings expertise. Exploded views of the model in Autodesk Revit were particularly useful for explaining details of and components' assemblies (Fig. 8). The reverse engineering process of modeling the different building features and their interrelationships in BIM software appears as a virtual construction site that enhances users' understanding of many characterizing aspects of the house contributing to its uniqueness and originality. Among other things, the implementation of this workflow allowed to reveal the functionality and role of all building assemblies, understand, and illustrate the implemented structural principles, highlight the modularity and compositional grammar of this architecture in the three dimensions, and the constant quest of the architect for rationality in all aspects despite the apparent complexity of its iconic geometric expression (Fig. 9). In addition,

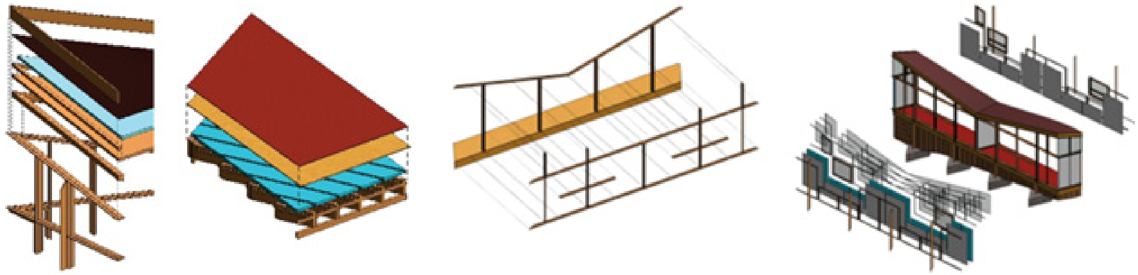

Fig. 8. *Exploded views of the 3D model used to visualize building assemblies and the interplay between building components and materials. Image edited by the authors.*

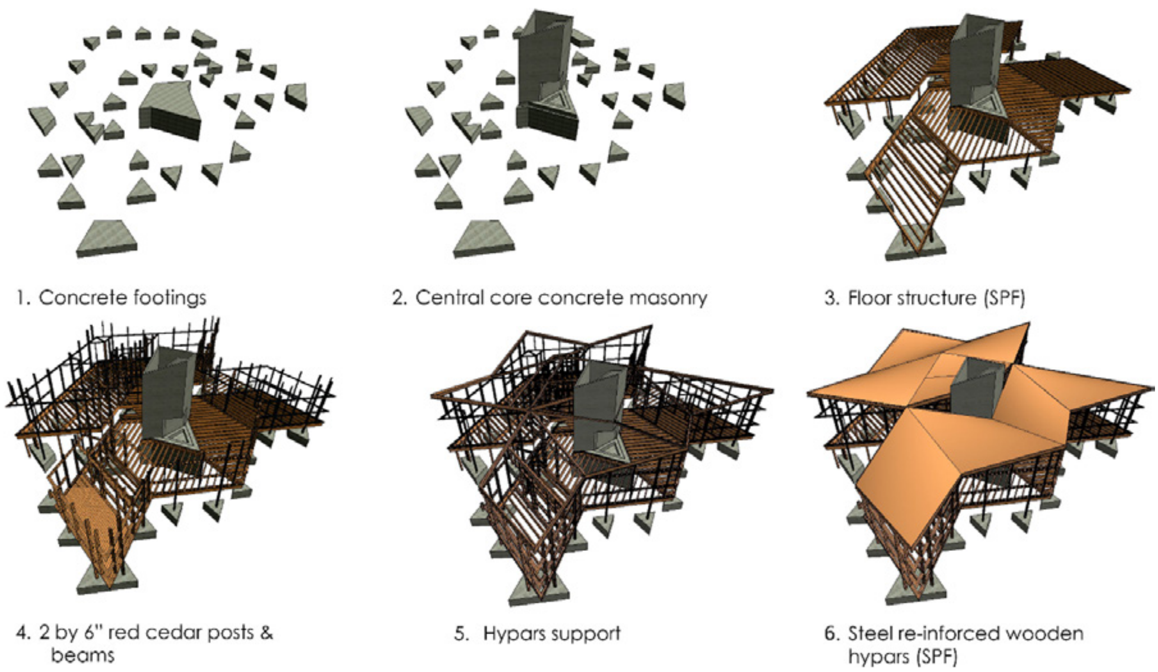

Fig. 9. *This set of perspectives shows the structural concepts behind the construction of the house and the rational principles implemented by the architect to optimize the weight-efficiency ratio and, therefore, the construction's cost-effectiveness. Source: authors.*

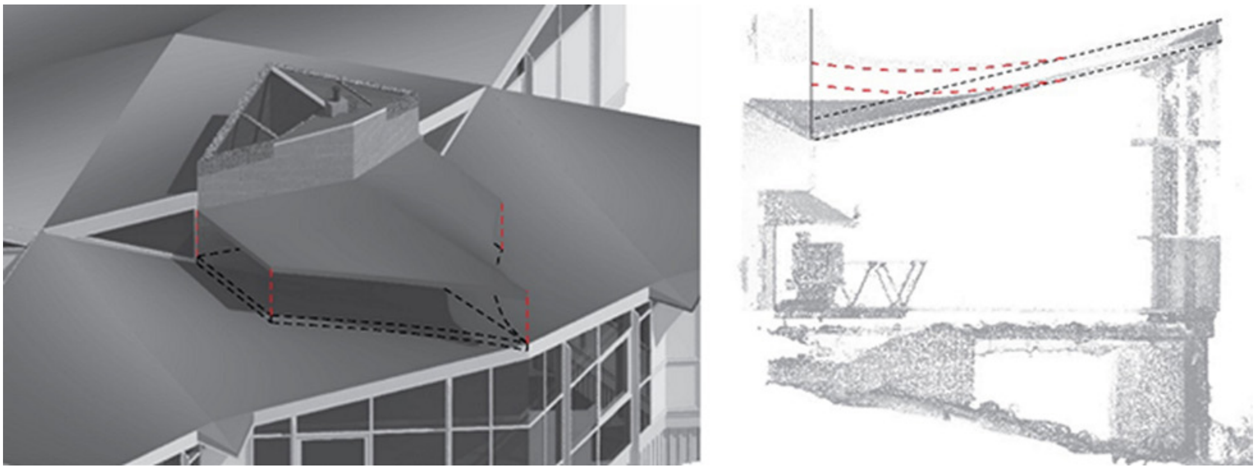

Fig. 10. *The use of the point cloud in identifying changes made to the original design, here with the two additional hypars built on the top of the southern hypars network against the central core. Source: authors.*

modeling the geometry based on point cloud data allows to highlight inconsistencies with the original design. In this case, the survey revealed an adaptation made by the architect quickly after the construction. Water infiltration issues at the house's southern side against the central core led the architect to add two trapezoidal hypars above the original roof to redirect rainwater towards the lower points of the facades' edges (Fig. 10).

4.3.3. SUPPORTING CONSERVATION ACTIVITIES

The HBIM of the Strutt House illustrates the opportunities to integrate geometric and semantic information about the condition and cultural significance assessments by mapping cultural values and pathologies on the geometry of associated features. Considering the specificities of the case study, the model was also used to inform about the order of dismantling of façade walls in the event of a restoration.

Finally, the model supports the communication of the different systems integrated into the building and tracks their evolution along their lifecycle.

4.4. DISCUSSIONS

Even though this research demonstrated the Suitability of the HBIM approach to support documentation and conservation activities related to post-war wooden architecture in Canada, its replicability must be evaluated by implementing this framework in other contexts. Besides, some limitations have been observed in the data modeling process.

Regarding the modeling of objects' geometry, the manual method was found unsuitable for modeling the non-orthogonal and irregular shape of hypars, considering the objectives defined in terms of accuracy. The deviations of 3D objects' geometry exceed the defined threshold at many places. Applying the Nurbs-based modeling approach [16] would allow respecting the deviation tolerance defined according to the adopted LoA [17].

Concerning the integration of semantics in the HBIM model, a dedicated workflow should be defined to enhance the interoperability of the database with other standards in the field of cultural heritage conservation. As indicated by [18], using data standards allows operators to «ensure that information is created in a consistent and valid way over time even through the contributions of a range of individuals who may have varying interests, expertise, and experience». The appropriate standards, controlled vocabulary, and thesaurus must be identified depending on the project goals and the particularities of the case study. A concept mapping should then be achieved to ensure interoperability amongst ontologies and data models from multiple disciplines. For instance, a workflow was proposed to associate knowledge with parametric objects in HBIM models by retrieving data from an ontology-based system [19]. The data conversion and connection between both environments were achieved in Dynamo, the visual programming interface of Revit. Another aspect that requires further attention is the integration of cultural significance data in HBIM models. The latter is particularly challenging as Cultural values are not necessarily positive, “not intrinsic; mutable, not static; multiple and often incommensurable or in conflict” [20] as they depend on the observed object, the observing subject and the context of their interaction [21]. As indicated in previous research [22], communicating such knowledge requires the adoption of a dedicated taxonomy to contextualize and enable multiple representations of the collected data.

Finally, many other benefits can be derived from the information stored in HBIM models in terms of knowledge dissemination and collaborative management of data along the conservation process. The semantically enriched model can be integrated into multimodal web interfaces to enhance its accessibility and usability by a wide range of stakeholders. Such platforms can also be used as digital twins to support preventive conservation approaches [23]. HBIM models integrated into serious games and AR/VR applications can finally help awareness about inaccessible places of significance and transmit associated knowledge [24].

5. CONCLUSIONS: OUTCOMES AND FURTHER RESEARCH PERSPECTIVES

The present study illustrates the role of survey and digital representation to document, understand, interpret, and manage the built architecture of the second half of the 20th century. Through the representative case study of the Strutt house, the research underlines the representation disciplines’ role in orienting and supporting compatible energy-efficient retrofits on post-war architectures in the global trend of carbon emissions reduction. More specifically, the main outcomes of the current research can be grouped as follows:

On a general level:

- The opportunities of digital representation to interpret and visualize the iconic language, the expressive matrix, and character-defining elements of the architecture of the second half of the 20th century.
- The present study tests an integrated documentation workflow and illustrates the relevance and the replicability of the adopted approach for the interpretation, analysis, and documentation of construction solutions and the architectural lexicon adopted.
- The paper highlights the importance of HBIM to generate coordinated representations of complex geometries and the management of related semantics among different stakeholders. The role of an HBIM approach to orient energy-efficient retrofits on post-war architecture is also illustrated.
- The research proposes an operative strategy to document, interpret and represent post-war architecture to orient the global trend of adapting buildings to comply with governmental emission reduction targets.

On a specific level:

- The research contributes to the knowledge of Canadian architecture of the second half of the 20th century and illustrates the potential of the proposed framework to generate targeted representations to sensitize stakeholders about Strutt’s design and its cultural significance.
- The documentation activities and the adopted workflow illustrate the role of integrated survey strategy and 3D modeling in an HBIM environment to visualize the complex architecture of the Strutt house.
- The adopted digital visualization techniques and tools allowed the dissemination of knowledge and the improvement of the understanding of James W. Strutt’s architectural lexicon and his built works.
- The relevance of the case study illustrates, with worldwide lenses, the threats of “sustainable” retrofits for the impoverishment of the built heritage of the second half of the 20th century.
- The present study underlines the pivotal role of digital models and 3D representations in orienting the retrofit process’s social, cultural, and environmental sustainability.

Further research opportunities include the development of an immersive environment that can be derived from a virtual reality (VR) model-based to communicate and visualize the design, architectural structure, constructive details, and functional and decorative elements. Immersive environments can lay the basis for the multi-level information scenario of the adopted case study to enhance the transmission of information. Some attempts at the VR project have been developed in the software application Twinmotion and Unreal Engine 5, which allows a real-time synchronization of the 3D model exported in McNeel Rhinoceros and then in the VR project.

Additionally, the development of an Augmented Reality (AR) project could be a further research line developing an informative layer overlapped on the existing Strutt house to visualize the meticulousness of the constructive details or to visualize the architect's references and source of inspiration for a full understanding of his architectural language. Moreover, the opportunity of AR is particularly relevant to assess the compatibility of recladding and retrofitting projects to represent multiple scenarios in the outdoor and indoor spaces of the house.

Acknowledgments

A special thank goes to Professor Mario Santana Quintero and Professor Stephen Fai, director of the Carleton Immersive Media Studio (CIMS) lab. Additionally, we would like to acknowledge the Fondation Strutt Foundation and Mrs. Titania Truesdale for their support throughout the research.

Authors contribution

Despite this publication being the result of collaborative research, Davide Mezzino wrote: Abstract, Section 1, Section 3, Section 3.1, Section 4.2, Section 4.3.2, Section 5; Pierre Jouan wrote: Section 4, Section 4.1, Section 4.3, Section 4.3.1, Section 4.3.3, Section 4.4.

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BEYOND THE APPEARANCE. OVERWRITTEN HERITAGE COMMUNICATION

TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

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DOI: 10.30682/tema090009

Abstract

The knowledge of an urban space does not end with the collection of superficial information but requires a two-way relationship between subject and object. We are talking about an active process in which man has the opportunity to interact; man is the protagonist of an urban experience that leads him to formalize an image in his mind. If we think about the whole process, the goal is based on a research process, systematization of existing and new data, and, therefore, of all the analyses and studies carried out so far to access a deep knowledge capable of achieving the standardization of the acquisition process. It is intended to establish a codification of data (e.g., texts, bibliographies, maps, drawings, traditional and massive surveys, virtual reconstructions, etc.) in order to create a virtual environment (digital library) of heterogeneous digital models of cultural heritage, from large to small scale, but also of intangible data. From this paper's specific point of view, this research presents a pilot experience that consists of structuring a protocol for documenting the eclectic historical heritage of the city of São Carlos, located in the State of São Paulo, Brazil. In addition to developing the protocol, this research also proposes that its results can be accessed digitally and democratically by society. Thus, it is emphasized that this work is the beginning of a process that does not end in this article, but rather, it will serve for the consolidation and systematization of data with the municipal institutions of São Carlos in order to value the eclectic style, which for many years was placed on the fringes of architectural studies in schools in the country.

Keywords

Documentation Protocol, São Carlos, Eclectic Heritage, Models 1D-2D-3D.

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1. INTRODUCTION

We can consider any urban space as a set of places experienced by man and characterized by the connections between the space that changes over time and the perception of those who live in it. The city is understood as the space of collective memory [1], stratified in a succession of changes linked to the passage of time. This change process has often transformed the urban image to the detriment of the legacy of the past. However, sometimes, we find ourselves in more or less profoundly transformed urban contexts with respect to an original aspect of which we can glimpse all those necessary and essential intangible values that we cannot ignore for the story of the same urban areas with a past that has characterized them. [2]. All these values constitute the "intangible heritage" that must be considered integrated with the current urban structure, of which profound knowledge guarantees us. The relationship between man and knowledge of the city is often difficult to understand; even if the city changes through events very close to the man and to his needs, its stratification is still a complex process, difficult to read as a whole because it is composed of elements that have disappeared, changed and added [3]. The knowledge of urban space is closely linked to the mechanisms regulated by perception, which are considered a tool for investigating the sensitive world [4].

Knowledge of urban space is not limited to collecting superficial information but requires a two-way relationship between subject and object [5]. We are talking about an active process in which man has the opportunity to interact [6], the man who is the protagonist of an urban experience that leads him to formalize an image in his mind [7]. The image thus becomes the synthesis between real and ephemeral, the only means to communicate [8] in an ever more complete and reliable way the perception and values of urban space [9].

Indeed, the integrated digital models (1D, 2D, 3D) are the means of excellence for the construction of the image of urban systems that are no longer usable. They are immediate, and thanks to their similarity with the reality that surrounds us, they can contain and communicate tangible and, at the same time, intangible aspects. This heterogeneity of information embedded within them makes them indispensable in every phase of a knowledge process between past and present.

If we think about the whole process, the goal is based on a research process, systematization of existing and new data, and, therefore, of all the analyses and studies carried out so far to access a deep knowledge capable of achieving the standardization of the acquisition process. It is intended to establish a codification of data (e.g., texts, bibliographies, maps, drawings, traditional and massive surveys, virtual reconstructions, etc.) in order to create a virtual environment (digital library) of heterogeneous digital models of cultural heritage, from large to small scale, but also of intangible data.

From this paper's specific point of view, this research presents a pilot experience that consists of structuring a protocol for documenting the eclectic historical heritage of the city of São Carlos, located in the State of São Paulo, Brazil. In addition to the development of the protocol, this research also proposes that its results can be accessed digitally and democratically by society. Thus, it is emphasized that this work is the beginning of a process that does not end in this article, but rather, it will serve for the consolidation and systematization of data with the municipal institutions of São Carlos in order to value the eclectic style, which for many years was placed on the fringes of architectural studies in schools in the country. Another point is that such a study of the city's architectural heritage still does not exist.

We chose the city of São Carlos as the object of this research for two main reasons: first, we would like to strengthen the Cooperation Agreement between the Institute of Architecture and Urbanism of the University of São Paulo and Sapienza University of Rome (Dipartimento di Storia, Disegno e Restauro), whose activities have been developed since 2018; second, is the importance not only of systematizing information about the entire historical heritage of the city but mainly, focusing on the eclectic period of São Paulo architecture between the end of the 19th century and the first decades of the 20th century, where there is strong evidence of Italian influence.

The development of the protocol can be divided into five moments (Fig. 1):

1) collection of textual data in primary documents, photos, urban cartographies, testimonials, among others (model 2D and 3D) – to preserve the heritage, as well as the cultural manifestations of different societies, this project starts from the need to think about new possibilities for reading information and the problem of the inexistent data in São Carlos about its eclectic buildings. For this moment, we are using the historical methodology to bring into view the influence of Italian architecture from the past on the local Brazilian architecture. Collecting historical data allows for creating a narrative of the urban evolution of the municipality, contextualizing the study buildings;

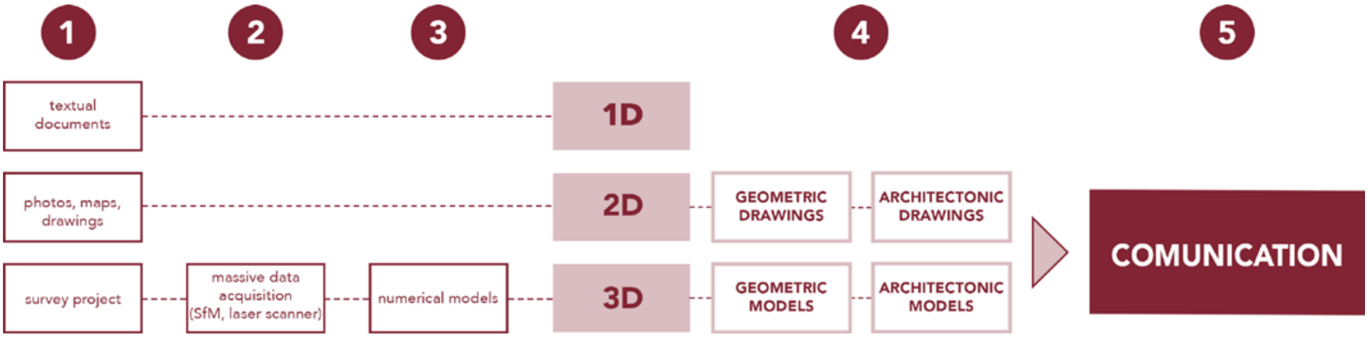

Fig. 1. *The five moments of the Documentation Protocol.*

2) massive data acquisition through 3D laser scanning, digital photogrammetry (SfM), observation of drawings – for this moment, the research focuses on the possibilities of massive acquisition data, not new in Europe (Italy), but recent in Brazil. Because of the high cost of the equipment, the use of the laser scanner is relatively new, and there is no digital database in São Carlos;
3) scientific elaboration of 2D and 3D graphic models – this part of the protocol consists of analyzing the database and creating new information as architectural drawings or 3D digital models. It is essential to highlight that in Brazil, mainly in São Carlos, we do not have plans, sections and facades of eclectic buildings and the few existing materials were executed without precision, which does not allow us to consider them scientific documents, that is, the drawings must be realistic so that professionals from other areas, engineering (pathology), restoration, for example, can use them as support for their work;
4) analysis of the collected data – based on the research methodologies presented by Groat and Wang [10], in this part of the protocol, we used the correlational method since part of the focus of this specific research was based on the identification of the metrics of the classic orders of Italian architecture in the ornaments of the eclectic buildings of São Carlos;
5) this last part of the protocol, the dissemination of information to society, is still under construction and without a defined deadline, as it is a long process. It involves the Qualitative Methodology described by Groat and Wang, in the sense that the evaluation of the impact of the results will not be measured by the scientificity of the products only but by the interaction with which the products will have among users. In this pilot work, it was possible to create a website where digital information can be easily accessed simply using a smartphone. In this specific case, the virtual tour of the CDCC (Centro de Divulgação Científica e Cultural) Building in São Carlos was placed on the public website of USP; this is one of the products intended to be included in the protocol of documentation and communication of the cultural heritage of São Carlos.

The relationships between the population and the urban environment change over time concomitantly with the changes produced by new technologies, space and society. Since the early 2000s, communication and information dissemination have diversified through the possibilities of virtualization and spatial digitization. These digital media have been used as memory support in spreading information and communication virtualization.

The direct interaction with the heritage was the key to the development of this research: the objective is to create a virtual space to place the information collected and shared with everyone. In addition, the virtual space has become an extensive database, an almost exploration territory, essential for citizenship, as it allows society to have direct access to sources of helpful information to know its identity.

Reinforcing the importance of this research, the popularization of smartphones is a fundamental fact that allows even greater access and participation in the understanding and disseminating of cultural heritage by the general population. The virtual representation of the heritage can integrate knowledge of physical properties with other information, allowing for continuous and uninterrupted updating and the possibility of direct communication between government agencies and the local community.

In this way, increasing the number of citizens who collaborate in actions on heritage is possible. Since this interface can reach the widest and most heterogeneous audience possible, it can also encourage them to move around the city in search of the history contained in the places, monuments and buildings.

2. A BRIEF HISTORY OF THE SÃO CARLOS CITY AND THE ECLECTISM STYLE

With a population of 256.915 inhabitants [12], São Carlos is located in the geographic centre of São Paulo State, approximately 230 km from the capital São Paulo.

The city of São Carlos developed with a strong Italian influence. Although the first immigrants who arrived in the city were Germans financed by Antonio Carlos de Arruda Botelho, the Count of Pinhal, the vast majority of immigrants came from Italy. The first Italians arrived in 1886, and until 1921, they formed a total contingent of 9,694 immigrants in São Carlos [11].

The period between the last decades of the 19th century and the beginning of the 20th century, the period called Eclecticism, was chosen as a starting point for this work. This choice is due to its significant historical importance because many cities in São Paulo still preserve buildings from that period and the notorious influence of Italian culture. It is a period with some gaps in buildings' documentation, given the little importance attributed to the style in the history of São Paulo architecture and the fact that Modern Architecture in Brazil, the style that followed Eclecticism, prevailed and still prevails today.

The history of the village of São Carlos begins in 1831, and after population growth, in 1865, the town was elevated to a city. The urban development core of São Carlos do Pinhal – a name referring to the natural forests of araucaria pines existing in the region – began at the end of the 18th century, with the opening of the path known as “Picadão de Cuiabá”, which connected the coast from San Paolo to the mines in the interior of the country. The year 1857 is officially considered the year of the São Carlos establishment [13].

With the arrival of the railways in 1884, São Carlos became one of the largest coffee exporters in the region [14]. In the first decade of the 20th century, the city became one of the biggest hubs for immigrants, mostly Italians from the northern areas of Italy, who arrived to work in the fields of commerce and manufacturing. The coffee crisis in 1929 led Italian immigrants to abandon farming and work in manufacturing and commerce, working in areas such as ceramics, service provision, woodworking factories and civil construction.

Investments in banking and other types of services by coffee growers and the presence of skilled labour in the 1950s made industrial activity the main driver of the city's economy [14]. According to documents referring to the city of São Carlos, Italian immigration greatly impacted the number of inhabitants, becoming the majority in the city, changing not only the field of work but also society as a whole. Among the immigrants who managed to develop outside the fields, we can mention Aurélio Civatti and Alexandre Masci, councillors of São Carlos. Not all Italians came to work in the coffee plantations; many continued to work in the same roles they had in their homeland, so São Carlos had a highly qualified workforce for its urban development [15].

During the period between 1857 and 1929, the economy and social organization of the municipality were structured in the rural environment, where coffee, the main product of the municipal, state and national economy, was cultivated.

With the decline of the coffee cycle at the beginning of the 20th century, the city plunged into a profound economic crisis. Rural-city migration was rising, changing the urban social structure and contributing to new industrial city paradigms. One of the most significant changes, which was reflected in the investigated process, was the approval of a new posture code for São Carlos in 1929.

This article does not intend to discuss the critical debate around Eclecticism; many European researchers have addressed the issue with different positions, but such debates did not arrive in Brazil with the same critical meaning of modernity. As stated by Fabris, «the affirmation of Eclecticism in Brazil does not imply knowledge of the previous tradition, but the radical rejection of the colonial vestiges that persisted in the country» [16]. The aim of this text is only to contextualize the period of construction of eclectic buildings in São Paulo - São Carlos; however, as mentioned above, historical research will be a fundamental part of the process in the protocol of documentation of eclectic buildings.

The transition from colonial to modern architecture in Brazil passed through neoclassicism and many other "neo", whose sum identified the Eclecticism that manifested itself differently in different Brazilian cities. According to Fabris [16], Eclecticism imposed itself as a modern style suited to the modernization process that the country had been experiencing since 1870.

The civil construction and marble works stood out both for their production and the number of Italian immigrants, as many had already brought handicrafts from Italy, and others developed it when they arrived in Brazil, working for the coffee elite and later for the Italian industrial owners.

According to Bortolucci [17], while in Europe, the various architectural manifestations of the 19th century were deeply marked by a process of constant self-criticism, in which they sought to find the "true stylistic expression" of that period, in Brazil, these manifestations were assimilated "without further explanation" and, at the same time, accompanied by a strong sense of "modernity and modernization". "Brazilian eclecticism" was assimilated as a sign of progress and freedom of expression, ignoring any type of philosophical considerations in which European neo-Classicals and neo-Goths were involved.

From the end of the 19th century and in the first decades of the 20th century, in São Paulo State, many Italian builders and architects were corroborated by the arrival of bricklayers and artisans who contributed to registering the Italian influence. The eclectic style of São Paulo resulted from a combination of local and foreign contributions, which spread through the cities of the interior of São Paulo, among them São Carlos.

São Paulo's Eclecticism was characterized by an approximation with neoclassical, gothic and art-nouveau architecture, very present in the ornamental elements of the facades. Several buildings show neoclassical influences, such as the arch in the windows and doors, the Greek pediment, platbands and window and cornice ornaments.

The emergence of *Palacetes* in São Paulo State dates from this period. According to Homem's definition [18], the São Paulo mansion was the wealthiest and most spacious house, built with stylistic precision, isolated from the lot's boundaries, located in the middle of gardens, and with a new internal distribution. With the advent of the railway and the importation of new materials such as slate and ceramics from Marseille, Belgian glass, wallpaper, mosaics, tiles, and marble, among many others, and the arrival of immigrant labour, the rammed earth of the houses was replaced by brick masonry. [17], It was this union of material and technique with styles brought from Europe, Neoclassical, Neo-Gothic, Neo-Romanesque, added to the local construction cultures, which gave rise to Eclecticism in the last decades of the 19th century.

São Carlos still presents examples of eclectic architecture, whose buildings range from public to private, from sumptuous farmhouses to illustrious public buildings and even houses. In São Carlos, we can list some Italian buildings (Fig. 2) and master builders, such as the Palacete Bento Carlos, built by David Pietro Cassinelli, which stood out at the time as one of the most luxurious eclectic mansions in São Carlos due to its size. Cassinelli also built the Palacete Pinhal (1893), the urban residence of Antônio Carlos de Arruda Botelho, the Count of Pinhal [15]. The construction of the Railway Station building dates from this period (1884).

Another example is the construction of the Center for Scientific and Cultural Dissemination at the University of São Paulo (CDCC USP), which was the responsibility of master builder Giuliano Parolo [19]. The State School Dr. Álvaro Guião, the forerunner of the faculties of Philosophy, training several professors for Grupo Escolares, was designed by the German architect Carlos Rosencrantz and built by the engineer Raul Porto together with the master builder Torello Dinucci, developed an eclectic style from São Paulo, inspired by the art-nouveau styles. And neoclassical [20].

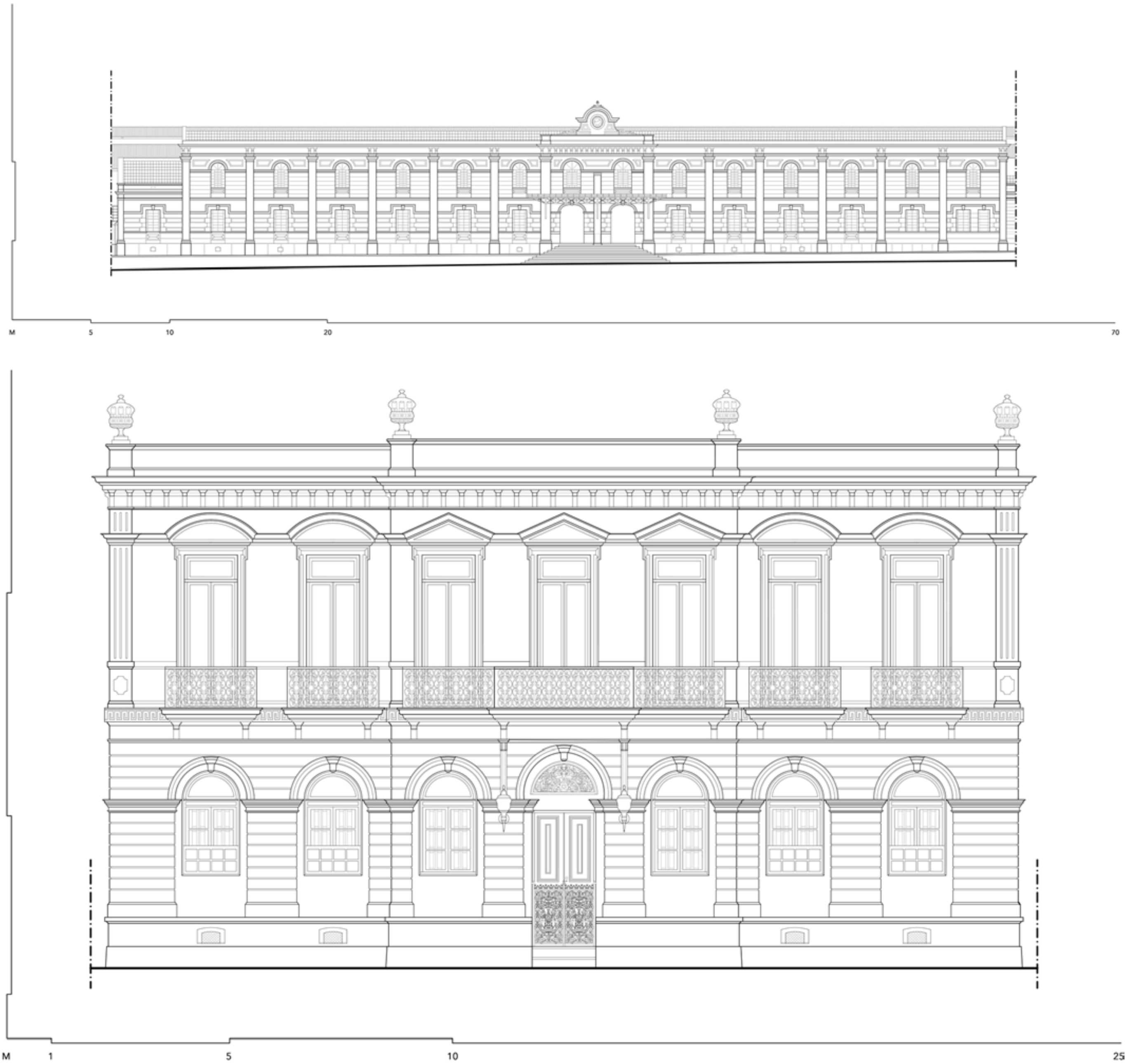

Fig. 2. *Eclectic Heritage of São Carlos City (São Paulo, Brazil): Railway Station building and Palacete Conde do Pinhal, São Carlos.*

3. THE PROCESS OF COLLECTING AND SYSTEMATIZING DATA

Based on the collaboration between Sapienza University of Rome, IAU USP and Fundação Pró-Memória de São Carlos, we intended to frame the objects of study, and based on the documents available, it was possible to analyze the eclectic style. Based on the scientific method, a pilot study was carried out with a classification that can be repeated as a matrix to explore each architectural typology.

The research that has been carried out intends to analyze, classify and deepen the studies on the architectural characteristics of the buildings of São Carlos to create a system of scientific data on the architectural heritage. From the analysis of existing materials, we sought, therefore, to understand the stylistic characteristics that developed in the state of São Paulo between the end of the 19th century and the beginning of the 20th century.

The city of São Carlos has an architectural language that does not fully value the expressive qualities of

Eclecticism, as there is a combination of neoclassicism, neo-Gothic and Art Nouveau that is expressed both in the various decorative elements and on the facades of the buildings. There are many stylistic elements linked to classical taste, but it was noticed that they are treated, both from the graphic point of view and in their execution, in an unreliable and little-detailed way. In civil construction, the use of this architectural language in the city of São Carlos is due to the strong presence of Italian immigrants. These were designers and engineers but also stonecutters and workers who had carried out the projects by often applying variations with respect to the classic European model according to their own knowledge.

As a pilot project for the implementation of the collection, analysis, systematization and dissemination of the São Carlos historical heritage, part of the research started in 2020 will be presented in this article. Among the different existing documentation methods, technologies based on three-dimensional digitization that have recently been highlighted, such as the laser scanner and photogrammetry, which generate mathematical models (cloud of points) and geometric models (mesh). Whether due to the rapid acquisition and generation of data, the extreme precision or the increasing availability, both have proved to be excellent techniques for the three-dimensional digitization of built heritage. Unlike the software used in the creation of models that depend on drawings and empirical measurements, these technologies have the method of capturing points from the object of study itself, in its current state, generating a precise digital model that can reveal imperfections, pathologies and layers of memories in a three-dimensional manner.

Currently, any heritage activity to be developed, whether documentation or restoration, must have a complete and accurate record, so the remote point capture technologies are fundamental for allowing long-term monitoring of the object. Based on this capacity for analysis, in the context of site conservation and management, they make it possible to locate and measure changes in all orders, assess their evolution, and place all interventions, analyses, and tests. Thus, it is possible to perform accurate comparisons of changes in the object of study on a millimetre scale [21].

Mixed techniques, direct and indirect measurements and photogrammetry were used to elaborate the first drawings and models in the process of systematizing data on the Eclecticism of São Carlos. The first step consisted of a bibliographic survey on the history of São Carlos and the architecture of the period. Some cartographic maps were identified; however, there was a significant absence of cadastral data and mainly graphics (plans, sections, facades) of the eclectic buildings of the city. Bortolucci [17] and Benincasa [22] are two researchers who have published material on the subject; however, few technical drawings exist. Thus, given the importance of documentation, we opted for a representation methodology that consists of 1D, 2D and 3D representations and communication of the generated results to the entire community.

4. ANALYSIS AND CORRELATIONAL METHODOLOGY

The buildings selected for the initial stage (2021) are part of a list of more than 100 buildings from the historical heritage of São Carlos, present in the publication of the 4 editions of the "Percursos" Project [23], developed by Fundação Pró-Memória. The objective of "Percursos" is to encourage the protection of heritage, promoting visibility and access to historical and technical information about properties in the city's central area, included in the list of declared assets of historical-cultural interest in the municipality. The second step of work was carried out by examining 38 of the São Carlos historic buildings. They were totally different building types, so it was decided to proceed to the deepening of 8 specific architectures, chosen on the basis of their qualities and on the material (1D – textual materials, 2D – graphic representations, 3D – tridimensional models) provided in order to have a reading of the architectural language of the city.

The methodological analysis was based on a reading of the cartographic and photographic material in the different methods of representation, which allowed the development of a critical understanding of each unique building. Three-dimensional models and typological and proportional analyses were created from the general presentation of the architecture in order to register the detailed characteristics.

The project also articulates actions aimed at promoting heritage education, tourism and dissemination of local culture, integrating various sectors of the City Hall, such as the Department of Tourism and the Departments of Transport and Education. All properties present in the project are included in the list of declared assets of cultural historical interest in São Carlos. In 2021, among the buildings that are part of the "Percursos" Project, studies were carried out on the following historical patrimonies of São Carlos,

1) *CDCC USP – Centro de Divulgação Científica e Cultural da Universidade de São Paulo*
2) *Núcleo Residência Silvio Vilari* (Figs. 7–9)
3) *Palacete Conde do Pinhal* (Figs. 4–6)
4) *Instituto INOVA – Residência Tolentino Guimarães*
5) *Estação Ferroviária de São Carlos – Fundação Pró-Memória de São Carlos*
6) *Residência Militão (antigo restaurante Cabanha)*
7) *Centro Integrado de Turismo – Casarão Eugênio Franco*
8) *Escola Estadual Paulino Carlos*

5. STYLISTIC CATALOGUE

The table (Fig. 3) describes the stylistic solutions for each decorative element of the buildings examined (frames, cornices) both through 2D models consisting of an elevation and a section explaining the geometric-morphological relationships by including a metrological analysis.

The analysis proceeded by examining 38 of the city's historic buildings, all belonging to totally different building types. In this way, it was possible to deepen the 8 specific architectures chosen on the basis of their qualities and of the material (1D, 2D, 3D) provided in order to have a complete reading of the architectural language of the city.

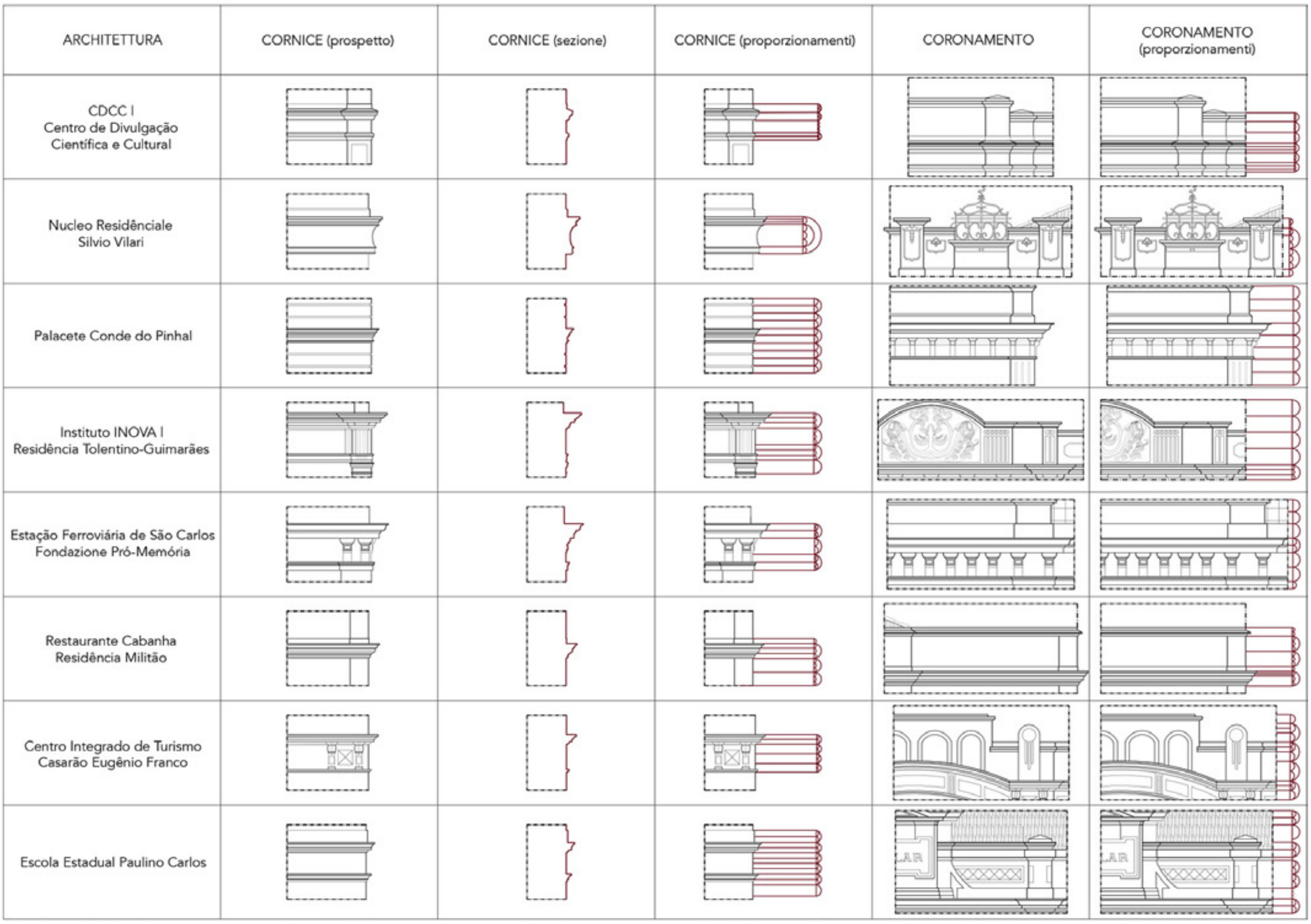

Fig. 3. *Graphic analysis and systematic elaboration.*

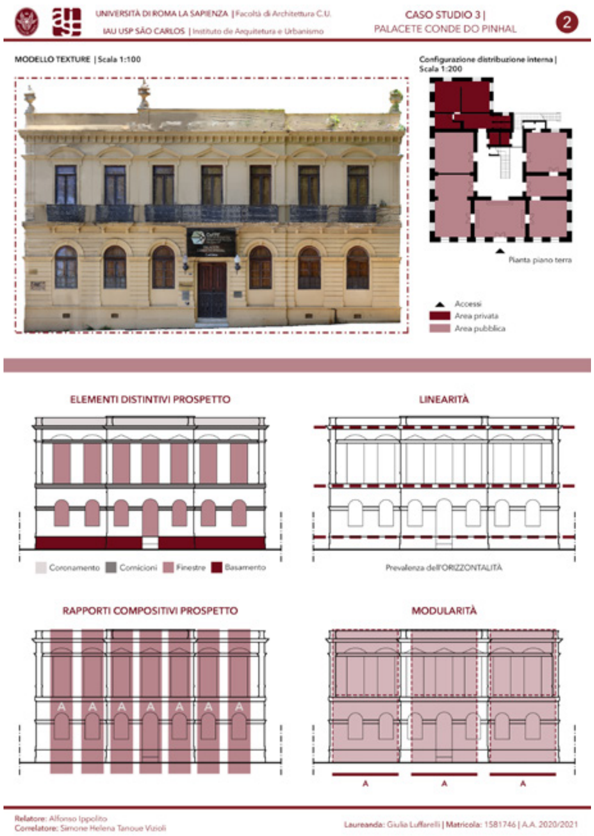

Fig. 4. *Left: Analysis and systematic elaboration - Palacete Conde do Pinhal.* Fig. 5. *Right: Morphological Analysis – Palacete Conde do Pinhal.*

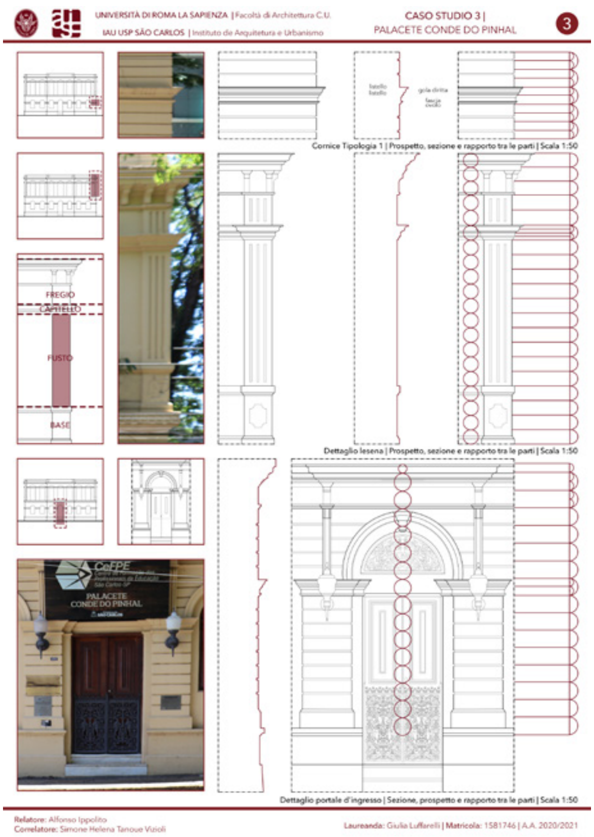

Fig. 6. *Left: Proportional ratios - Palacete Conde do Pinhal.* Fig. 7. *Right: Graphic analysis and systematic elaboration - Nucleo Residênciale Silvio Vilari - Rua Episcopal 1421.*

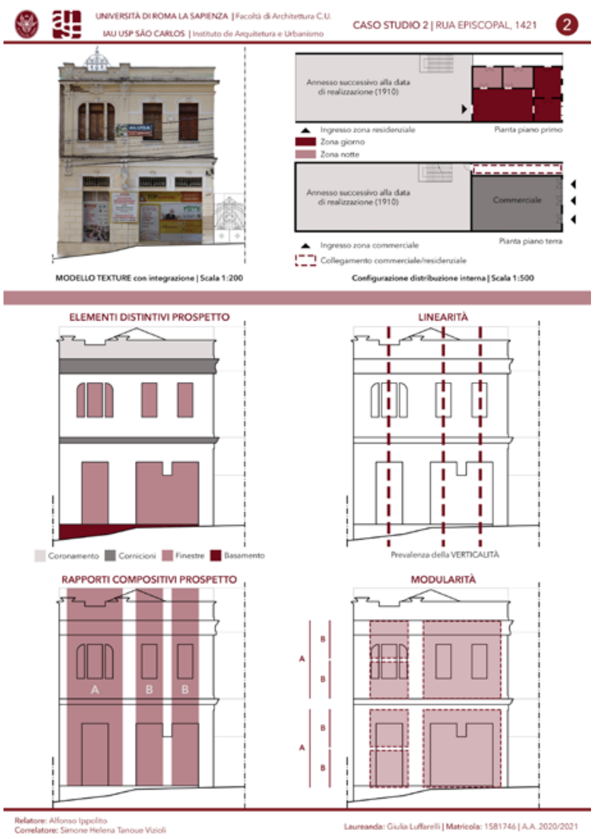

Fig. 8. *Left: Morphological Analysis - Nucleo Residênciale Silvio Vilari - Rua Episcopal 1421.*

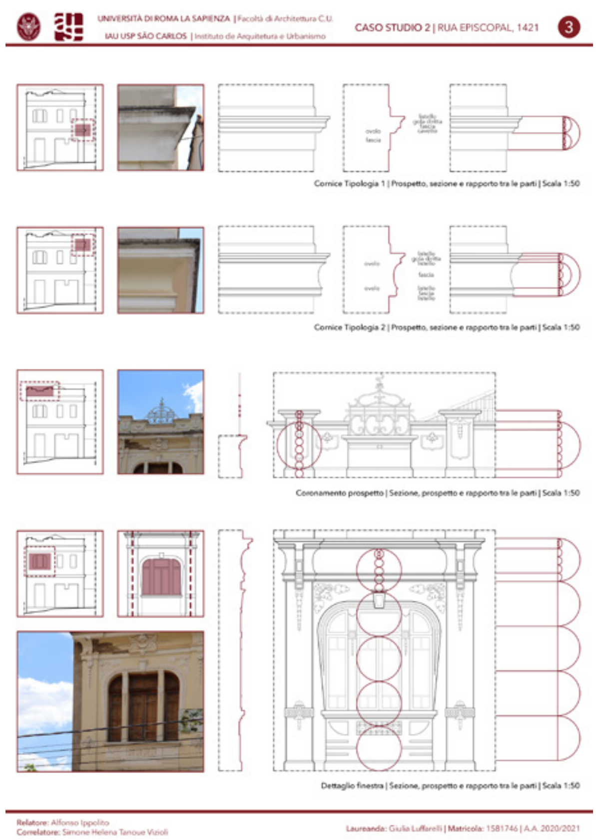

Fig. 9. *Right: Proportional ratios - Nucleo Residênciale Silvio Vilari - Rua Episcopal 1421.*

The methodology of analysis was based on a reading of the cartographic and photographic material in the different representation methods, developing a critical reading that made it possible to study the single building. Starting from the general presentation of the architecture, three-dimensional models, typological and proportional analyses were created up to the definition of the detailed characteristics. For each case study, a process of data capture, graphic analysis and systematic elaboration of the products was developed, as can be exemplified in the following studies.

6. DISSEMINATION OF INFORMATION

The virtual space has become an extensive database, an almost exploration territory, essential for citizenship as it allows society to have direct access to sources of valuable information for knowing one's identity. The dissemination and interaction of information about cultural heritage to the general community can occur in different interactive ways, among them, communication through QR-Codes placed directly on the buildings, through informational totems scattered at strategic points in the city and also through virtual interactivity, as in the case of the virtual tour (Fig. 10).

As one of the mechanisms of interaction between the heritage and the São Carlos community, in 2020-2021, the Instituto de Arquitetura e Urbanismo (IAU) da Universidade de São Paulo Campus de São Carlos (USP) created the graphic design of a virtual tour to commemorate the 40th anniversary of the Center for Scientific and Cultural Dissemination (CDCC-USP), with the photogrammetry of sculptures, mapping of the main facade and three-dimensional models of objects of historical importance. This interaction is part of the data systematization presented in this paper. The directors of the CDCC coordinated the curatorship and content of the exhibition. The virtual tour has 47 360° views that go through the exterior and interior of the CDCC/USP building, creating the ambience for the virtual exhibition installations. It can be accessed free of charge by computer or smartphone from a link presented below. The virtual tour uses the hotspots

Fig. 10. *Comparison of different modes of communication.*

as variable elements according to the selected panoramic image, enabling different forms of interaction during the visit. Using Sketchfab, links were created to access photogrammetry models, improved in 3ds Max 2020, such as the 3D model of the CDCC façade [24].

7. CONCLUSIONS

The research project developed from an agreement that obtained cooperation funding from Sapienza University of Rome and the Instituto de Arquitetura e Urbanismo (IAU) da Universidade de São Paulo Campus de São Carlos (USP). It moves within protocols aimed at the classification and communication of Cultural Heritage (CH), with the idea of bringing a method for the documentation and dissemination of CH with particular reference to the city of São Carlos to the Brazilian reality. The field of application concerns a stratified context that starts from the early 1800s and reaches today but is poorly supplied with textual and graphic material. The ongoing research attempts to build a repeatable classification model that contains all the information related to the architectural unit studied with the support of 1D, 2D, and 3D models. Regarding the communication of the first results, a website has been built that allows anyone to access this information to provide specific training to Brazilian students and professionals. In this way, a social role is also fulfilled, enabling universal access to scientific knowledge by structuring the memory of the city, previously lost, within the research itself.

Acknowledgements

Fundação Pró-Memória, São Carlos, San Paolo, Brazil.

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ARCHITECTURE AND CIVIC ENGAGEMENT. AN ETHICAL BALANCE BETWEEN SOCIAL, ARCHITECTURAL, STRUCTURAL, AND ENERGY ISSUES IN THE REDEVELOPMENT OF EXISTING BUILDING STOCK

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TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

DOI: 10.30682/tema090010

Abstract

Contemporary architectural criticism is characterised by a dichotomy that could be described as of an ethical nature. On the one hand, the belief is that architecture is limited to the physical dimension of the building. On the other, the understanding of architecture as an expressly media event separated from reasons of physicality. This requires a rethinking of the role of architecture, of a discipline that, to preserve its scientific status, can understand the new demands of cultural and technical interdisciplinarity that characterise the contemporary context. The design practice of AdESA (Adeguamento Energetico, Sismico e Architettonico – Energy, Seismic and Architectural Adjustment) stems from these concepts, a path linked to the analysis of the building's function, genesis, and history. The city, the context and the social aspects of a place are indispensable settings for choices through multidisciplinary contributions that are certainly part of technical choices but, at the same time, a synthesis of them in the public service. The case study of the Don Milani Gym in the Villaggio Badia in Brescia, where the AdESA project was realised, allowed us to enter into the life of the neighbourhood and, through architecture, to generate new relationships, gathering spaces and community dynamics. In doing so, architecture has once again assumed a pivotal role in the design process between the demands of a technical nature and those of responsibility in terms of social and environmental sustainability.

Keywords

Eutopia Strategy, Urban Commons, Combined redevelopment, Offsite Architecture, Suburban Landscape.

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1. INTRODUCTION, METHODOLOGICAL AND DESIGN REFERENCES

In contemporary metropolitan contexts, there are conditions for the reuse of existing spaces and buildings that, as with raw materials, require targeted transformations to convert them in an ecological way. The practices of building renovation are an opportunity to reactivate the city's hidden potential through re-appropriating obsolete spaces and/or updating those still inhabited.

The dissemination of pragmatic design thinking for the ecological redevelopment of the existing building stock – now more than shared at the EU level, given the urgency of reducing the environmental impact of the construction sector – was seen in Germany's participation at the 13th International Architecture Exhibition during the 2012 Venice Biennale as a moment of notable interest for architects and engineers. This exhibition entitled *Common Ground* was curated by David Chipperfield. The title also explicitly alludes to the ground between the buildings and the city's spaces. The projects investigated the meaning of the spaces generated by buildings: the political, social, and public fields of which architecture is a part.

The aim of the German exhibition *Reduce/Reuse/ Recycle. Architecture as Resource* was to clearly make the value of the city in shaping the future of the next generations. According to the general commissioner of the German Pavilion, Muck Petzet [1], projects to reduce land use, together with large-scale urban redevelopment projects, must be approached with methods by which the building stock – built mainly after the Second World War – can be redeveloped through pragmatic transformation strategies. In this way, says Petzet [1], the project of architecture does not lose its quality; rather, it can be improved by new techniques that can acknowledge a complex system of values in the built environment.

This transformation can take place through a paradigm shift in the role of the architect and engineer, who is increasingly more a "developer of the built environment" than a designer of new urban contexts. Moreover, for the commissioner of the German Pavilion, an effective method for identifying new design strategies is to re-evaluate deteriorated existing buildings as "valuable raw materials" [1].

This approach is summarised in the slogan for the exhibition: *3R: Reduce, Reuse, Recycle*, key concepts of the so-called "waste hierarchy". A principle of action on waste materials according to which the least amount of processing is, in any case, the most advantageous in terms of energy savings and ecologically achievable results.

Applying the *3R* formula in architecture can have more or less favourable aspects. This approach makes sense in terms of energy savings by determining, in some cases, the positivity or otherwise of performance upgrading, but it could also impede building and social design developments that attempt to find new uses for existing spaces. In fact, in addition to the energy balance of building processes, in the redevelopment of the built environment, there are other factors to be considered, such as the "hidden potential" in each building in historical, structural, architectural, and social terms, under which it is also possible to evaluate a complete *remodelage* [2] of buildings. Moreover, still, in a design vision of a holistic nature – the building is unique and must be considered in its totality and in the interdependence of the properties (intrinsic and extrinsic) that compose it – it is possible to estimate the degree of improvement achieved thanks to the redevelopment action not only in function of the energy consumed.

In our opinion, the pragmatic criterion of the *3R* formula defines new perspectives of action for transversal design approaches that can include structural, energy, architectural, and social issues through the possibility of juxtaposing technological elements.

However, it is essential not to lose sight of the building's relationship with the urban and social context in which it is inserted.

In the ten years since the German exhibition of the *3R* formula at the Venice Architecture Biennale, the approach described above has produced positive and tangible effects, especially in urban peripheries, places where it is not easy to make relevant contributions, mainly for economic reasons.

Moreover, in these contexts, informal community hubs, often self-managed, are very frequent and charged with welcoming some people looking for sharing and, maybe, for redemption from a problematic everyday life. This aspect can be found in various global urban realities and shows how community activities can regenerate abandoned spaces and/or people's use of them. These examples of collective living become the "trigger fuse" [3] for broader architectural and urban redevelopment plans also in an ecological key.

Today, such design beginnings can be identified in the work of an increasing number of researchers and designers engaged in "weak" and deprived peripheral contexts.

Among Italy's most interesting examples, the project *Civico* is worth mentioning. *LURT, Laboratorio Umano di Rigenerazione Territoriale (Human Laboratory for Territorial Regeneration)*, (Fig. 1) carried out in Riesi, a small urban reality in the province of Caltanisetta, by the "Orizzontale" collective of architects [4].

This project becomes a tool for sharing actions aimed at the social emancipation of the inhabitants and – simultaneously – is a way of denouncing a reality strongly

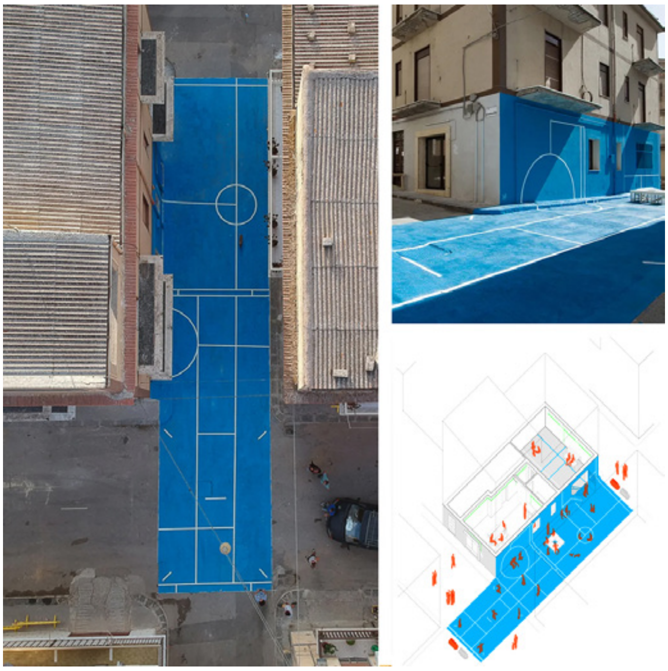

Fig. 1. *Orizzontale, Civico Civico. LURT, Laboratorio Umano di Rigenerazione Territoriale (Human Laboratory for Territorial Regeneration). Riesi (Caltanissetta, Italy), 2020. Source: Orizzontale, La Flora Sita.*

Fig. 2. *Collectif Etc, Le Rin-té, Marseille, 2017. Source: Collectif Etc.*

marked by phenomena of depopulation and marginalisation. The Workshop, in parallel with the sustainable and ecological recovery of existing buildings, proposes a reflection on the abandonment of historic villages in the country's inland areas, which today are experiencing a condition of marginalisation and lack of opportunities.

The project's overall objective – which passes through the planning, implementation, and operational phases – is to create a stable system of relations between people. A community that, when involved in the urban regeneration process and the cultural initiatives activated, can develop a renewed sense of identity and belonging to the neighbourhood. This feeling can, in fact, become the driving force for more sustainable development and a better quality of life for people.

Another noteworthy project was developed in France by "Collectif Etc" in 2017. *Le Rin-té* is a small redevelopment project of a courtyard near a building owned by the *Fraternité Belle de Mai* association, a Voluntary Sector organisation operating in an area of the city of Marseille characterised by a solid multicultural component. The intervention consists, in addition to the energy upgrade of the existing buildings, of the valorisation of the outdoors through the additions of community functions [5].

Adding a staircase to reach the street level becomes a reason to design a seating system for meetings and communal events: a multifunctional space to welcome the inhabitants of the neighbourhood (Fig. 2).

These experiences show a possible way of ecological urban regeneration through the simultaneous use of technology for buildings and socio-cultural mechanisms for inhabitants. The aim is to transform degraded urban areas into many "good places" [6] where new forms of sociality and ecological awareness can also be achieved for the people who live in those spaces.

This paper emphasises the part of the Applied Research Project AdESA, where the architectural and urban regeneration aspects follow the methodological and design references described above. The applied research project was submitted to the Lombardy Region's call for proposals entitled Experimental development and innovation (S&I) projects in favour of the Smart living supply chain, in implementation of Lombardy Region Law 26/2015: Diffuse, Creative and Technological Manufacturing 4.0 and was admitted for funding. The partners involved are the companies Marlegno (Lead Partner), Edilmatic, Harpaceas, the University of Bergamo (scientific responsible: Alessandra Marini) for structural and energy surveys, and the University of Brescia (scientific responsible: Barbara Angi), involved for in-depth studies of an architectural and urban nature. In addition to the scientific responsible in charge, the UniBS team that worked on the AdESA project is composed of Barbara Badiani, Massimiliano Battisti, Massimiliano Botti, Andrea Ghirardi, Renato Marmori, Marco Preti and Alberto Soci.

2. METHODOLOGY: BEYOND TECHNOLOGY-BASED SOLUTIONS

It is precisely in the ambition to intercept the constellation of "good places" hiding within many European suburbs that the AdESA project begins.

The applied research project has a multidisciplinary nature. It offers designers tools that want to go beyond technology-based solutions for applicative experimentation that is also careful to the needs of those who live in those spaces [7].

AdESA is the brainchild of cooperation between different skills that work together from the design phase, thanks to shared design platforms (BIM - Building Information Modelling). The software's use has not only been a technical support of AdESA but has been the conceptual framework in which it has developed (Fig. 3). With this approach, AdESA plans to operate on the built tissue burdened by chronic structural and energy deficits and wants to solve them by limiting energy consumption.

However, AdESA is not just stopping there. It focuses on the people living out of the buildings, trying to increase their ecological awareness through a human-based approach to redevelopment. In the first step, AdESA uses an "engineered skill" [8] to cover the existing building and its urban context by overlapping different layers, each with its own specificity. To be fitted on the buildings, the first layer consists of X-Lam type cross-laminated solid wood panels bonded with the existing structure to correct and strengthen its static behaviour. The second layer, also to be set up on the buildings, is the energy barrier, the materials and size of which change upon the building's thermal insulation needs and the analysis of the climatic context. The third layer is the final surrender of AdESA. It is not the result of a simple *camouflage* of the building but offers the city what it covers: the other layers and their powerful performance (Fig. 4) [9].

Also, this layer is crucial because it returns a new building, and thanks to this "new look", people can find new relationships with outdoor spaces. The issue of the ground connection of a building is relevant to the ongoing effectiveness of an architectural work.

The design of the ground around a building lead to externalising its content – its functions – and linking it with the surrounding city. This layer changes the paradigm of AdESA by transforming hermetically sealed "skin" – for building security requirements – into a "po-

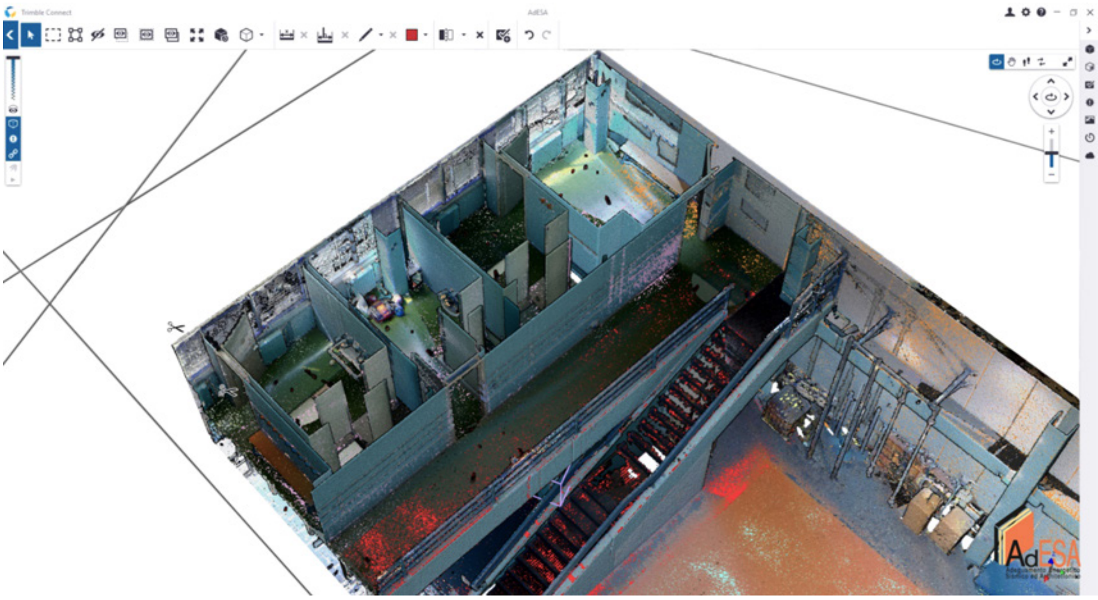

Fig. 3. *The AdESA project, BIM as a combined design tool.*
The mapping of the building and its sharing via the Trimble platform. Source: Research Group (Harpaceas).

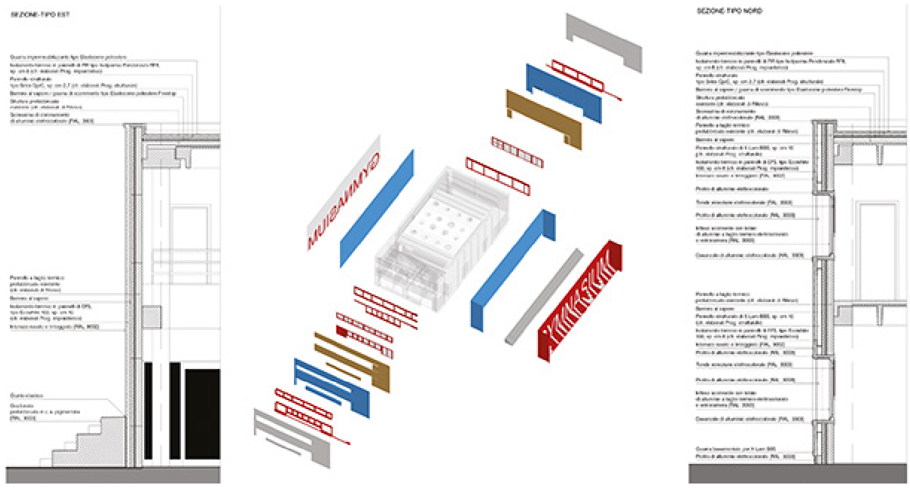

Fig. 4. *The AdESA project's stratifications. Source: Research Group.*

rous blanket". This conceptual blanket can activate social mechanisms for the *Urban Commons* [10] by raising the inhabitants' ethical value of sustainability. This is fundamental to combining highly technical solutions with people's community-oriented solutions.

Furthermore, as Walter Benjamin describes the city of Naples: «Porous as this stone is the architecture. Building and action interpenetrate in courtyards, porticoes and stairways» [11]. Porosity seems to describe, in this passage, the way urban space is executed in the process of appropriation [12]. It is not that action is contained within the space. Instead, a rich network of practices transforms every available space into a potential theatre of expressive acts of encounter.

The fourth layer's characteristics are the study of open spaces, their possible re-functioning, and their relationship with the neighbourhood bordering the building (Fig. 5). This layer deals with the city community through human-centred design [13].

The desire to motivate a renewed awareness in the community with respect to the natural and urban environment is at the heart of ADESA's design concept. This concept is oriented towards the next generation benefitting from the redeveloped spaces.

The first AdESA application was built at the Don Milani primary school gymnasium in Brescia. The construction was the natural link between the building's structural and energy redevelopment and the building's renewed function within the school community. The upgraded gymnasium has become a concrete example of best practice in the energetic and socially sustainable reuse of the built heritage.

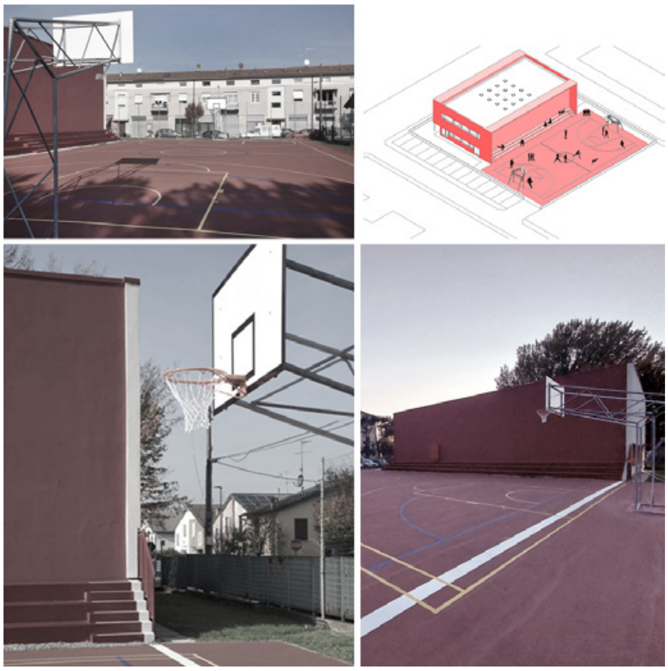

Fig. 5. *The AdESA project's playground. Source: Research Group.*

3. THE CASE STUDY: THE DON MILANI GYMNASIUM IN BRESCIA

«When architecture leaves the historic centre or the urban tissue, the structural module changes definitively. Therefore, the model is the industrial building where functionality becomes the reference element also at a formal level. This is declined under the sign of a repeatability understood in a contemporary way, which originates in

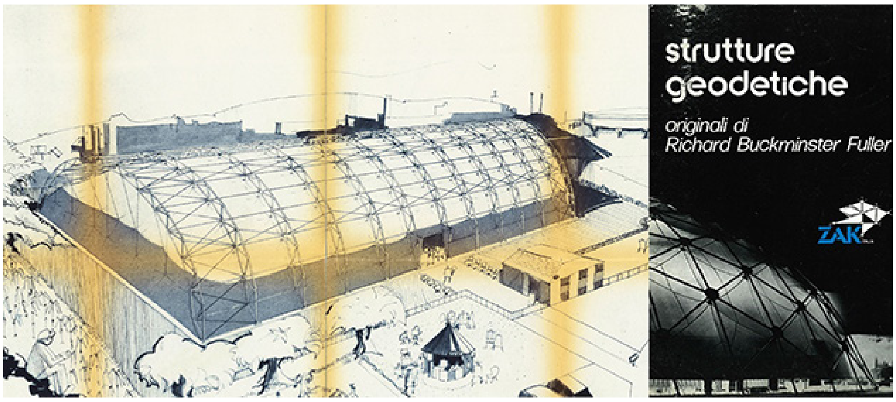

Fig. 6. *'Villaggio Badia' Elementary School, Preliminary project by the Company ZAK with Buckminster Fuller, 1978. Source: Brescia City Council Archives.*

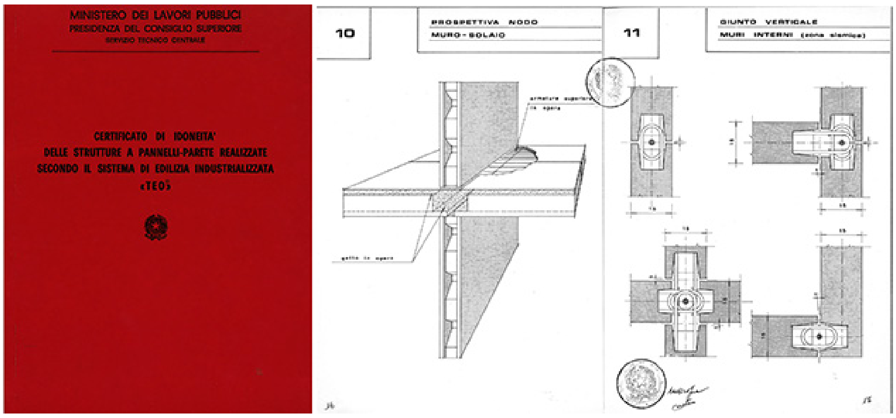

Fig. 7. *Ministry of Public Works, Certificate of Suitability Teo-Valdadige System, 1979. Source: Brescia City Council Archives.*

prefabrication. Consequently, were born the projects for the Messaggero Veneto headquarters in viale Palmanova (1967-1968), the Geatti showroom (1973-1974), the Valdadige prefabricated school (1976)»[14].

The Don Milani Primary School gymnasium is a rectangular building constructed using heavy prefabrication technology in 1980. Its construction was indispensable because the school had no space for physical activity. This lack forces children and teachers to spend their gym time in corridors or undercrofts. The inadequacy of the spaces is obviously functional, but it also involves static safety issues. In fact, the load-bearing structures of the spaces, so improperly used, are not dimensioned for this type of load and are not adapted to the existing regulations.

The preliminary design for the construction of the new gymnasium in the area adjacent to the school was entrusted by the Municipality of Brescia to ZAK Italia, «the exclusive concessionaire of Richard Buckminster Fuller's original geodesic structures», as read in the advertisements of the period [14].

Three contractors responded to the call for tenders [15], submitting the project and the relevant technical documents for economic evaluation. Among these companies was Valdadige s.p.a. from Verona, which won the tender despite not presenting the most economically advantageous solution. The winning company's architectural and structural design is by Gino Valle's studio. Gino Valle's work is linked to the industrial development of north-eastern Italy in the last century. The numerous projects he carried out describe a process of transformation of the Po Valley area, from rural to industrial, demonstrating his ability to meet at the same time all the technical and economic requirements imposed by the client, strong experimentalism of solutions, and extraordinary attention to the relationship with the urban context and the rural landscape [16].

In 1974, the Friulian architect had begun a collaboration with Valdadige s.p.a. to design a prefabricated building system called "Teo" (Fig. 7). The goal of the project was to construct buildings for middle schools, which Italy needed at that time. Around thirty were built with this construction system in Veneto, Friuli, and Lombardy. According to Giorgio Macola, Valle's collaborator at the time [17], at least twice as many were designed.

In this respect, the gymnasium of the Don Milani school represents the first prototype realized with the 'Teo' system that Gino Valle would later use in a long architectural work (Fig. 8).

The structure of the building consists of prefabricated reinforced concrete elements assembled on site and reinforced concrete foundation plinths cast in situ. The pillars, except for the one supporting the mezzanine floor slab, are spaced 6.00 meters apart. All the prefabricated elements, as is customary for buildings adopting this technology, are part of an "Abaco," and each corresponds to a unique identification code. The ground floor accommodates the gymnasium, service areas, changing rooms and the heating plant.

The mezzanine floor, accessible by a staircase that was to become the signature of the schools designed by Gino Valle, has a balcony distribution and houses shower and storage rooms (Fig. 9).

The two long sides (west and east) have blank walls and overlook the street and an enclosed outdoor space. The two short sides (north and south) have ribbon windows with aluminum frames – fixed and sliding – for natural lighting and ventilation of the gymnasium areas and service rooms on both levels. Along the same sides are access doors to the heating plant and the gymnasium (south); an emergency exit on the opposite front (north), along Via Settima del Villaggio Badia. Sixteen fixed domed skylights, evenly spaced on the roof, contribute to the zenithal illumination of the gymnasium. Green areas are planted along the north and south sides and west-facing sides. A perimeter pavement is made of prefabricated concrete grit elements and runs almost attached to the building. The fence is made of painted metal grating (Orsogrill type) mounted on a reinforced concrete wall of variable height. A pedestrian gate and a driveway gate provide access to the area.

Furthermore, as noted, the urban area of the Don Milani gymnasium is the Villaggio Badia in Brescia [18].

The neighborhood retains a morphological layout consisting of the rational distribution of housing units

Fig. 8. *Project location and status elaboration of the original project. Source: Graphic restitution by the research team.*

Fig. 9. *Gino Valle, Schools that were built using the Valdadige system. (Seriate, 1979, Chirignago, 1976, Zelarino, 1977, Negrar, 1980). Source: Gino Valle Archives.*

arranged on individual plots with private gardens. The typological coherence of the semi-detached houses with pitched roofs has been significantly altered over time – due to numerous additions. Today, the image of an architectural approach like English garden cities is only conceptionally visible.

From this point of view, the gymnasium (a box volume built with prefabricated systems) is a foreign object to the urban context of the Badia village, both in terms of building type and the construction techniques used.

The first prototype of the AdESA project was applied to it and its outdoor area without demolishing the existing building. Therefore, the case study was redeveloped by juxtaposing the "engineered skill" that intervened on the building for a structural and energy upgrade and the outdoor space where the playground was restored in a multi-sport key, the "porous blanket".

In developing the AdESA prototype, only the north and south façades are subject to the combined application of the structural and energy layers. In addition, there are windows in them, which required a specific technical study to propose a structural securing strategy – through steel hoops – that would not alter the architectural character of the façades, one of which is the entrance. The energy layer was applied on the east and west façades, and a simple but figuratively uniform cladding was applied.

A new bleacher (not initially present) was inserted along the west façade to accommodate the audience during the primary school children's amateur events (Fig. 10).

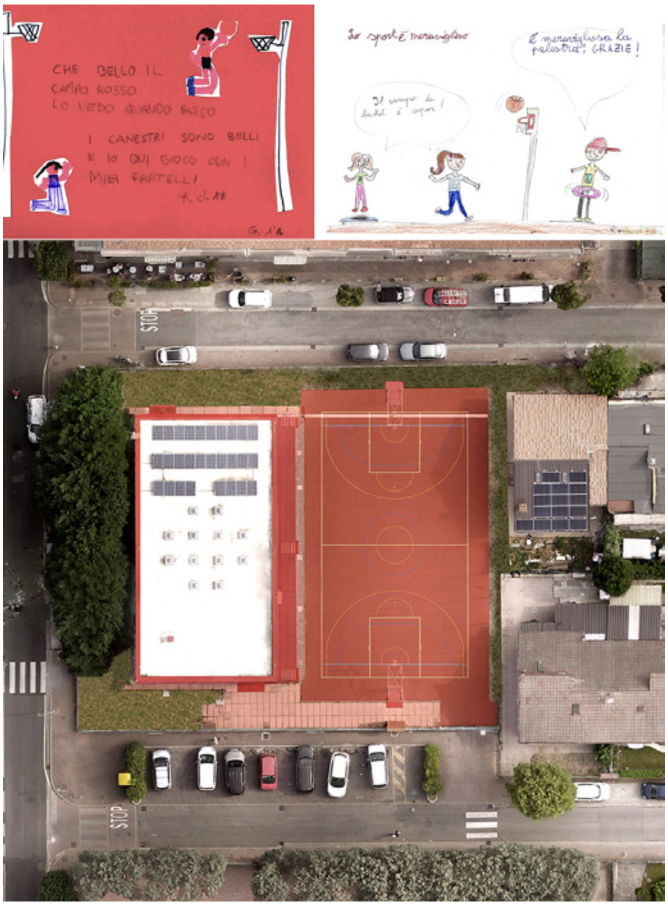

Fig. 10. *Children's drawings after the application of AdESA and Don Milani and the Gym after the intervention and the construction of the multi-sports playground. Source: Don Milani children, University Graphics Laboratory.*

The bleachers generate new relationships – the Smithson "patterns of associations" [19] – with the surrounding urban context not only of a school nature.

It opens towards a new multi-sport ground whose realization was made possible by private funds from the local civil society. Its aspect is proof of the great attention of the Brescia community towards actions that favor social interaction. The new social relations (sporting events, association assemblies, cultural and solidarity events, etc.) established through the sustainable redeployment of the Don Milani gymnasium have become a reference point for the inhabitants of the Villaggio Badia. They approach it with a renewed ecological awareness that has emerged from the "shared" reuse of the building.

Once the realization was completed, the children of the Don Milani school were asked for their opinion on the result (Fig. 10). Their responses were enthusiastic and gave hope that, for the next generation, the ecological issue will be considered an essential aspect of their actions in the world.

4. FINAL CONSIDERATIONS

Rejecting the complete demolition of the built environment is perhaps ascribable to the vision of redevelopment projects as a "civil commitment" that puts the moral responsibility of the architect and engineer towards society first.

The AdESA project stems from this principle and envisages a theoretical/scientific integration of several disciplines (structural engineering, energy engineering, architectural and urban design) into a unique system of actions for the multidisciplinary redevelopment of the existing building stock. Moreover, the case study of the Don Milani gymnasium (Brescia) is an expression of this approach. The analyzed building reveals to us how small but timely interventions – in some cases – can become an ensemble capable of redetermining the identity of a place and giving rise to new social relations between the inhabitants.

«Dal cucchiaio alla città» (from the spoon to the town), in this famous expression by Ernesto Nathan Rogers [20], we find the meaning of a different approach to an established redevelopment method. The latter too often seems to forego the possibility of increasing the project with issues related to the real use of places.

It inevitably follows that the paradigms we must focus our attention on are three: a human-centered design method, the importance of the urban context in which the redevelopment project originates, and the objectives it should set itself.

It is our opinion that, as Lina Bo Bardi pointed out in 1958: «[…] Those who design in their studios leafing through architecture magazines without thinking [of the community for which the buildings are intended] will only create abstract buildings and cities. [Architects] must put in the first place not their formalizing individualism but their awareness of wanting to be useful to people by putting their art and experience at their service. […] This is the true meaning of architecture today. Is not the modern architect, builder of cities, neighborhoods and houses, an active fighter for social justice? […]»[21].

These statements are still highly relevant today. Nevertheless, in the severe ecological crisis that the world is going through, this ethical vision of the architectural and urban project must be integrated with the requests for environmental sustainability.

We believe that by working on these three registers – ethics, sustainability and *urban commons* – it is possible to identify novel, hybrid approaches to research, of which AdESA is a case.

Acknowledgments

Heartfelt thanks are addressed to all those who made the AdESA project possible. We extend our special gratitude to the Municipality of Brescia, the project partners (Marlegno, Harpaceas, Edilmatic), the University of Brescia, the University of Bergamo and the Lions Clubs International.

Funding

The AdESA applied research project was submitted to the Lombardy Region's call for tenders, "Experimental Development and Innovation (S&I) Projects in favor of the Smart living supply chain", in implementation of the Lombardy Region Law 26/2015 and was admitted for funding.

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GREENERY AS A MITIGATION STRATEGY TO URBAN HEAT AND AIR POLLUTION: A COMPARATIVE SIMULATION-BASED STUDY IN A DENSELY BUILT ENVIRONMENT

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DOI: 10.30682/tema090003

TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

This contribution has been peer-reviewed.

Abstract

The urban heat island and the urban air pollution concentration are two major climate-change-related phenomena affecting the built environment worldwide. This paper aims to verify the potential effect of different mitigation measures through a simulation study. In detail the present study focuses on the analysis of the environmental impacts of urban vegetation, such as green facades, vertical greenery, and green pavements. After an extensive screening of the literature review, an investigation of the impact of the most common built environment design variables in a defined case study led to the definition of a typical urban canyon was tested. The results show that the presence of trees in a street canyon could reduce the air temperature peaks by 5-10°C, while the high-level vegetation canopies can lead to a deterioration in air quality with increasing concentration of particulate matter by 1.2-1.5%. Instead, using low-level green infrastructure improves the air quality conditions on the sidewalk, reducing the NOx in the range of 10-20%. The analyzed high-level greenery generated an air temperature reduction effect on a street level ranging from 8 to 12°C. The present work contributes to clarifying the potential mitigation effect of green infrastructure in a densely built environment, where the risk of increasing temperatures and air pollutants is foreseen to be more intense in the coming years.

Keywords

Urban Heat Island, Air Pollution, Mitigation Strategies, Built Environment, Resilience.

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1. INTRODUCTION

Greenhouse gas emissions are progressively less driven by industrial activities and instead mainly originate from energy services required for providing suitable indoor environments (e.g., heating and cooling, lighting, appliances) and mobility [1]. In addition, cities are becoming greyer: they are made of dense building materials, absorbing energy from the sun; fewer trees to provide shade and cooling effect; and fewer green areas to cool by evapotranspiration and absorb air pollutants. Thus, cities are becoming more frequently prone to suffering intense Urban Heat Island (UHI) and Air Pollution (AP), especially within dense Built Environments (BE).

In addition, cities and dense urban areas are now more densely populated. Therefore, more people would be exposed to UHI and related risks. In fact, the United Nations estimated that in 2018, 55% of the world's population lived in urban areas, and in the next two decades, it will reach 66% [2]. In particular, cities' common characteristics enhance UHI and AP related to

Slow Onset Disaster (SLOD) risks; that is: low albedo materials, human gatherings, increased use of air conditioners, reduced green areas, urban canopy, blocked wind flow and pollutant emission [3]. In order to contrast such conditions, existing literature has reported that the presence of vegetation plays a key role in improving air quality and enhancing the microclimate of the open space [4].

Consequently, this research work aims to study natural-based solutions, testing and quantifying the potential impact that selected green mitigation strategies (MS) (i.e., hedges, trees, and green facades) can have at a large scale and their effectiveness in different contexts based on the comparison of PET (Physiological Equivalent Temperature), NOx concentrations and PM (Particulate Matter) concentrations as performance indicators. The large-scale impact is extrapolated from the results of different computer-aided simulation tools on the study case's simplified urban canyon archetype. These simulations were also employed to perform sensitivity analysis on influencing parameters to explore multiple configurations and effects. In addition, the presented work can be embraced as a protocol for designers to demonstrate the relevance of some design decisions toward a more salutogenic urban design. Finally, in contrast with some of the previous works on UHI, the analysis is focused on reducing the stress on pedestrians during daylit hours instead of studying nocturnal UHI.

1.1. OVERVIEW OF UHI AND AP MITIGATION STRATEGIES

Evidence on the UHI effect and AP have been documented in cities worldwide [5]. As mentioned before, cities are more likely to suffer these phenomena, and certain portions of the city are more prone to increase the intensity of UHI and AP [3].

Although several studies have researched the causes of UHI and AP and the possibilities to reduce them, most have focused on the relevance of urban morphology and materials to environmental conditions [6, 7]. The geometry of the canyon influences the urban energy balance in various ways. For example, it increases/decreases the surface exposed to the exchange processes (allows/blocks solar radiation influx), determines the level of interaction between the surfaces that compose the BE, limits/augments the ability to disperse the long-wave infrared radiation, and limits/enhances air turbulence. Regarding canyon morphology, the parameters proven most influential on temperature and radiation exchanges are canyon orientation, aspect ratio (H/W), and sky view factors [8]. For example, according to Biaio et al. [9], the building disposition directly impacts temperature levels: in narrow street canyons, the air temperature increases by 2-4°C. In fact, long and narrow street canyons are characterized by poor ventilation (i.e., low wind velocity), which in addition contributes to the accumulation of air pollution. At street intersections, buildings should be receded, and open plazas or green spaces should be created to stimulate the diversion and distribution of wind flows to different directions, hence avoiding the formation of vortex zones that hamper the dispersion of air pollutants. Nevertheless, these are not very likely to change in a privately owned area of a dense urban space.

Instead, it is more likely to profit from the properties of cool surface materials/typologies within urban areas to greatly contribute to tackling the UHI. For instance, the extensive use of high-albedo or highly reflective materials has been advocated to mitigate the urban heat island, especially in warm-climate cities [10]. These properties determine how the sun's energy is reflected, emitted, and absorbed [1]. By increasing the reflectivity of the building materials, the daytime surface temperature is reduced, mainly during the summer season. In fact, it has been proven that under the same peak solar conditions, the surface temperature for a black material is about 50°C higher than the air temperature. In comparison, for a white material, the surface temperature is only 10°C higher [15]. Specific building surface types, such as cool roofs, reduce, in the long-term, the temperature of the urban environment; they are characterized by materials with high albedo coefficient and/or evapotranspiration (e.g., water pond), allowing materials to stay up to 28-33°C cooler than conventional rooftops during peak summer [15]. Also, the high reflectivity of building walls tends to decrease the canopy air temperature [15].

However, some constraints should be considered for the strategies: restricting the maximum pavement albedo to avoid potential glare effects on drivers and pedestrians and increased reflected solar radiation directly towards pedestrians resulting in higher thermal stress (thus, lower outdoor thermal comfort).

On the other hand, it is possible to act on the building envelope by using photocatalytic materials to manage AP. These types of interventions allow air purification by contrasting the concentration of particles through the degradation of nitrogen oxides. However, these materials must be constantly maintained to avoid diminishing their air purification capacity due to saturation.

In contrast, green strategies have been documented to contribute significantly to both phenomena, without intrusive interventions on the built fabric and with rather a positive impact on the building performance and pedestrians' comfort [15].

1.2. STRATEGIES TARGETING UHI AND AP WITH THE PRESENCE OF HIGH AND LOW-LEVEL GREENERY

The use of high and low-level vegetation (e.g., trees and hedges) is also widely recognized, in general, as a promising strategy for mitigating UHI and AP [14]. It can regulate and lower surface and air temperatures through the evapotranspiration process and by providing shading, which directly reduces the building's consumption during the summer season, a higher outdoor thermal sensation, and a lower heat stroke risk [15]. Moreover, the most suitable tree and plant can be chosen according to their size (i.e., canopy dimensions), seasonality (evergreen/seasonal), and pollutant absorption characteristics [17].

It is widely agreed that green areas integrated into the BE can improve air quality conditions by acting as natural filters of air pollutants [18]. Still, within street canyons, high-level vegetation canopies (trees) have led to a deterioration in air quality, while low-level green infrastructure (hedges) improved air quality conditions. The use of shrubs or hedges with heights lower than 2 m should be encouraged to improve roadside air quality, and large, dense trees should be avoided around roads with heavy traffic [9]. The greenery position is also important; roadside trees and hedges reduce the heat perception in highly polluted areas [19].

Also, it has been demonstrated that leaves can deposit and capture particulates on their surface [20], and plants' presence increases the turbulence of the air flows, which favors the dispersion of the pollutants particles [21]. Therefore, green areas are highly recommended near highly trafficked zones or those likely exposed to sensitive demographic groups (e.g., schools and hospitals) [22].

Regarding the materials used in the BE, high albedo, high thermal emissivity, and low heat capacity play a key role in UHI mitigation [11]. For instance, vegetative facades can also reduce up to 7.7°C the surface temperature peaks of the building facades through evapotranspiration and shading in summer [24] and increase the thermal insulation in winter. The use of green roofs with limited vegetation (e.g., extensive green roofs with sedum herbs) can moderate the effect of the urban heat island, especially during the day, reducing surface temperature up to 5°C [12] and on top city-wide ambient temperature up to 10°C [15]. However, the extent of these MS depends on the climate, plant density foliage, and land coverage intensity.

Nevertheless, UHI should also be tackled at the ground level to improve the quality of the surroundings for pedestrians directly. Increasing green areas (intended as heat sinks) can lower air and surface temperatures at the street level during the day. Vegetative facades can be another solution, improving building energy performance while absorbing pollutants. Moreover, when integrated with the built environment, large areas of greenery (e.g., urban forest) help suppress dust particles, improving air quality around buildings and busy highways; and reducing inhabitants' respiratory illness. Green roofs can also be used as effective air pollution abatement measures [25]. However, their ability to remove pollutants is normally lower compared to trees, vegetation barriers, and green walls, given their low surface roughness and distance away from pollutant sources [26]. Nevertheless, green roof technologies require less walkable space than trees and green belts and can be adapted to arrange part of building surfaces and structures such as bridges, flyovers, retaining walls, and noise barriers.

Although direct reductions of traffic emissions have been enforced, passive pollutant control measures are considered suitable for remedy. Areas with limited natural ventilation in the street canyons enhance the accumulation of air pollutants at the footpath level, augmenting exposure for pedestrians. In this context, solid and porous vegetative structures immersed in urban street canyons (e.g., low boundary walls, shrubs, hedges), which affect less wind flow and pollutant dispersion, should be preferred.

Most of the screened literature and previous works on greenery MS have concentrated on analyzing large portions of the urban built environment or open areas, thus reducing the possibility of extrapolating the analysis to the rest of the urban space or other contexts. Moreover, most strategies have been tested singularly by tackling one aspect only (UHI or AP), without combining different greenery MS, specifically trees combined with green facades. Therefore, this work has concentrated on studying in parallel the UHI and AP effect of singular and combined greenery MS on a basic typological urban unit.

2. METHODS

In order to measure the effect of selected MS, different tools have been integrated into a structured workflow because of their capabilities, the required computing time, and the large number of variables to consider. The simulation process was divided into two steps, and the whole procedure is summarized in Figure 1. As described in §2.1, the first part comprised a set of parametric simulations with Rhino and Ladybug Tools to construct and analyze different urban unit archetypes considering the surface materials' dimension, orientation, and albedo. This preliminary study led to finding and establishing the most critical and representative archetype configuration, heat-wise, characterized by higher solar exposure and mean radiant temperature; as the tested parameters do not modify the air pollutant distribution, and no wind direction was set at this stage. The second part encompassed a set of simulations for evaluating the effectiveness of the green MS on the defined canyon archetype, all modeled with ENVI-met.

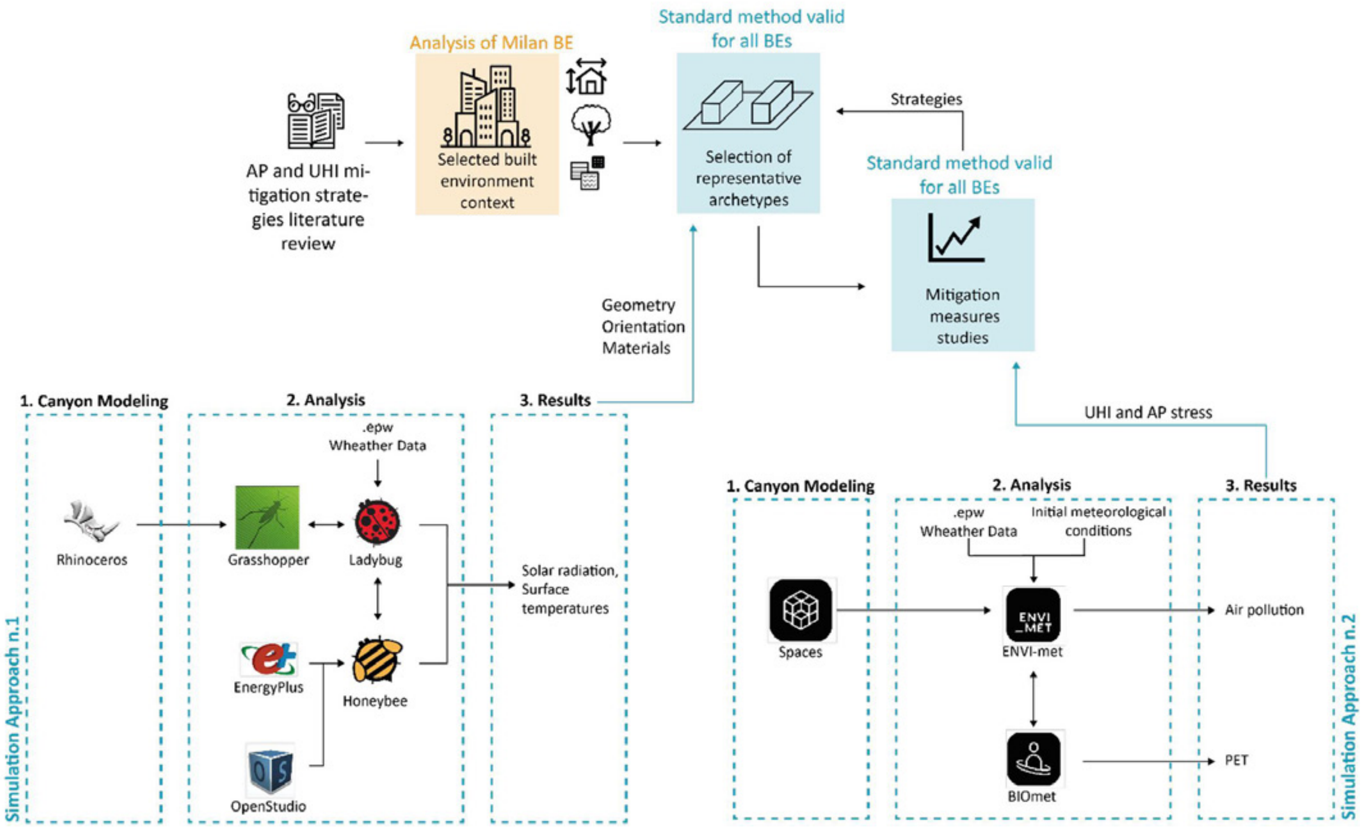

Fig. 1. *General description of the methodology proposed for detailed UHI and AP analysis within the BE.*

2.1. CANYON ARCHETYPE AND SITE-SPECIFIC MITIGATION TESTS

This step is focused on narrowing the typical geometrical characteristics (i.e., H/W and orientation) and materials (albedo). In this respect, Rhinoceros and Grasshopper have been chosen to test different canyon configurations parametrically. Initially, the 3-dimensional geometry is constructed using Rhinoceros. Then, Grasshopper and Ladybug Tools are exploited to parametrically set the environmental conditions and compute the behavior of solar radiation and surface temperatures. Specifically, Ladybug has been used to perform and visualize detailed climate data analysis for supporting environmentally informed design. It has also been used to import standard EnergyPlus Weather files (.epw) into the Grasshopper environment. Instead, Honeybee (coupled with OpenStudio and EnergyPlus) was used to run and visualize solar radiation distribution simulations, to study surface temperatures of building facades and ground.

All the simulations have been carried out on canyons with buildings with heights equal to 25 m and different road widths (H/W<0.80). The geometry has been selected as a representative representation of a typical suburban Italian city area characterized by buildings with floors ranging from 5 to 12. In order to avoid having a significant impact on the edge effect, a reduced analysis grid surface has been placed in the center of a 100 m-long canyon to speed up the simulation process and enable the study of all involved variables. The analysis grid is 10 m wide and has a sensor spacing of 2 m, which covers both sides of the canyon's building facades and the road width.

Grid properties				
Grid size dimension	x-nodes	100		
	y-nodes	150		
	z-nodes	50		
Size of grid cell in meter	dx	2 m		
	dy	2 m		
	dz	2 m		
Canyon Geometry				
Canyon length		100 m		
Building width		15 m		
Building height		25 m		
Canyon width		15 m / 20 m / 25 m / 30 m		
Weather data				
Climate file [.epw]		Milan (Linate Airport)		
Analysis period				
Solar radiation analysis		21^{st} June for 24 hours		
Surface temperatures analysis		21^{st} June from h14.00 to h16.00		
Canyon azimuth				
North orientation		0° / 45° / 60° / 90° / 135° / 150°		
Common color associated radiative properties				
Percentage of absorbed solar radiation	White	25 %		
	Grey	50 %		
	Black	90 %		
Surface Material associated properties				
	Asphalt	Ground	Plaster	Walling
Roughness	Elevated	Elevated	Low	Medium
Thickness [m]	0.5	2	0.025	0.13
Conductivity [W/mK]	0.75	0.32 - 4	0.6918	0.89
Density [kg/m^3]	2360	2050	1858	1920
Specific Heat [J/kgK]	960	800 - 1480	836	790
Thermal absorption coefficient [%]	90	70	50	50

Tab. 1. *Energy model and simulation settings of the selected representative canyon following the described Approach 1 in Fig. 1.*

The simulations on the canyons were tested under the Milanese climate context on June 21st, selected as a representative summer day characterized by high solar radiation and elevated air temperatures. Different combinations of H/W ratios, albedo coefficients, and orientations have been tested, providing information on the incoming solar radiation and surface temperatures, useful to determine the most critical canyon configuration to try the MSs later. The relevant radiative properties of surface materials have been selected from the approximate values and ranges presented in BS 8206-2 [27] and by Salleh et al. [28]. The simulation settings for this preliminary study have been summarized in Table 1. A total of 13 simulations have been conducted and compared. The configuration that can guarantee lower solar exposure and lower surface temperature distribution has been selected for each simulation.

The tests have been planned to select a relevant canyon width before testing the canyon orientation and finishing radiative properties. The selection of the H/W ratio to study in depth is based on the criticality of the conditions found and their representativity. Likewise, the effect of the canyon orientation/azimuth has been evaluated by rotating the canyon 0°, 45°, 60°, 90°, 135° and 150° from the north, and a relevant orientation has been selected to further consolidate a canyon archetype. Finally, different façade finishing surface colors (i.e., white, grey, and black) have been allocated and compared to see their variance and select the most appropriate for the canyon archetype.

2.2. BE MITIGATION STRATEGIES TESTS

After selecting the typical canyon, the second part of the simulations study was carried out through the ENVI-met environment to analyze the potential effect of different MSs on the chosen geometry.

This software is a validated three-dimensional computational fluid dynamics (CFD) model tailored for parallel simulations of urban atmospheric processes, such as pollutant dispersion and microclimate effect. The flow solver of this program is based upon the Reynolds averaged Navier-Stokes (RANS) equations and uses the E-ε model for turbulence effects. This software has been exploited in this work to obtain results on perceived temperatures and air pollution concentration distribution (i.e., PM and NOx).

The geometrical model has been directly constructed on ENVI-met's GUI, and a grid of 100x150x50 cells, each of 2x2x5 m, has been set for analysis. Within this area, the identified critical street canyon has been modeled. Buildings have been modeled following the most common construction characteristics of the Italian BE, selecting a moderately insulated wall and roof with a surface material with a medium albedo coefficient (albedo=0.5). Then, only traffic has been added as a pollution source, which has been modeled as linear along the canyon, considering daily intensity variations. The heat stress is computed as PET [29] for a representative pedestrian based on the representative building occupant described on ISO 8996 [30]. Different strategies are applied and tested independently once the street canyon has been modeled with its materials and sources. For the MS based on vegetation, one type of tree, hedge, and green wall have been selected with the characteristics summarized in Table 2. Following the approach in §2.1, simulations were carried out on June 21st, but on only the warmest sunlit half of the day, to avoid extensive simulation times and ensure both critical temperatures and pollution are present. The time window has been selected to include the highest solar radiation intensity and the most polluted hours (during the evening). The results obtained from these simulations have been later used to evaluate and compare the effectiveness of strategies to provide guidelines for urban planners, aiming at mitigating the UHI and AP phenomena.

Different greenery MS have been foreseen and grouped into 7 types (G1-G7) (Fig. 2), which have been applied individually or combined. The results have been compared based on the absolute arithmetic difference of PET, NOx, and PM concentrations between the current state and the cases with greening MS.

As discussed in §1, vegetation can improve the UHI and air quality. The selected natural-based MS (Fig. 2) comprises the use of single or multiple-row trees, hedges with different heights (1.5 m or 3 m) on the sidewalk, and green facades (5 m height).

Grid properties			
Model dimensions	x-grids	100	
	y-grids	150	
	z-grids	50	
Size of grid cell in meter	dx	2 m	
	dy	2 m	
	dz	5 m	
Method of vertical grid generation		dz ol lowest gridbox is split into 5 subcells	
Nr. of nesting grids		5	
Geometry			
Canyonlength		100 m	
Building width		15 m	
Building height		25 m	
ENVI-met Weather data (initial conditions)			
Wind measured in 10 m height m/s		0.5	
Wind direction		NORTH	
Roughness length at measurement site		0.01	
Min and max temperature of atmosphere		14 – 30 °C	
Min and max relative humidity in 2m		50 - 75 %	
Buildings' materials			
Typology		Default wall – moderate insulation	
Thickness of layers		0.01 plaster - 0.12 insulation- 0.18 concrete	
Possible usage		Wall or roof	
Roughness length		0.02	
Albedo		0.5	
Traffic			
Default height		0.15 m	
Source geometry		Line	
Daily traffic value veh/24h		8000 (Medium/High intensity)	
Number of lanes in the street segment		2	
LDV (light duty vehicles)		5%	
HDV (heavy duty vehicles)		2.5%	
MC (motocycles)		0.5%	
Urban bus (public transport)		3%	
Coaches		1%	
Cars		88%	
	Loamy soil	Asphalt	Grey pavement
z0 roughness length	0.015	0.01	0.01
Albedo	0	0.2	0.5
Emissivity	0.98	0.9	0.9
Background pollutants concentration			
NO		10 µg/m³	
NO_2		90 µg/m³	
Ozone		60 µg/m³	
PM 10		40 µg/m³	
PM 2.5		30 µg/m³	
Trees characteristics			
Typology		Platanus x Acerifolia	
Height		15 m	
CO_2 fixation type		C3 - Plant	
Leaf type		Deciduous Leafs	
Foliage shortwave albedo		0.18	
Foliage shortwave transmittance		0.3	
Leaf weight [g/m²]		100	
Isoprene capacity		12	

(segue)

Green Wall characteristics	
Typology	Green facade + mixed substrate
Wall height	5 m
Plant thickness	0.15 m
Albedo	0.2
Substrate thickness	0.15 m
LAI [m^2/m^2]	1.5
Leaf angle distribution	0.5
Emissivity of substrate	0.95
Water coefficient of substrate for plant	0.5
Air gap between substrate and wall	0.1
Hedge characteristics	
CO_2 fixation type	C3
Leaf type	Deciduous
Albedo	0.2
Transmittance factor of leaf for shortwave radiation	0.3
Plant height	1.5 – 3 m
Root zone Depth	0.5
Lead Area (LAD) Profile	2.5
Root Area (RAD) Profile	0.1
Season Profile	1
Average male human parameters	
Age of person	35
Gender	male
Weight	75 kg
Height	1.75 m
Surface area	1.91 m^2
Static Clothing Insulation (clo	0.9
Total metabolic rate	86.21 W/m^2

Tab. 2. *ENVI-met model and simulation settings, considering materials, geometry, traffic, vegetation, and specific simulation inputs.*

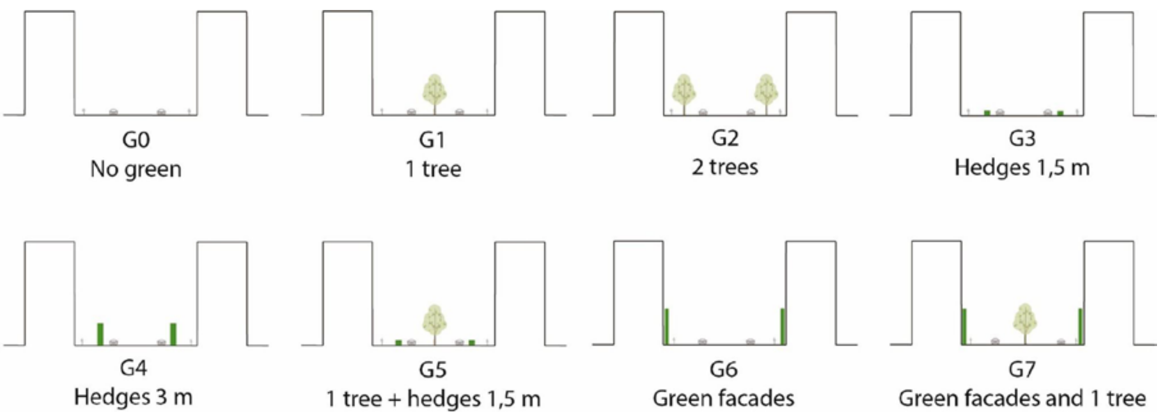

Fig. 2. *Representation of the seven tested greenery solutions for UHI and AP mitigation strategies.*

3. RESULTS

3.1. SELECTION AND STUDY OF REPRESENTATIVE ARCHETYPE: SIMULATION RESULTS ANALYSIS

This section presents the results of simulation approach 1 (Fig. 1) for selecting the typical BE archetype. Different H/W, orientations, and albedo coefficients were combined and tested (Tab. 1); regarding the width of the canyon, different dimensions were considered (while orientation and albedo remain fixed) given the assumption that in dense BE, it is common to have both large avenues and small secondary roads.

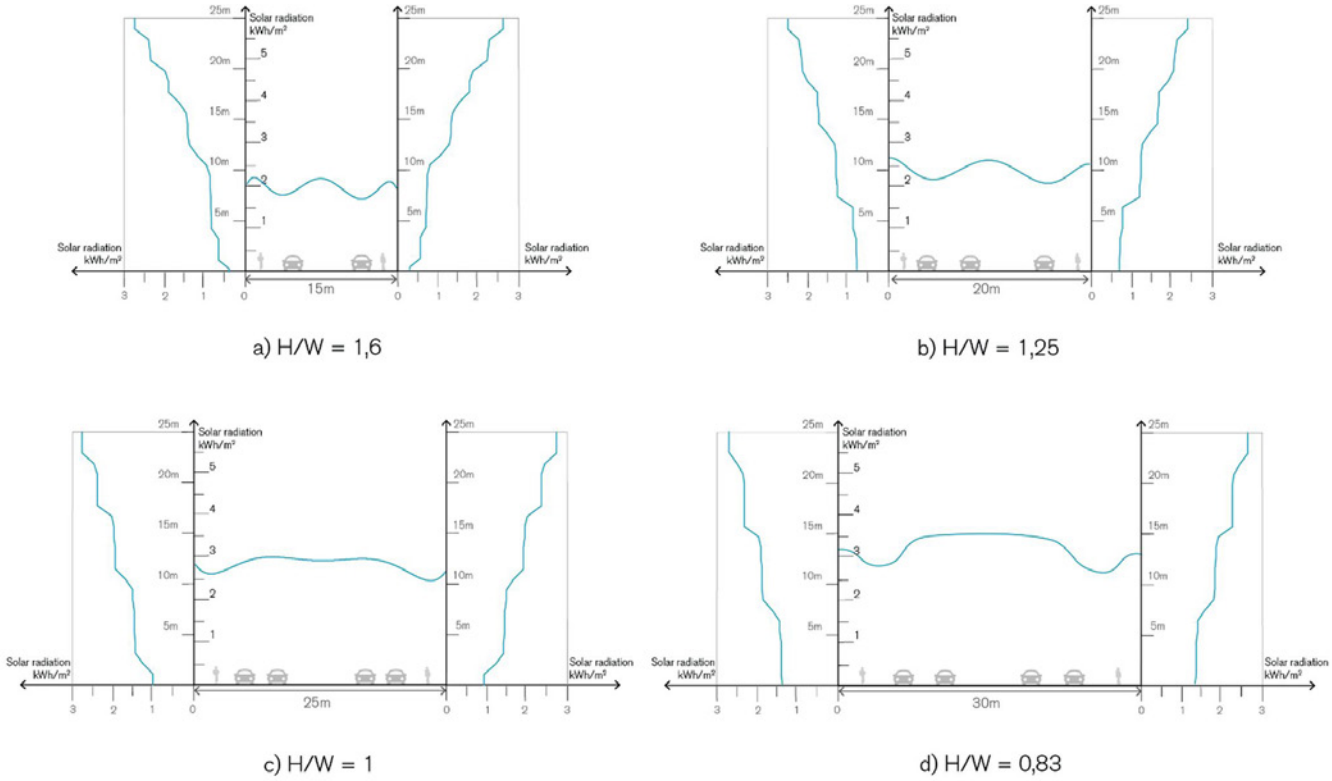

Fig. 3. *Solar radiation analysis on June 21st for different H/W urban canyons oriented at 0º.*

Simulations were conducted by analyzing the solar radiation intensity on different canyon configurations at 0º azimuth during the summer solstice's hottest hours (14.00 to 16.00) (June 21st). Fig. 3 shows the estimated solar radiation distribution on outdoor surfaces for the different composed canyon geometries. The canyons with aspect ratios H/W=1 and 0.83 resulted in the highest intensity of solar radiation during the investigated hours (solar horizontal distribution level approximately equal to 3 kWh/m^2). As reported in the following sections, the authors selected the case study with an aspect ratio H/W equal to 1 for the in-depth simulation study. The solar radiation on the vertical surface of the canyon is comparable with the widest configuration, showing a similar mirrored shadow trend produced by the building facades. Thus, a geometry with two sidewalks, two carriageways for each direction, and additional space for trees in the center and/or on the sides has been chosen, considering that it is representative of most of the BE.

Different canyon orientations have also been analyzed since the city's streets do not always follow a defined and regular orthogonal grid. From north, 0°, 45°, 60°, 90°, 135° and 150° have been tested as relevant street directions.

As shown in Fig. 4, the incident solar radiation changes significantly for a canyon with the same geometry and different orientations. In a canyon-oriented north/south (Fig. 4a), the curves are symmetrical, indicating that, during the sun hours, both sides of the canyon are exposed equally. Rotating the geometry, as expected, one side of the canyon is more directly exposed to the sun than the opposite side. Moving to East/West, the solar radiation becomes irregular, with the exposed side having 45% more solar radiation and the other side 66% less than the North/South orientation. The canyon rotated by 45° to the east (Fig. 4b) has been selected as a relevant archetype because it shows a good compromise among the different configurations with a reduced solar exposure mismatch (25%) between the different canyon sides.

After setting the geometry and orientation of the canyon, three different finishing colors, resulting in different albedo coefficients, have been analyzed: C0 - white (ε=0.8, ρ=0.85), C1- Grey (ε=0.55, ρ=0.94) and C2 - Black (ε=0.2, ρ=0.96). These represent the extremes and a balance option in terms of reflectivity

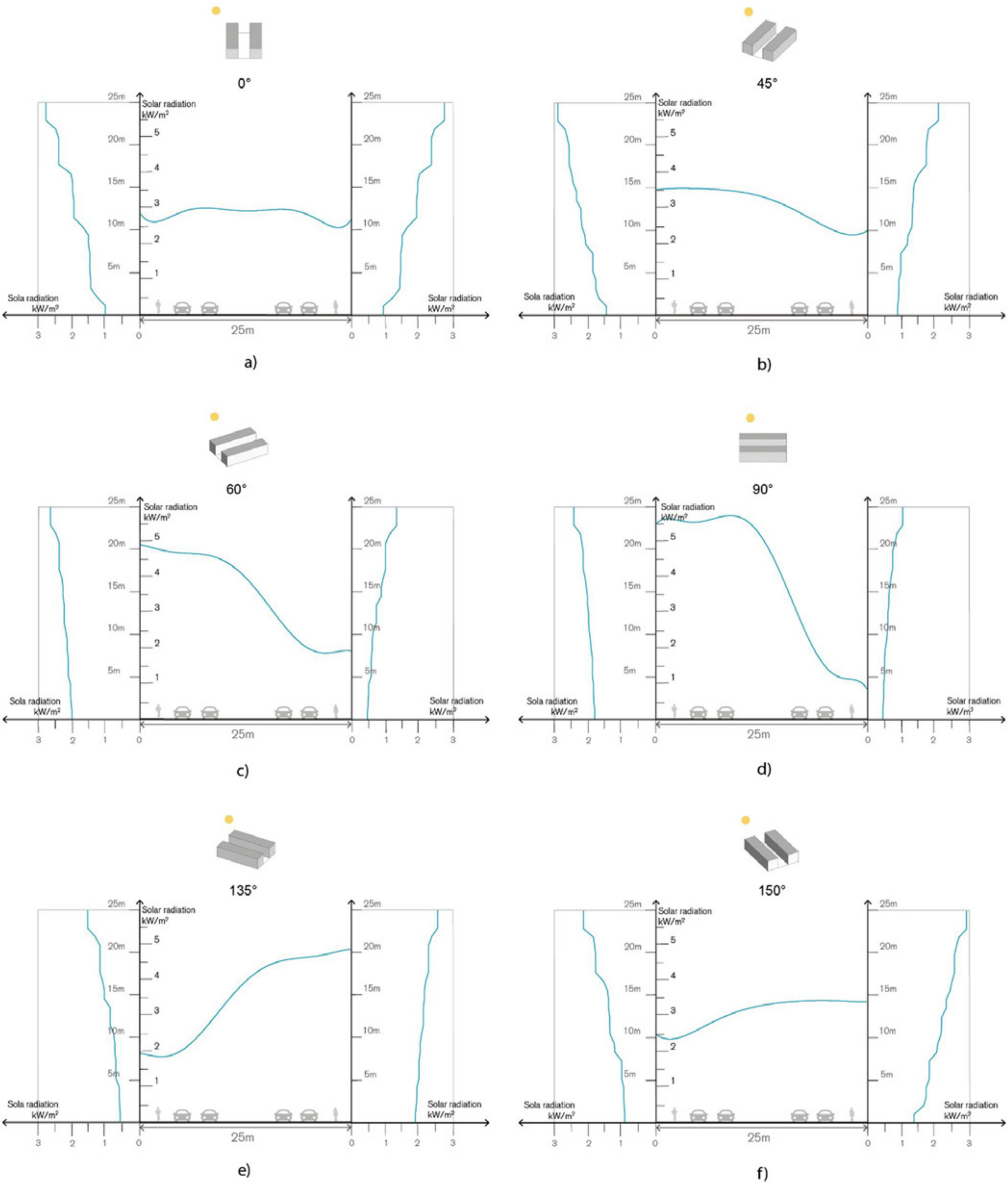

Fig. 4. *Solar radiation analysis (June 21st) for different orientations a) 0°; b) 45°; c) 60°; d) 90°; e) 135°; f) 150°.*

and emissivity of the surfaces. The results have been summarized in Fig. 5.

The simulations have been carried out from 13:00 to 20:00 on June 21st concerning the impact of the surface materials on temperature levels – Fig. 5b) shows the temperature level for all three selected façade colors applied to the canyon archetype. As expected, the maximum surface temperature on the façade is highly correlated to the

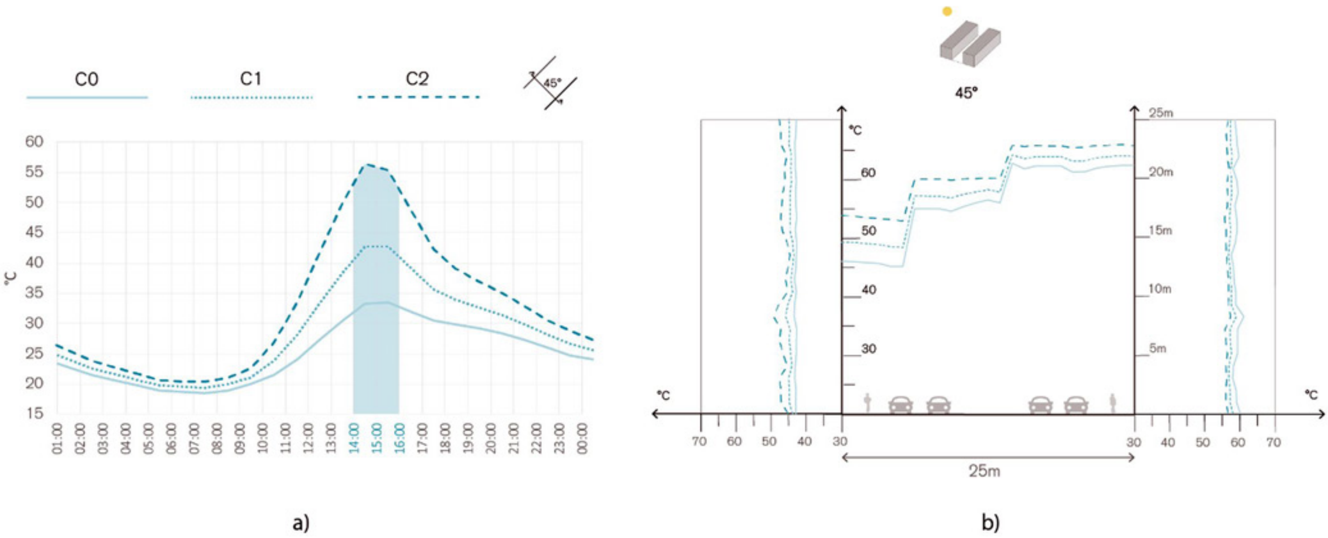

Fig. 5. *Color effect on temperature comparison for the 45° orientation on June 21st. a) Average surface temperatures daily trend. b) Surface temperatures inside the canyon (June 21st) for different materials.*

albedo coefficient and to direct sun exposure. The higher surface temperature is reached by the C2 configuration, characterized by high emissivity (ε=0.96) and low reflectivity (ρ=0.2). In fact, as presented in Fig. 5, black materials (lower albedo coefficient) reach a surface temperature of around 55°C while materials with high albedo (i.e., white color) show temperature levels 15-20°C lower.

Although the black material is the most critical, and such facades should be intervened promptly (unless mostly shaded), grey was chosen for the canyon archetype since it is more representative of streets and buildings. In conclusion, the canyon archetype selected for the green infrastructure mitigation potential analysis is characterized by a H/W equal to 1, orientation 45° to the east, and a general albedo coefficient of the surfaces equal to 0.5.

3.2. UHI AND AP MITIGATION MEASURES IMPACT ANALYSIS

All the measures have been simulated during the summer solstice for the time period between 13.00 to 20.00; to ensure model convergence before 14.00 (Most critical PET condition – Fig. 5a). However, the simulation results have been displayed considering the values calculated at 14.00, representing the most critical time period for both temperatures and traffic pollution. In addition, at 14.00, no shadows generated by the buildings could influence the perceived temperature values.

3.2.1. UHI IMPACT ANALYSIS

To study UHI, Figure 6 reports the perceived temperatures measured in PET for a middle cross-section of the constructed archetype canyon, where different strategies have already been applied (G0-G7).

The perceived air temperature trend at a height of 1.5 m along the canyon section has been presented in Fig. 6b). The G0 configuration represents the base case where no vegetation is present in the canyon, used as a reference for comparing the different scenarios. In that case, the temperature level is homogenously high, with PET values close to 41°C. The MS certainly led to different results; some have a clearly localized impact (e.g., G3 and G4) compared to others (G2, G5, G7). In fact, registered temperatures may vary from 27°C to 41°C. For instance, looking at the values reported across the canyon section base, the results obtained for G1 simulation have a completely different trend compared to G0: on the edge of the street, temperatures are still around 40-41°C, but in the center, under the area of influence of the tree canopy, temperatures drop by more than 10°C potentially increasing the comfort level. Increasing the number of tree lanes and locating them closer to the canyon sidewalks (G2), the simulation results show a temperature level trend characterized by an extended lower and homogenous temperature area in proximity of the trees (28-29°C) with a punctual peak

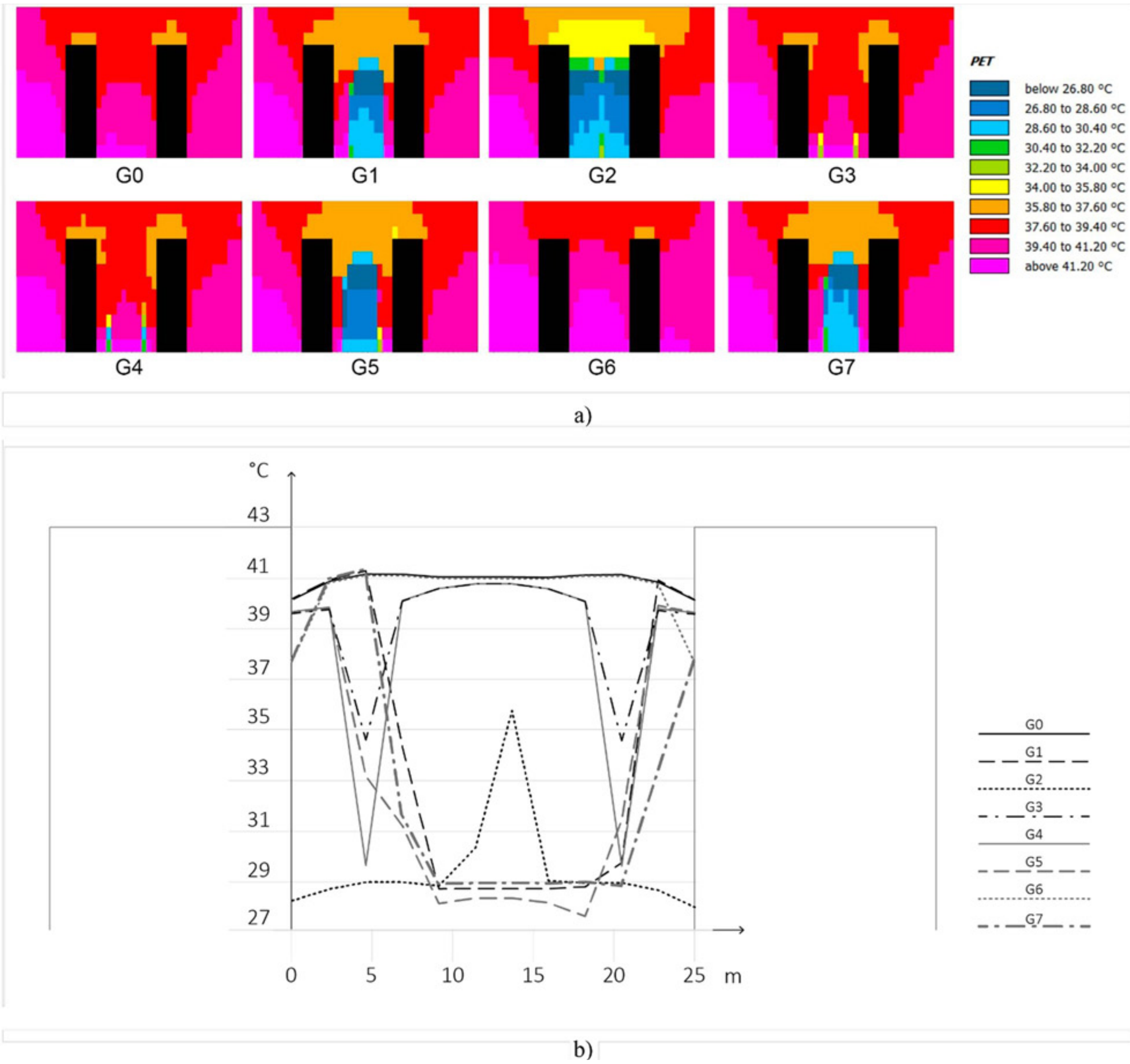

Fig. 6. *Simulation results of PET for all strategies inside the representative H/W=1 canyon at 14.00 on June 21st. a) Heat maps. b) Horizontal temperature at 1.5 m height.*

in the unshaded street center (35.7°C), evidently out of the area of influence of the trees. The temperature trends are different for the cases where the greenery is represented by hedges (1.5 m high for case G3 and 3 m high for G4), having a very localized PET drop on the exact location where the hedges were placed. Probably given the low shading that these provide. The results show that in the area where hedges were applied, temperatures drop by 5°C for G3 and 10°C for G4 cases. The combined use of trees and hedges was studied in case G5. Such presence of multiple greenery leads to lower perceived temperatures with a minimum of 27.6°C found in the middle of the street, with a similar trend as G1, confirming a low spatial contribution of hedges against UHI. G6 and G7 cases combined the presence of 5 m high green walls, respectively, with and without a central row of trees. In general, as shown by the simulation results, the green wall (G6) decreases the perceived temperature level on the sides of the canyon. In the G7 case, temperatures are lower than G6 due to the presence of tree canopy that contributes to diminishing temperatures also in the central part of the canyon, thus confirming the considerable effect of high-level greenery MS, the low effect of low-level greenery MS and suggesting a negligible impact of green facades for pedestrians regarding UHI.

3.2.2. AIR POLLUTION IMPACT ANALYSIS

The same mitigation measures applied for lowering the UHI (G0-G7) are tested in terms of PM and NOx concentration. Both are screened given their high impact on human health, which can result in respiratory disease and/or cardio-circulatory system affections.

Fig. 7 resumes the simulated PM concentrations in a middle section of the canyon. Such distribution follows the evidenced vortex generated by the north wind on an urban canyon with a 45° orientation, in which the pollutants dispersion is minimal in the middle upper part, where the primary vortex surges, and the leeward side. It is noteworthy to mention the small variations within the canyon, with an approximate amplitude of 0.48 µg/m3.

As expected, different greenery configurations led to different PM concentration trends. The base case (G0) shows little variance in PM concentration in the contained air volume with values around 40.20 µg/m3. The configuration with one tree inside the street (G1) shows a moderate reduction of the PM concentrations throughout the section (vertical and horizontal), with the minimum horizontal values on the street sides equal to 39.95 µg/m3, while the lowest values present right above the tree canopy 39.65 µg/m3. In the configuration with two tree lanes (G2), the increased canopy density seems to reduce the PM dispersion in the atmosphere under the tree can-

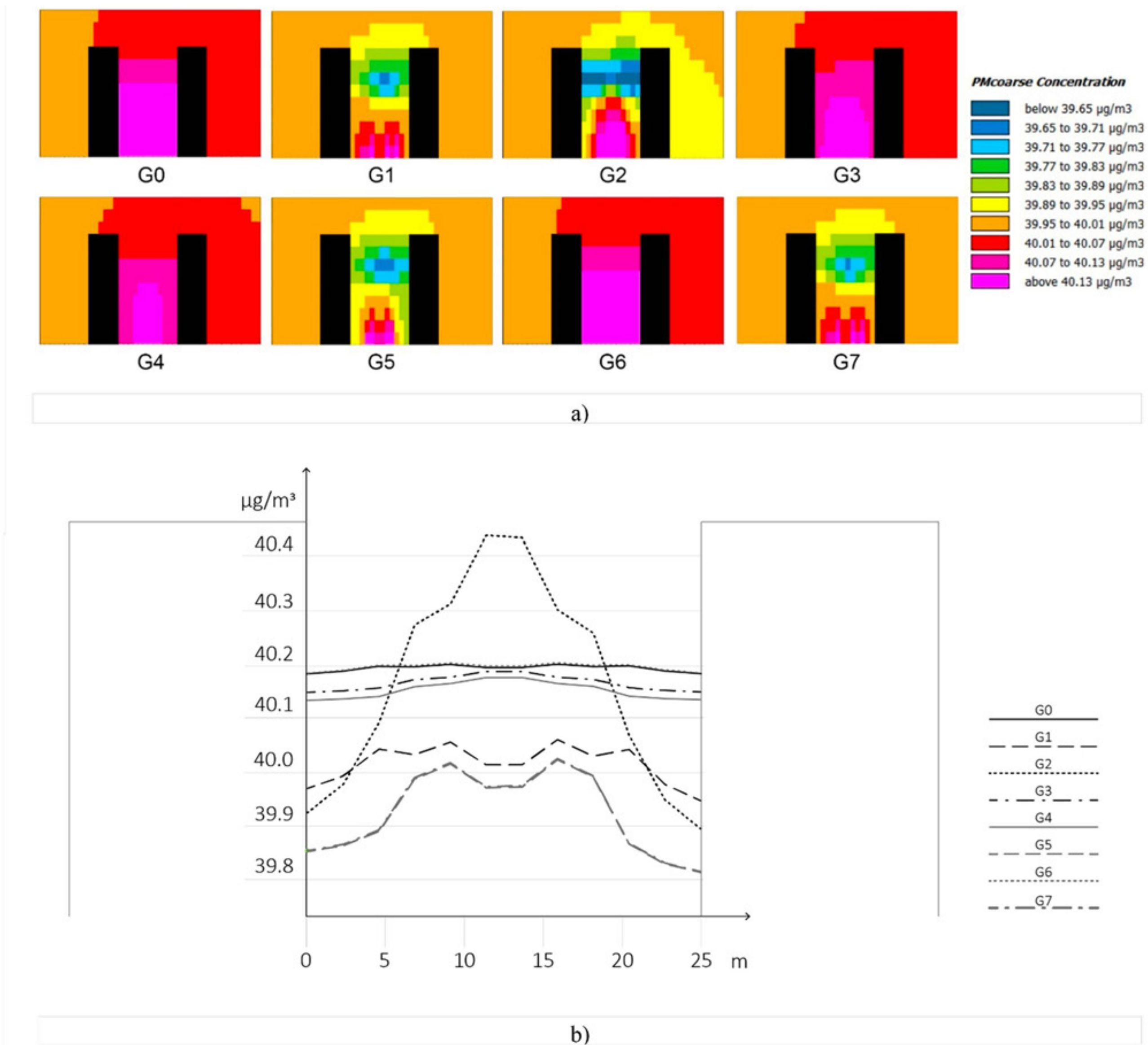

Fig. 7. *Simulation results of PM coarse concentration for all strategies inside the representative H/W=1 canyon at 14.00 on June 21st. a) Heat maps. b) Horizontal temperature at 1.5 m height.*

opy height while reducing PM concentrations above it. The curve of MS G3 and G4 results show mutual similarity with the slightly reduced PM concentration on the sides of the street, indicating that the hedges might act as barriers insufficiently protecting sidewalks from the more polluted road. Nevertheless, the protection against road pollution is higher proportionally to the height of the greenery. Case G5, representing the combined use of trees and hedges, shows the lowest pollutant concentration at the canyon's sidewalks with levels between 39.8 and 40,0 µg/m^3, which could be attributed to the air pollutant entrapment at street level, generated by the low-level greenery acting as vertical barriers and the high-level greenery canopy acting as a horizontal obstruction. For case G6 (green walls only), the PM concentration is similar to G0 because the PM moves within the canyon before being deposited by the green wall. The case in which the green walls are applied together with one row of trees (G7) shows a PM reduction similar to the G1 (single tree lane) and G5 configuration (hedges plus trees) where even though there is a single row of trees, the correct ventilation of the canyon is not obstructed, and green barriers absorb the pollutants underneath canopies. Therefore, it is possible to deduct that there is also a considerable effect of high-level greenery MS, a localized and low effect of low-level greenery MS, and a negligible impact

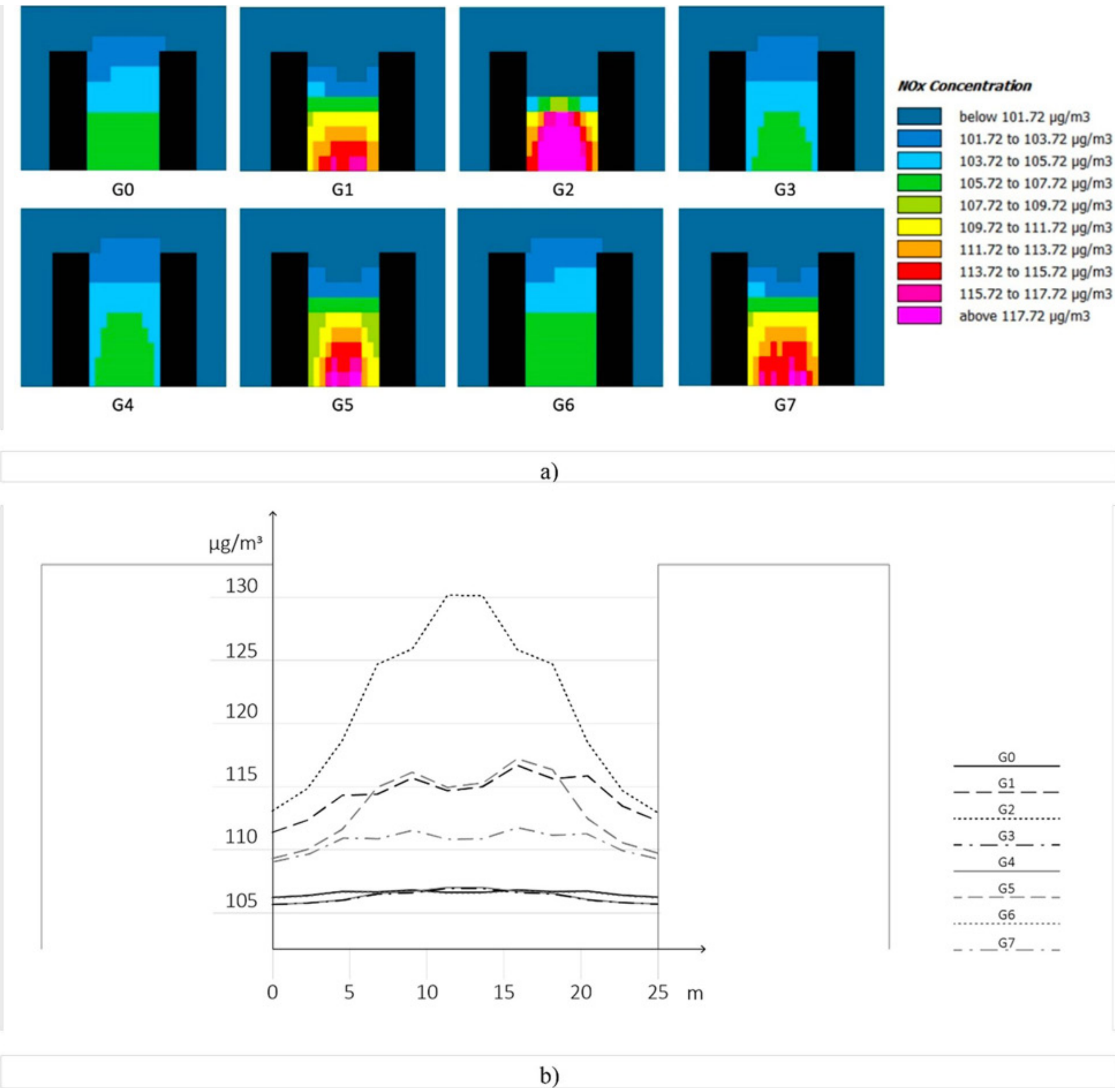

Fig. 8. *Simulation results of NOx concentration for all strategies inside the representative H/W=1 canyon at 14.00 on June 21st. a) Heat maps. b) Horizontal temperature at 1.5 m height.*

of green facades for pedestrians regarding AP. However, the integration of different types of vegetation (high and low-level greenery MS – Trees plus hedges (G5)) is welcome and helps further increase the PM reduction for a more livable built environment for pedestrians.

Figure 8 resumes the simulated NOx concentrations in a middle section of the canyon. Besides a significant variation amplitude of approximately 16 µg/m3, the resulting air pollutant concentration follows the PM distribution trend.

As experienced for PM coarse concentrations, not all greenery solutions act similarly. Compared to PM concentration, the scale of NOx concentrations is larger because traffic is more strongly linked with NOx emissions than PM.

All MS involving trees (G1, G2, G5, and G7) generally reach higher NOx concentrations. This is probably due to the presence of tree canopies that can obstruct the wind flow and thus the natural dissipation of the air pollutants emitted by traffic, resulting in air stagnation, hence the higher concentration of pollutants below naturally generated canopies. Meanwhile, G3 and G4 (low-level greenery MS) performed best, creating a barrier from traffic on the street towards the pedestrians on the sidewalks. Green facades (G6) showed no noticeable difference from the baseline scenario. This can be attributed to their low effect on wind flow dynamics and the low air pollutant deposition capacity of the selected species. Considering NOx only, high-level greenery MS has a rather detrimental effect compared to low-level greenery MS.

Aggregating PM and NOx results, the implementation of hedges will efficiently protect users on sidewalks from traffic emissions. At the same time, trees with low foliage density could also be used to guarantee correct canyon ventilation, facilitating NOx dispersion and PM protection.

4. CONCLUSIONS

The present study has been carried out to identify and quantify the potential UHI and AP mitigating effects of typical greenery solutions applicable in urban canyons of dense BE. Through computer-aided simulation, the proposed method has been proven useful and verified that natural-based solutions (i.e., vegetation) could positively impact both perceived temperatures and air pollution concentration, but not in all cases as it is commonly expected. Some measures positively impact mitigating the effect of both UHI and AP, while others mitigate only one of them. Therefore, because results depend on many factors, interventions in the built environment shall be studied and tailored for the specific case, and it is impossible to establish a unique optimal strategy for all cities and critical areas. Hence, identifying, utilizing, and investigating a canyon archetype allows for standardizing the process and predicting the potential effects of vegetation that must be considered progressively more in the urban design process. Despite there might be levels of uncertainty in this analysis due to the considered scale, the results partially confirmed what has been stated in the literature. In general, from the results of the H/W=1 urban canyon, the following considerations can be made:

- The use of trees is a promising option to tackle the UHI effect. The canopies can decrease the PET by 9-15°C and benefit users' well-being.
- Green walls have, in general, a lower impact on PET reduction. The low albedo of the foliage can sometimes increase the outdoor temperature level.
- The tree canopy can reduce airflow into the canyon, reducing pollutants dispersion. Proper tree distribution and foliage density must be carefully considered.
- Considering NOx, the integration of hedges represents a good strategy for containing traffic pollution in the road section. From the perceived temperature point of view, the hedges are locally useful if they are sufficiently high. A 3m hedge, with its shade, can diminish PET up to 6°C. However, a high hedge is a visible obstacle inside the canyon that might not be visually appealing.
- Trees and hedges were proven to be valid options when dealing with UHI and AP.

Nevertheless, the results hereby presented are incomplete and could differ; thus, more research is foreseen to complement them. For instance, the analysis was mainly performed on a single day with the highest solar angle, but it might not be the hottest day. Also, the analysis carried out considering the contribution of wind was limited as a single wind speed and direction was set.

Authors contribution

Conceptualization of the research, G.S. and E.Q.; conceptualization of the paper, G.S, J.D.B.C, and M.C.; methodology, G.S, J.D.B.C, and M.C.; investigation, G.S. J.D.B.C.; data curation, M.C. and G.S.; writing - review and editing, G.S, J.D.B.C, M.C., and E.Q.; data visualization M.C.; supervision, G.S.; project administration, G.S., and E.Q.; funding acquisition, G.S., and E.Q. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the MIUR (the Italian Ministry of Education, University, and Research) Project BE S2ECURe - (make) Built Environment Safer in Slow and Emergency Conditions through behavioral assessed/designed Resilient solutions (grant number: 2017LR75XK).

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GREEN ROOF AS A PASSIVE COOLING TECHNIQUE FOR THE MEDITERRANEAN CLIMATE: AN EXPERIMENTAL STUDY

TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

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DOI: 10.30682/tema090006

Abstract

Urban areas are undergoing increasing growth and land consumption. Through sustainable design and strategies, the built environment can contribute to mitigating the pressure on urban systems. To this aim, passive strategies can be integrated into buildings to improve their performance and that of the entire urban infrastructure system. Green roofs are among the most encouraged passive strategies, which can be added to both new and existing buildings. Green roofs reduce the Urban Heat Island effect, keeping the building and the city cooler; contribute to the stormwater management system, reducing runoff-flooding risk. However, while these advantages have been studied extensively, the actual cooling potential from evapotranspiration of green roofs has not been the subject of many studies. This work investigates the passive cooling potential of green roofs by evaporation through preliminary experimental studies on two green roofs. In greater detail, we aim to disentangle the substrate layer's peculiar role, without vegetation, during both a simulated extreme rainfall event and regular irrigation regime, and we compare it to the performance of a gravel-composed reference roof, whose performance with respect to cooling is already good. Results demonstrated that the green roof without vegetation can cool down the roof, and the intense rainfall event was the one that provided the highest thermal performance to the roof.

Keywords

Substrate layer, Thermal performance, Evapotranspiration process, Building envelope, Urban Heat Island.

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1. INTRODUCTION

The ongoing reduction of natural land and the increasing urbanization have resulted in environmental issues due to changing land cover into impervious surfaces. This change inhibits global evapotranspiration rates, intensifying the Urban Heat Island (UHI) effects and the building energy consumption [1, 2]. In order to address these problems, various greening measures have been proposed. In greater detail, the use of green roofs can bring multiple environmental and social benefits [3]. Green roofs are suggested as a sustainable urban design strategy able to reduce the energy consumption of buildings through solar shading, passive cooling, and thermal insulation, as well as to mitigate the increased risk of flooding in urban areas [4].

For these reasons, green roofs are increasingly encouraged to green the urban built environment. For example, in Basel, Switzerland, all the new buildings with flat roofs and all the retrofits of existing buildings with flat roofs must integrate green roofing [5], and the Basel Municipality estimates that 40% of Basel roofs are green now. However, the employment of green roofs on new and existing buildings needs careful consideration, as they constitute a peculiar architectural and construction feature. Continuing with the Basel example, indications for successful green roofs include that the substrate should be native regional soil, with a minimum thickness of 12 cm, and vegetation must be a mix of native species, characteristic of Basel [5]. Also, the architectural features of buildings should be considered, as only flat or slightly inclined roofs can host greenery. In the context of Mediterranean cities, where most buildings are historical [6], their implementation should be carefully evaluated. In addition to their integration in buildings, green roofs should be integrated with urban stormwater management infrastructures to provide relief from UHI and reduce runoff.

The passive cooling effect is attributed to the evapotranspiration process (ET), the water vapor surface flux resulting from the combination of evaporation and plant transpiration. Evaporation is the transformation of water into vapor at the surface of the wet growing media, while transpiration is the physiological process of transforming water into vapor at the plant surfaces, primarily leaves.

This process occurs when there is a vapor pressure differential between the plants and surrounding air. ET is influenced by precipitation history (intensity, duration, inter-event times), climatic conditions (net radiation, temperature, humidity, wind), vegetation characteristics (species, leaf area index, stage of growth), and substrate properties (porosity, permeability, field capacity, capillary pressure-saturation relationship) [7]. In addition, ET has recently drawn increased interest from the green roof research community because of its importance in heat and mass transfer at the level of green roof components [8, 9]. However, ET not only impacts the thermal effect and energy balance of green roofs through surface cooling but also significantly contributes to reducing the water runoff generated by rainfall on building rooftops by storing precipitation (reducing runoff volume and retarding runoff peak) and facilitating ET [10].

While several studies have documented a reduction in stormwater runoff volumes from green roofs [11], few have directly quantified rates of ET in terms of passive cooling potential, although they agree that green roofs mitigate rooftop overheating. He et al. [12] quantified the hourly rate of ET for four plant species typically planted on green roofs in Singapore through a field experiment and subsequently analyzed correlations between the rate of ET and weather parameters. The authors concluded that outdoor air temperature is the weather parameter showing the highest correlation with the rate of ET, followed by solar radiation, wind speed, and relative humidity. Chen [13] explored the effects of the meteorological variables, soil water content, and the ET in relation to the thermal performance indicated by Urban Heat Island and building energy consumption of green roofs. The author found that ET may have a higher influence on the difference in surface temperatures of green and original roofs than the meteorological variables or substrate water content, although the radiative heating is sometimes more influential than the cooling caused by ET of the green roof in thin substrate condition. Ouldboukhitine et al. [14] investigated the ET for green roofs under controlled laboratory conditions. Side-by-side experiments were used to measure evaporation compared to ET and to determine the effect of irrigation water quality on evaporative cooling. When exposed to warm ambient conditions, ET provided evaporative cooling that increased thermal resistance for a green roof, with an increase of 13% for ryegrass and 37% for periwinkle. Jim and Peng [15] investigated the effects of weather types in conjunction with soil moisture states on green-roof ET and thermal performance based on scenario and correlation analyses. The correlation analyses demonstrate stronger relationships between substrate moisture and subsurface temperatures but weaker with subaerial temperatures. Higher substrate moisture could cool soil, rockwool, and concrete tile on sunny days and warm them on rainy and cloudy days. The substrate-moisture effect on subaerial temperatures is only expressed on rainy days, with little effect on sunny and cloudy days. Boafo et al. [16] evaluated the ET effect of an extensive green roof on the annual energy consumption of an office building. Increasing the Leaf Area Index (LAI) from 20% to 100% cover increased ET flux by 10.4% in summer and 80.2% in winter. In [17], the authors studied the effect of vegetation type and climatological conditions on ET and demonstrated that substrate moisture content and atmospheric forcing are the most significant variables influencing ET. All of these results demonstrated the importance of ET in the reduction of thermal loads on a green roof.

In a previous review study, Cascone et al. [18] reported that ET rates can be obtained by direct measurement or indirect approaches with mathematical models. Because the cooling effect is invisible and difficult to measure directly, many studies have calibrated empirical and analytical equations to evaluate ET rates. In 1998, the Food and Agriculture Organization (FAO) standardized the equation elaborated by Penman and Monteith as the FAO model to calculate the ET of an extensive land-surface fully covered by grass of uniform height in a well-watered condition. Jahanfar et al. [19] have reported that the FAO method underestimates ET for green roof systems, especially during dry periods. The inaccuracy of ET prediction methods in water-limited conditions is a significant gap in assessing the performance of green roofs. ET rate can be directly evaluated by measuring water losses from a roof assembly. Previous research studies have quantified ET with weighing lysimeters that directly measure water loss using a load sensor or scale. Alternatively, a few studies have used the soil-water balance approach. The soil water balance is performed by tracking changes in the substrate water content that can be measured with probes based on different measurement methods. Tabares-Velasco and Srebric [20] developed a laboratory setup that measures ET to quantify the heat and mass transfer in a vegetated green roof. The ET values obtained with a substrate water content of 0.15 (m^3/m^3) was approximately 150 (W/m^2) or 5.29 ($kg\ m^{-2}\ day^{-1}$). Higher values of ET were obtained in the study by Tan et al. [21] in small green roof plots of 1 m^2 on the National University of Singapore rooftop. The experiments were performed in a tropical rainforest climate (*Af*) according to the Köppen-Geiger climate classification. The substrate used is a 30 cm lightweight soilless consisting mainly of perlite and organic matter to improve soil water retention, and the vegetation is *Cyathula prostrata.* The nine analyzed plots reached maximum ET rates between 6 and 8 ($kg\ m^{-2}\ day^{-1}$) with a daily watering of 12 ($l \cdot m^{-2} \cdot day^{-1}$), where the maximum VWC ranged between 0.22% and 0.35%. The higher and more constant VWC values were obtained in the plots with a 5 cm water retention layer. Finally, there is a lack of information about the specific location of the watering drip system in the green roof section. Another study by Chenot et al. [22] in a Mediterranean climate (Csa) shows similar ET results.

In summary, there is no consistent agreement with respect to ET's contribution to energy balance and the green roof's thermal performance. To clarify the benefits of ET in varying conditions, a method to accurately predict the ET effect is crucial in the planning for green roofs designed especially for cooling purposes.

In order to fill the literature gaps, this paper aims to develop an experimental setup for the evaluation of the passive cooling potential of green roofs, improving the knowledge of the correlation between evaporation (EP) and the thermal performance of an extensive green roof. To this end, a new experimental setup was designed and built on the University of Lleida (Spain) rooftop. It allows for determining the latent heat flux, temperatures at different layers, substrate moisture content, and the specific microclimatic conditions of a green roof solution. Since ET in green roofs strongly depends on the water content in the substrate, the passive cooling potential was evaluated by varying the amount of water supplied by the irrigation system. Therefore, in this work, following the description of setup design and implementation, preliminary results from the experimental evaluation on passive cooling of green roofs are reported for the case without vegetation, thus considering evaporation only.

2. METHODOLOGY

The employed method consists of two experiments investigating the performance concerning evaporative cooling of two green roof fields and a reference, non-green roof portion. The following subsections illustrate the procedure in greater detail. They are structured as follows: the experimental setup is described first, then the local climate conditions, the instruments employed to monitor the experiments, the green roof and the water retention layer case study, and finally, the procedure for the experiments.

2.1. EXPERIMENTAL SETUP

Two weighing lysimeters are designed and assembled (Fig. 1) to evaluate the ET of two green roofs (named Substrate 1 and Substrate 2, with the same composition to duplicate the results) under different irrigation scenarios. They are made of a 3 cm section of plywood structure (λ=0.138 W·m^{-1}·K^{-1}) with a total area of 4 m^2 (Fig. 1A) and reinforced below with rectangular laminated tubes (40x60x2 mm). Immediately after the plywood base, each lysimeter is insulated from the bottom part with 8 cm of XPS panels (λ=0.036 W·m^{-1}·K^{-1}) and completely waterproofed with a bituminous dense layer (Fig. 1B), a drainage hole allows water runoff. The whole system is weighed with eight load cells (Fig. 1C) using four of them in each lysimeter. Since a single load cell has a maximum load service of 450 kg, each lysimeter allows a total of 1,800 kg of service. Both lysimeters are completely equal and allow testing extensive and semi-intensive green roof samples of up to 250 mm depth, as can be seen in Figure 1.D. The irrigation system is controlled by GARDENA devices (Model: 1885) that allow personalized daily irrigation schedules. The water distribution system consists of 14 auto-compensating dripping valves distributed in 4 rows (Ø 25 mm) every 50 cm (Fig. 1B).

2.2. CLIMATE CONDITIONS

The experimental setup is located at the University of Lleida, Spain. The specific climate conditions are considered continental Mediterranean (Cfa) according to the Köppen-Geiger climate classification. The summers are dry and hot, while the winters are cold and foggy. The mean annual precipitation is 423 mm, generally distributed between April-May and October-November. The mean temperature in Lleida is 15.2ºC, with a maximum mean temperature of 32ºC in July and a minimum mean temperature of 1.5ºC in January.

2.3. INSTRUMENTATION

Figure 2 shows the distribution of the sensors in both the green roofs and the conventional flat roof that was used as a reference system. The following data was recorded at 5 min intervals:

- Temperature between plywood and insulation (Point D in Fig. 2) [˚C]
- Temperature between waterproof and drainage layers (Point C in Fig. 2) [˚C]
- Temperature between drainage and substrate layers (Point B in Fig. 2) [˚C]

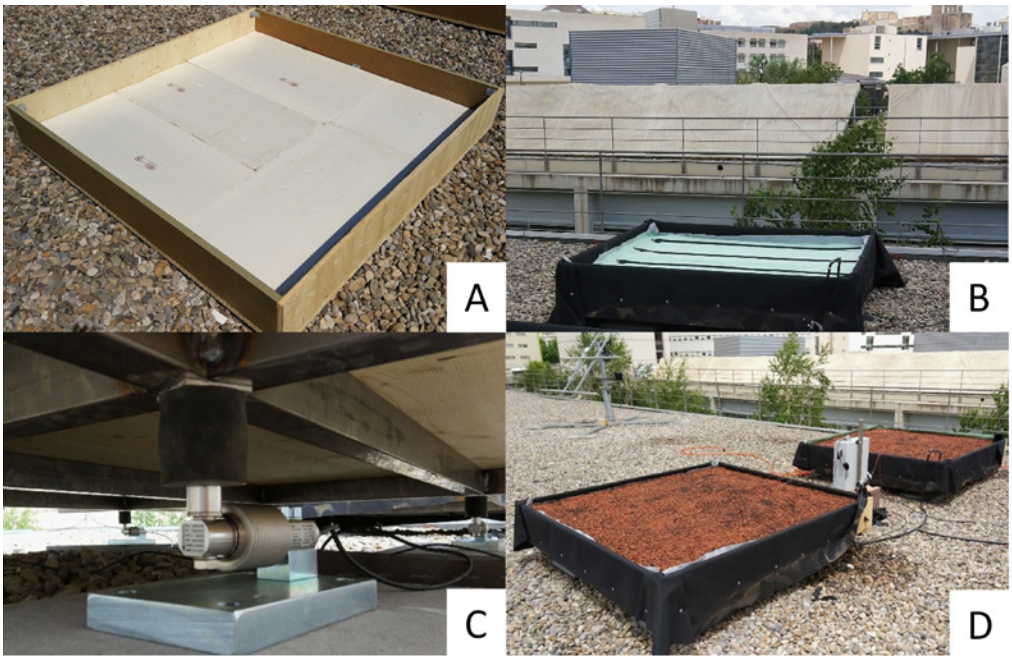

Fig. 1. *(A) Insulated plywood structure, (B) waterproof membrane (black), drip irrigation system, and anti-root membrane (green), (C) load cells and laminated steel tubes, (D) experimental setup based on two identical lysimeters of 4 m^2.*

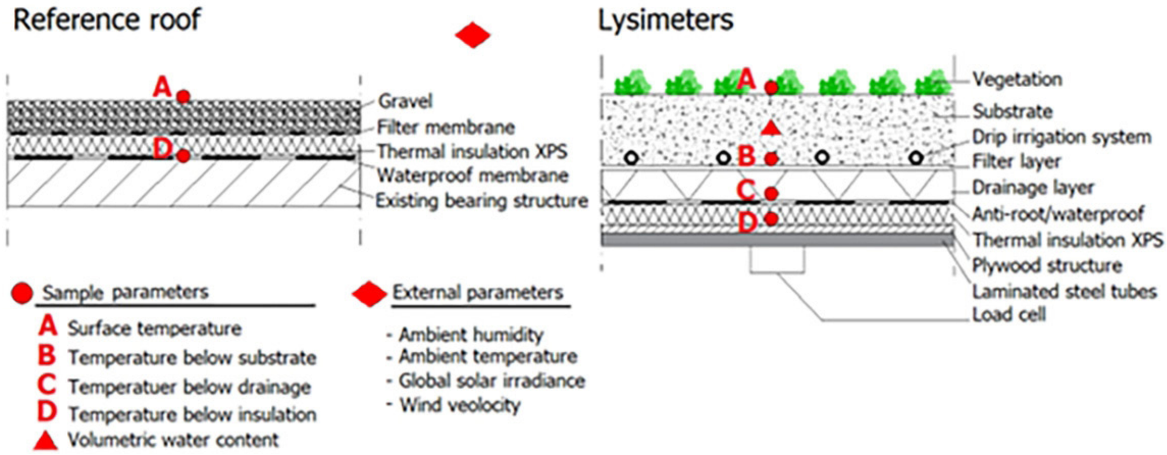

Fig. 2. *Distribution of the different sensors in the two lysimeters and the conventional reference roof.*

- Temperature on the surface sample (Point A in Fig. 2) [˚C]
- Volumetric Water Content (VWC) in the substrate [%]
- Outdoor ambient temperature [˚C] and humidity [%] at the height of samples (60 cm)
- Global horizontal solar irradiance [W/m^2]
- Wind velocity [m/s]
- Rainfall [mm]
- Constant weight of samples [kg]

Pt-100 DIN B probes (accuracy ± 0.3 ºC) are installed to measure the surface temperatures across the green roof section. The air temperature and humidity were measured with a TESTO transmitter (model 6651) with an accuracy of ± 0.2 ºC and ± 1.7 %, respectively. An anemometer AN046 (G.I.S Iberica) with an accuracy of ± 3% and 0.1 m/s of resolution is used to measure the wind velocity. Volumetric water content (VWC) is measured with Decagon EA-10 Soil moisture sensors with an accuracy of ± 0.03 m^3/m^3 typical in mineral soils (± 3%) and ± 0.02 m^3/m^3 in any porous medium (± 2%). A Middleton Solar pyranometer SK08 is used to capture the global solar irradiance. Finally, the load cells (UTILCELL Model 300) with accuracy class 3000 (a minimum division of 30g) were used to measure the weight evolution of the lysimeters.

2.4. GREEN ROOF

The extensive green roof consists of five different layers, from the top to the bottom: 80 mm of substrate, 2.4 mm of water distribution filter, 40 mm water retention layer, and 3 mm protective layer (Fig. 3). Without considering plants, the total thickness of the system is about 130 mm, and it weighs approximately 83 kg/m^2 (dry) and 127 kg/m^2 (saturated), allowing up to 44 l/m^2 of water retention capacity.

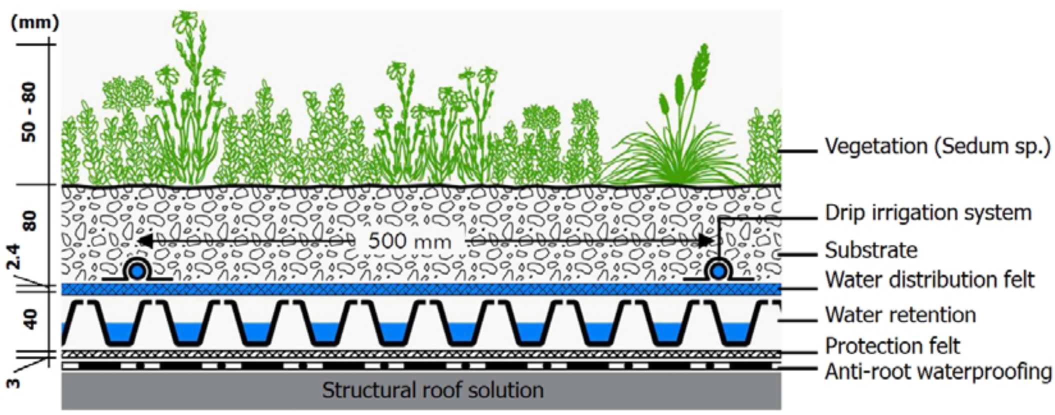

Fig. 3. *Detailed section of the extensive green roof system.*

2.5. WATER DISTRIBUTION AND WATER RETENTION LAYERS

These are the two most important layers of the green roof system that manage the water available for plants. The water distribution felt (100% polyacrylic) spreads the water over the entire green roof surface and temporarily stores from 3 to 4 l/m^2 before releasing it into the retention layer. Once the felt is completely wet, the water permeability is approximately 20 $L \cdot m^{-2} \cdot S^{-1}$. Then, water comes into the retention layer, allowing an extra storage of 5 l/m^2 in case of drought periods. In addition, the engineered design of water storage also contains air to have oxygen for better root development.

2.6. METHODOLOGY OF EXPERIMENTS

Two different types of experiments were carried out to evaluate the evaporative cooling potential of the specific substrate commonly used in extensive green roofs in a continental Mediterranean climate, one simulating an intensive rainfall event and the other obtaining the maximum field capacity. Summer data was collected between June 30 and September 18, 2018.

In addition to the weighing capacity of the lysimeters, during all the experiments, the global horizontal solar irradiance [$W\ m^{-2}$], wind speed [$m\ s^{-1}$], relative humidity [%], and air temperature [ºC] were monitored because they are the principal meteorological parameters affecting the evaporation [$kg\ m^{-2}\ day^{-1}$] by removing water content from substrate and plants.

2.6.1. EXPERIMENT 1: NATURAL PRECIPITATIONS

This experiment quantified the substrate's field capacity and water evaporation after simulating an intensive rainfall event. As a starting point, the samples were irrigated before sunrise until they reached the saturated condition of the system. Then, the lysimeters were evaluated under free-floating conditions until the mean VWC of the substrate was 0 (dry condition). The total period of this experiment was from August 7 to 23, 2018. It is important to highlight that there were no additional irrigations except the punctual natural precipitations.

2.6.2. EXPERIMENT 2: IRRIGATION

The second experiment only aims to obtain the maximum field capacity using the drip irrigation system below the substrate layer. This will help evaluate the system's evaporation potential by comparing two irrigation methods, natural precipitation and actual maintenance irrigation, to guarantee the survival of Sedum sp. in summer conditions.

At the beginning of the experiment, the samples were irrigated from the bottom part until reaching the drainage layer saturation that occurred when water input and drained water were equal. Then, the system worked under free-floating conditions until reaching the dry condition.

3. RESULTS AND DISCUSSION

3.1. EXPERIMENT 1: NATURAL PRECIPITATIONS

3.1.1. COOLING POTENTIAL

Figure 4 shows the daily evolution of the ambient parameters that affect the ET in the setup. The highest ET_{Rate} was 5.1 ($kg\ m^{-2}\ day^{-1}$) with a mean VWC of 15.5 % on August 7, 2018, as expected, because it was the day of the rain simulation event. Notice that this date was the warmest day of the period with a mean daily temperature and solar radiation of 31ºC and 451 $W\ m^{-2}$. During this experiment, three relevant natural rainfall events on August 8th, 12th, and 17th, 2018 have added 6.6, 3.6 and 3.5 ($kg\ m^{-2}\ day^{-1}$) into the system, respectively. On the same rainy days, the bare substrate showed significant evaporation rates of about 3.8, 2.1, and 1 ($kg\ m^{-2}\ day^{-1}$), respectively, because the rainfall events occurred after 7:30 p.m. in all cases. In addition, the water stored during the evenings was the reason why the days after a rainfall event showed higher ET values than the days before (Fig. 4). From saturated to dry conditions, the total evaporated water from the bare substrate in this period was 39.3 ($kg\ m^{-2}$), and the entire water input (rain) was 15.9 ($kg\ m^{-2}$).

The negative water balance and the hot summer conditions directly affected the trend of VWC, which showed a fast decrement in the first week despite the

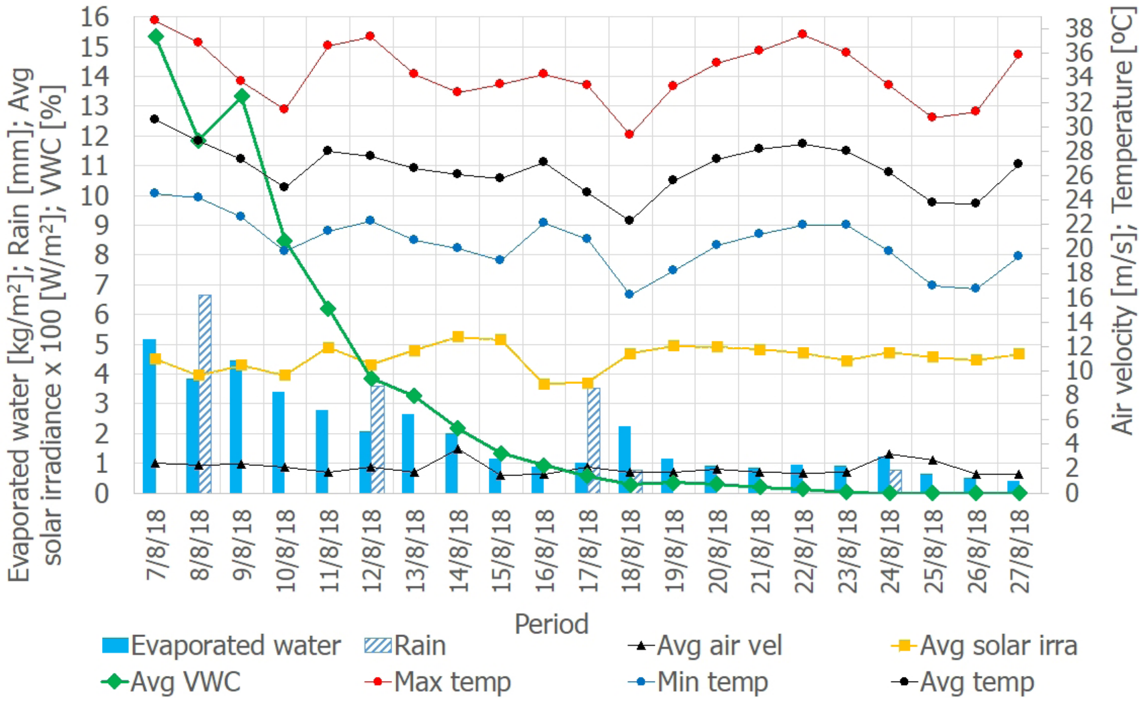

Fig. 4. *Water evaporation from saturated to dry conditions and daily ambient parameters during the experimental summer period.*

received rainwater (Figure 4). The rain on August 8 increased the VWC from 11.9 to 13.3 %, while the rainfalls on the 12th and 17th only cushioned the fast decrement of VWC. From August 20, the ET was below 1 (kg m^{-2} day^{-1}), and the VWC was almost 0%.

Using the conversion table created by Cascone et al. [18], the total amount of water evaporated can be easily translated into energy and directly compared with the results from similar studies. For example, considering the water evaporated on 18/8/2018, i.e., 2.2 kg/m^2, it corresponds to 0.90 MJ/m^2 because the conversion factor from mass to energy is 1 kg/m^2=0.408 MJ/m^2.

The aim of the study was to evaluate how substrate composition and depth affect moisture behavior and plant development in a Mediterranean context. A total of 96 trays of 1 m^2, varying the depth from 5 to 15 cm and the substrate composition with different % of coarse and fine materials, were tested in the summer and autumn periods of 2016. A mean ET rate of 4.23 (kg m^{-2} day^{-1}) was obtained using the Thornthwaite method after a rainfall of 77.28 mm distributed over 18 days in summer (from June 17 to July 18).

The VWC in the samples was collected manually every two days after a rain event. The results showed a maximum moisture content of 12% and 8% in 5 cm and 15 cm substrates, respectively, one day after rain. After three days, this result was inverted: the 5-cm substrates dried up more rapidly than the 15-cm substrates, which had longer moisture content. The moisture amount of the 15-cm substrates tended to be stable five days after rain and higher than that of the 5-cm substrates, where moisture was near 0%. The experimental correlation between the daily evaporation and the VWC of the bare substrate is presented in Figure 5.

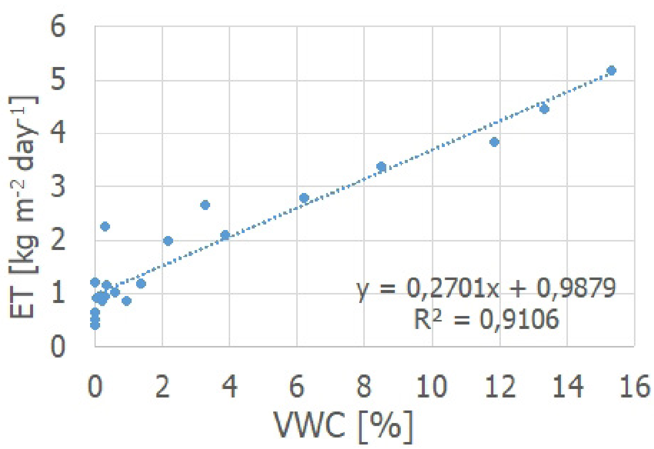

Fig. 5. *Experimental correlation of the daily evaporation rates and volumetric water content (VWC) of the substrate.*

3.1.2. DISCUSSION ABOUT COOLING POTENTIAL IN EXPERIMENT 1

For comparison and discussion purposes for this specific experiment, it is interesting to highlight the results of similar studies that employ similar methods. Tabares-Velasco and Srebric [20] results related to laboratory measures of ET to quantify the heat and mass transfer in a vegetated green roof are similar to those obtained in the present experimental setup under real conditions, namely 5.1 (kg m^{-2} day^{-1}) with a mean VWC of 15.5% on August 7, 2018. Results were higher in the study of Tan et al. [21], while the work of Chenot et al. [22] in a Mediterranean climate (Csa) shows comparable ET values with respect to the results obtained in Experiment 1.

The substrate composition, thickness, vegetation, and watering system are the two main technical differences when the results of previous studies are compared to those of this experiment. However, the moisture content and ET rate values showed similar trends in all the studies, such as fast decrements of VWC after a week from the last rainfall or watering, especially for the thinner substrates of 5 to 8 cm, and similar daily ET rates.

With respect to the correlation between the daily evaporation and the VWC of the bare substrate, this linear correlation confirms the similar expected results by Tabares-Velasco and Srebric [20] in their study in which they have stated that a linear relationship for evaporation and the bare substrate water content (without plants) could be obtained.

However, the same authors obtained a non-linear correlation between VWC and ET when using plants in laboratory experiments because of the different parameters affecting their water loss, such as photosynthesis and stomatal resistance.

3.1.3. TEMPERATURE EVOLUTION

The thermal performance of the substrate showed an important reduction of the surface temperatures by adding water at the beginning of the experiment, as expected (Fig. 6). The gravel reference system registered higher daily peak temperatures of about 14ºC compared to the saturated substrates. However, the fast reduction of moisture content after nine days, represented in Figure 6, had a direct impact on increasing the surface temperature of the substrate (Fig. 6).

From August 16 onwards, both substrates and gravel systems showed similar temperatures on the surface because of the low daily ET rates. Only from August 18 to 21st, there were small reductions of peak temperatures in the substrate compared to the gravel system due to the rainfall (3.5 mm) on August 17.

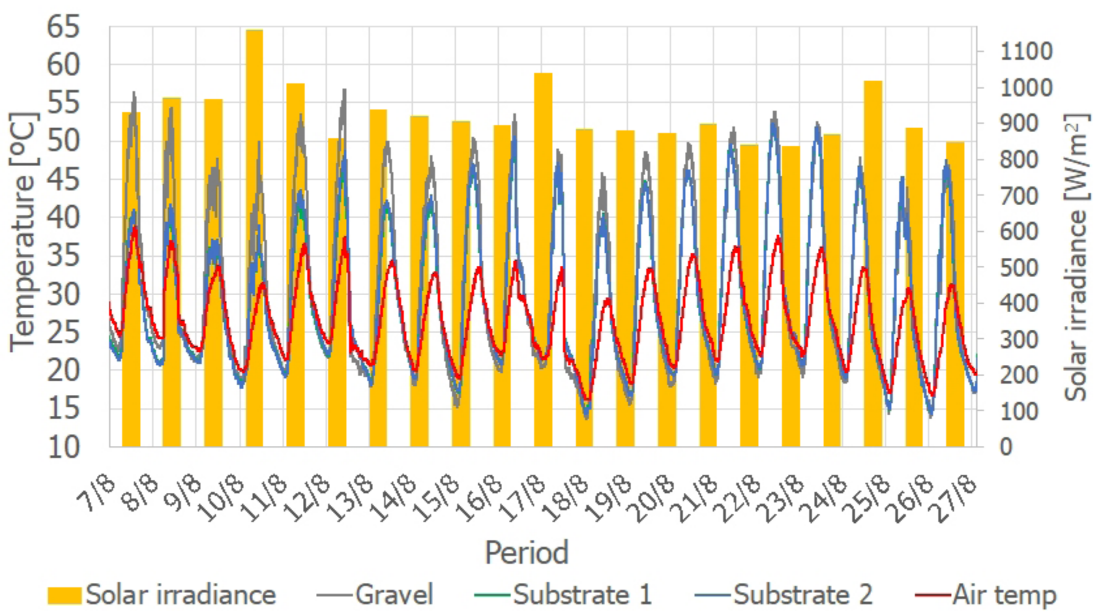

Fig. 6. *Thermal performance of the surface of substrate and gravel systems (probe A in Fig. 2).*

3.2. EXPERIMENT 2: IRRIGATION

3.2.1. COOLING POTENTIAL

Figure 7 shows the evolution of VWC, which registered a peak of 5.3% four days after the irrigation event. This value represents approximately one-third of the maximum water content registered in experiment 1 (15.5%), which was saturated, simulating an intense rainfall event. Thus, an important difference in the peak and the time lag of the VWC peak was observed when two different irrigation systems were compared; a delay of 4 days after the system's saturation was observed in the moisture content peak. Since the water input in experiment 2 is from a drip watering system allocated below the substrate (Fig. 7) instead of the outermost surface as in experiment 1, the water movement is mainly characterized by water sorption of the substrate and because of evaporation but not by precipitation. Thus, a drip irrigation system cannot provide the same water distribution to a substrate as a rainfall event.

The daily mean of the air temperature during this period was 28.9 ºC with a mean RH and solar irradiance of 60.2% and 321 W/m^2, respectively. The highest ET rate was 1.2 (kg m^{-2} day^{-1}), with a mean VWC of 2.1 % on July 8, 2018. Water evaporation is limited for this specific watering system because of the substrate's low VWC. The incremental trend of VWC was not linear, being 2.18% on July 1, 1.49% on July 2, and 1.05% on July 3 until it reached the peak of 5.3% on July 4. However, the VWC trend showed a linear decrement from the peak until it reached the dry conditions with a daily reduction of about 0.75%.

3.2.2. DISCUSSION ABOUT COOLING POTENTIAL IN EXPERIMENT 2

The results presented in Experiment 2 highlight the importance of the irrigation system, as also demonstrated in previous studies, such as Chenot et al. [22], where it is demonstrated that the substrate moisture behavior during summer dry periods in Avignon, South-eastern France (Csa), is influenced by the type of rainfall event (intensity, duration).

3.2.3. TEMPERATURE EVOLUTION

Compared to Experiment 1, where a higher quantity of water was provided by manual irrigation, the differences in temperatures are reduced in Experiment 2 (Fig. 8). Substrate surface temperatures were always higher than both air temperatures and gravel roofs. This is due to the white color of the gravel and its reflective capacity, which allows the gravel to maintain lower temperatures [23]. In this experiment, the water provided by the drip irrigation could not reduce substrate temperatures through the evaporation phenomena.

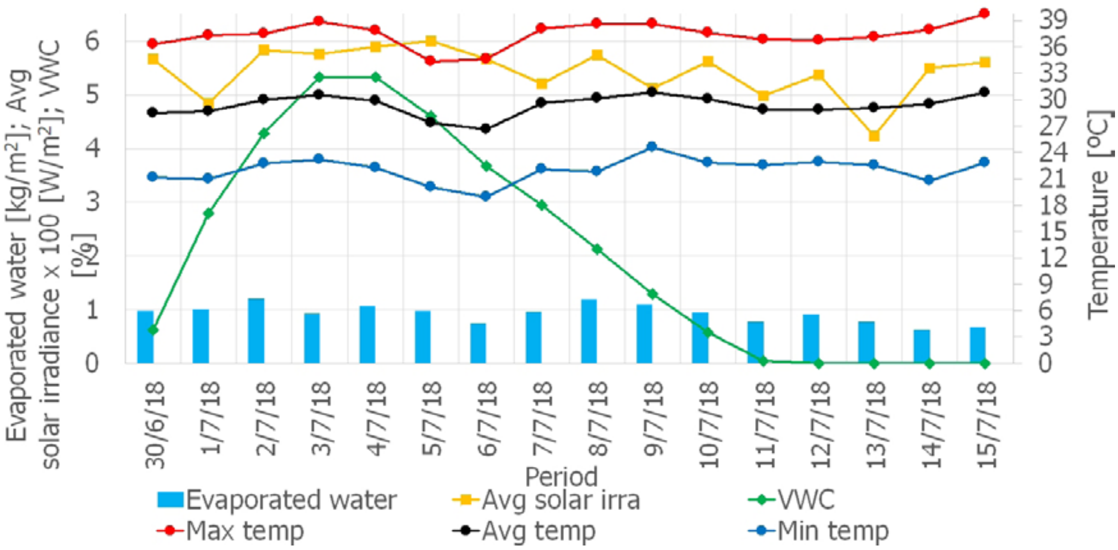

Fig. 7. *Water evaporation from saturated to dry conditions using an internal drip irrigation system and daily ambient parameters during the experimental summer period.*

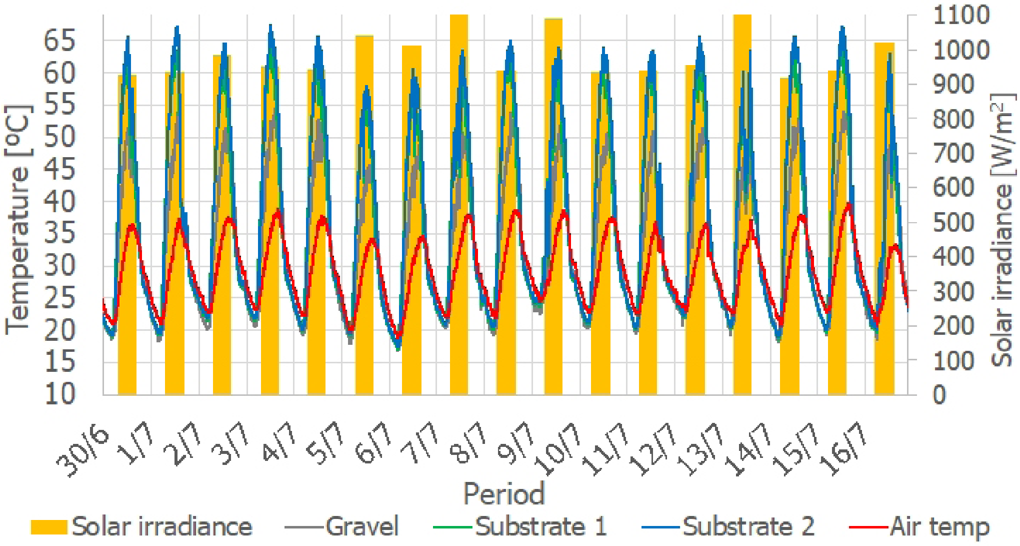

Fig. 8. *Thermal performance of the surface of substrate and gravel systems (probe A in Fig. 2).*

4. CONCLUSIONS

In this paper, an experimental setup was developed for the evaluation of the passive cooling potential of green roofs to improve the knowledge of the correlation between ET and thermal performance. The passive cooling potential was evaluated by varying the water supplied by the irrigation system simulating natural precipitations and irrigation regimes. First, results from the experimental evaluation on passive cooling of green roofs showed that when a high quantity of water was provided manually (Experiment 1), simulating an intensive rainfall event, it increased the thermal performance of the green roof. On the other hand, when the water was provided only by the drip irrigation system, the thermal performance was not so far from that of one of the bare reference roofs covered by high-reflectance cool gravels. It should be highlighted that these are only the first results from the experimental setup, which was mainly carried out to check that the experimental setup works properly and to establish preliminary settings by comparing the results to similar studies. The ongoing research will evaluate the cooling effect following the vegetation installation, comparing its thermal performance with the performance of green roofs without vegetation. The second step of the research will be the comparison between the cooling effects of two different plant species to identify the vegetation with the highest cooling potential in the continental Mediterranean climate. Finally, this work considers green roof solutions for flat buildings in the Mediterranean climate. Still, future studies could include other solutions that could fit the varied architectural panorama of Mediterranean historical buildings. Still, the findings and methodology of the study are of general relevance and useful for other types of green roofs.

Acknowledgments

The publication was created with the co-financing of the European Union – FSE-REACT-EU, PON Research and Innovation 2014-2020 DM1062/2021.

Authors contribution

S.C. conceived and designed the analysis, collected the data, contributed data, and performed the analyses, and S.C. and F.R. wrote the paper.

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VIRTUAL REALITY AS A NEW FRONTIER FOR ENERGY BEHAVIOURAL RESEARCH IN BUILDINGS: TESTS VALIDATION IN A VIRTUAL IMMERSIVE OFFICE ENVIRONMENT

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TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

DOI: 10.30682/tema090001

Abstract

Occupants' behaviour and strategies to encourage behavioural changes need to be addressed in workplaces to reduce energy consumption. In this study, the Theory of Planned Behaviour (TPB) was integrated for the first time with an office virtual environment (VE) to investigate the adequacy of the VE in the comfort and behaviour domain while understanding its effect in predicting individuals' energy-related intention of interaction with the building systems. One hundred four participants, randomly divided into two groups, were recruited to answer questionnaires (TPB, comfort, interactions, sense of presence and cybersickness). Two test sessions were conducted at a constant indoor air temperature: an in-situ experiment was compared with the virtual counterpart. Findings revealed an excellent level of presence and immersivity and the absence of high disorder levels. A good agreement between the two environments was highlighted in terms of thermal comfort, number, and type of interactions (one interaction focused on window opening for 71-81% of subjects). Moreover, no differences were discovered between the results of a multiple regression model in both real and virtual environments. In particular, the analysis identified the knowledge of energy consumption as the main predictor of behaviour because it accounted for about 12% of the variation in the intention of interaction in both tested environments. Thus, the suitability of the virtual environment could offer an effective tool for decision-makers and researchers to develop strategies aimed at designing more comfortable and less energy-consuming buildings.

Keywords

Immersive Virtual Environments, Office buildings, Indoor comfort, Intention of interaction, Theory of Planned Behaviour.

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1. INTRODUCTION

A Renovation Wave for Europe was proposed by the EU Commission in 2020 to allow buildings to be less energy-consuming while creating more liveable spaces. In this domain, an important target for researchers, policymakers, and public administrations is a clearer understanding of the factors driving energy consumption in the built environment. The aim is to develop suitable strategies to aid economic and environmental targets while increasing end-users comfort, satisfaction, health, and performance. However, technological progress and investments alone rarely guarantee low or net-zero energy in buildings because «human factors» play a crucial role, and while the awareness of their impact has improved, it is often ignored in building design. Indeed, it is well-established that occupants' behaviour is a major factor affecting the energy performance of buildings. It is important to notice that users' energy-related behaviour differs significantly between domestic and non-domestic use, where the dwellers directly pay for the energy consumption while the company provides free energy for workers. Employees seem less motivated to engage in energy-saving behaviour than households that are more willing to save energy in their daily lives. As a result, during the last years, energy consumption in commercial and services has increased, accounting for about 30% of European energy demand [1]. Due to the large amount of time spent in workplaces (60-70% every week), workers constantly try to provide comfortable working conditions [2]. Thus, a hot research topic has emerged to understand the factors affecting people's behaviour and willingness to save energy in workplaces. Accordingly, technological development promoting energy efficiency needs to be integrated with a programme to encourage behavioural changes that could be a potential solution to be adopted immediately.

Most of the research has already indicated that energy behaviour is a relatively complex task to understand because it depends on several drivers: internal (occupants' activities and preferences) and external (building, equipment, environment, time, contextual, random) factors. Thus, various theories and models have been introduced in this field, such as the Theory of Planned Behaviour (TPB) developed by Ajzen et al. [3]. It explains that human behaviour is guided by three factors: behavioural beliefs about the consequences of the behaviour itself, normative beliefs about the expectation of others over the users' behaviour, and control beliefs related to the presence of factors that may facilitate or limit the implementation of the behaviour. In particular: behavioural beliefs produce a favourable or unfavourable attitude toward the behaviour, normative beliefs result in perceived social pressure or subjective norm, and control beliefs determine perceived behavioural control. The combination of the attitude toward the behaviour, subjective norm and perceived behavioural control produces a behavioural intention. In general, the users' intention to perform a behaviour would be greater the more favourable the attitude, the less social pressure, and the greater perceived control. In addition, in the presence of an opportunity and sufficient control, building users are expected to finalise the intention, which is why it is assumed to be an immediate antecedent of the behaviour itself. Figure 1 shows a schematic representation of the TPB as developed by Ajzen et al. [3].

However, to the authors' knowledge, only a few studies [2, 4–7] have applied the TPB to environmental behaviours in workplaces. In general, several hundred office building occupants were surveyed (i.e. a university in Malaysia [5], companies in China [2], in the U.S. [6], and across the UK [4, 7]) to examine how much the TPB constructs explain the variance in employees' energy-saving behaviour.

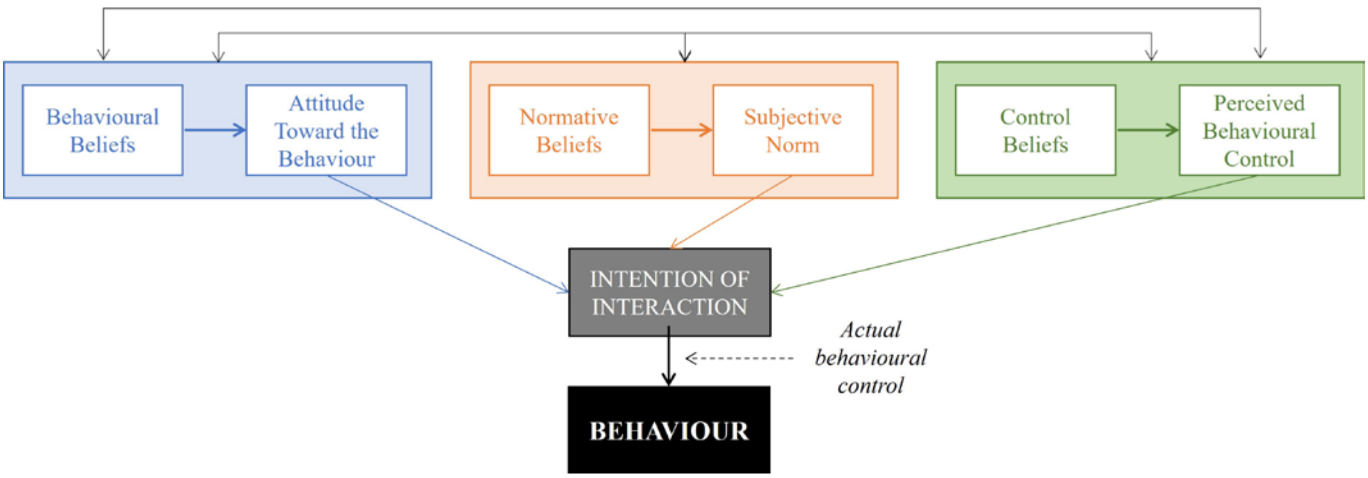

Fig. 1. *Schematic representation of the Theory of Planned Behaviour (Figure redrawn from Icek Ajzen [3]).*

This research topic is still emerging. Moreover, an improvement in implementing suitable programs to understand energy behaviour and encourage occupants' sustainable choices in offices is needed. A proper strategy to pursue this goal could be the use of Virtual Reality (VR). This technology allows the researcher to create specific correlations for each office building configuration already in the early design stage. The end-user experience in energy-saving programs could be enhanced through suitable Immersive Virtual Environments (IVEs), which create a psychological state in which the users perceive themself as existing within the virtual space. Only a few studies examine the adequacy of VR in the occupant behaviour research domain focusing on blinds and lighting systems [8–11] and climatic equipment (heater, fans, air conditioning) [12, 13], but the factors influencing the behaviour were not contextually examined.

Concerning these viewpoints, this research tries to contribute to the current literature by integrating, for the first time, the TPB with a virtual environment to understand individuals' energy-related intention of interaction with the building systems. This study compared results from a laboratory-based experiment in a real office room to those obtained in an equivalent immersive virtual model. The thermal comfort and interactions with the room components (a fan, a heater, an air conditioning system, and windows) of 104 participants were recorded to fit this purpose. The main goals of the study are to verify the adequacy of IVE in comfort and adaptive behaviour research and validate the integration of TPB within the IVE by exploring its suitability in predicting behavioural intention in workplaces through self-reports in both tested environments.

2. MATERIALS AND METHODS

The present study involved an independent-measure design experiment (52 subjects per group) in investigating the adequacy of the virtual environment in the comfort and behaviour domain. Two test sessions were conducted: each participant was randomly assigned to a virtual condition or «immersive virtual environment» (group 1) or an in-situ condition, or «real environment, RE» (group 2) session.

2.1. TEST ROOM

An office was set up like a test room located inside the Department of Engineering, Civil, Construction and Architecture (Università Politecnica delle Marche, Ancona, Italy). The test room had an internal dimension of 5.93x4.38 m and a floor ceiling height of 3.00 m. The room contained furniture to replicate an office working environment and was equipped with a computer station to carry out the tests and the equipment for the IVE visualisation (Fig. 2). The thermal environment depends only on the central HVAC system of the room, and the indoor air temperature was recorded by several probes (temperature range: from +5° to +60° and accuracy ±0.3°) located at the feet (0.10 m), waist (0.60 m) and head (1.10 m) of the seated participants and above the table where the test was performed. To detect participants' energy-related intention of interaction, a window, a fan, a heater, and an air conditioner were added to the room, but they were set off and did not influence the thermal environment. Indeed, the participants did not directly interact with the climatic systems; they only reported the adaptive response they would have wanted to carry out to improve their thermal comfort induced by the HVAC of the room. So, no thermal outcome was experienced by the subjects. This strategy is supported by the TPB, which states that the intention of interaction is antecedent to the behaviour itself, and as the occasion occurs, the users would perform the intended behaviour.

2.2. VIRTUAL ENVIRONMENT

To create an IVE that can adequately replicate the double-occupancy office space, an extremely detailed 3D model was created using CAD software and afterwards exported to *Unity* software [14] to apply materials, lights and cameras. The luminance parameter (L*) and chromatic components (a*, b*) of the CIELab model were detected using a spectrophotometer (*CM-2500d Konica Minolta*) to address the correct representation of surfaces' colour and materials. Indeed, 5 measurements were carried out with a diameter of 8 mm for each surface of the office room: walls, desk, chair, and floor tiles. Then,

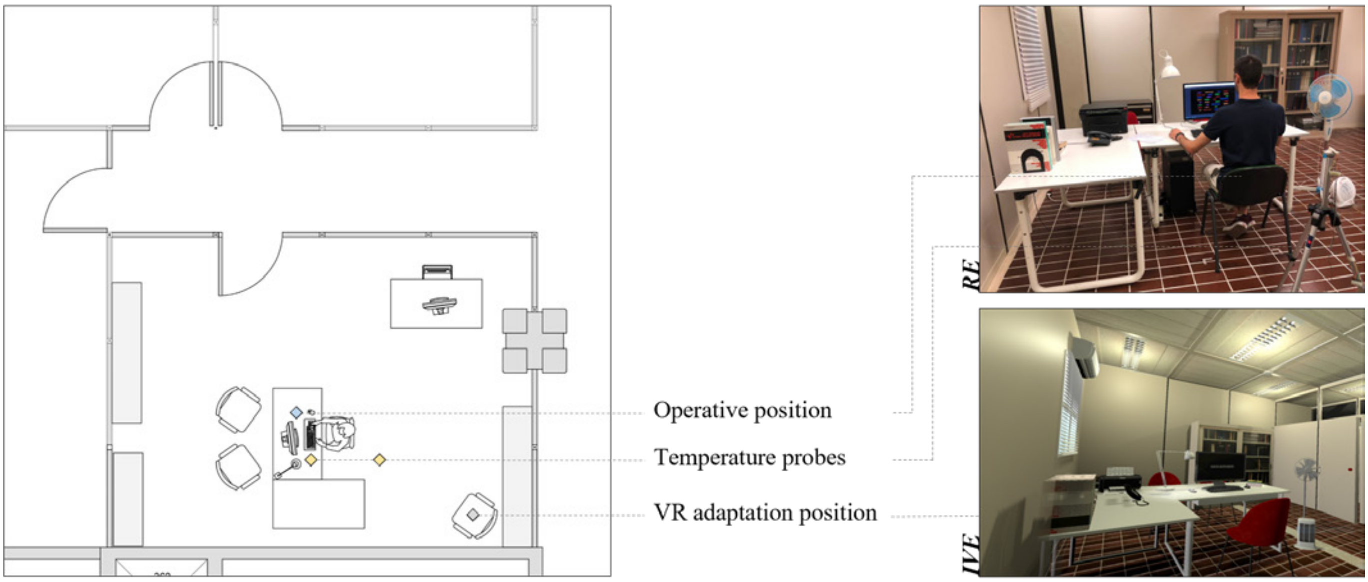

Fig. 2. *Test room setup, RE setting and IVE scenario.*

the resulting L*a*b* parameters were converted into RGB coordinates for the Unity model.

The authors created two basic virtual scenarios (Fig. 2): the first was located far from the virtual desk to have a complete view of the room to allow the adaptation to the virtual environment, while in the second, participants were virtually seated at their desks to perform the performance tasks and the questionnaires (operative phase). In order to achieve the highest level of realism and verify the external-ecological validity of the created model, the productivity tests and surveys were shown through the virtual computer monitor, then avoiding also the so-called «break-in-presence». Scripts were designed to visualise the scenes sequentially and automatically while collecting the participants' answers to minimise the interactions with the researcher managing the test. The *HTC Corporation VIVE PRO Eye* head-mounted display (1440x1600 resolution images per eye) allowed the visualisation of the virtual model.

To create a model coherent with its real office counterpart for validation, the climatic systems (a window, a heater, a fan, and an air conditioner) were also added in the virtual environment. After selecting their intention of interaction, the subjects did not experience dynamic visual changes and thermal outcomes as in the real environment.

2.3. SURVEY

The survey consisted of three main sections for both RE and IVE tests: two for the pre-experimental phase and one for post-experiments. There were 24 questions in the pre-experimental questionnaire and 19 in the post-experimental one.

The first section included within the pre-test survey focused on socio-demographic questions (gender, age, height, eyesight problems, educational level) and garments worn during the test to estimate the clo value according to standard UNI EN ISO 9920:2007 [20].

The second section of the pre-experimental questionnaire was designed to contain four main parts associated with the Theory of Planned Behaviour constructs. It was intended to measure respondents' awareness of consequences, attitudes toward reducing energy use, knowledge about the energy consumption of electric appliances and perceived behavioural control. A seven-point Likert scale was adopted for the TPB questions asking participants to indicate their level of agreement for each indicator ranging from «totally disagree» to «totally agree». Table 1 presents the overall questions to investigate the TPB and the related literature references [15, 16] adopted to develop the questionnaire. Anyway, the questions were revised to be suitable for the present research aim.

Construct		Indicators
Awareness of consequences (AC)	AC1	Interacting with the control systems to make myself comfortable in my workplace will influence MY COMFORT
	AC2	Interacting with the control systems to make myself comfortable in my workplace will influence ENERGY CONSUMPTION
	AC3	Interacting with the control systems to make myself comfortable in my workplace will influence MY PRODUCTIVITY
Attitude toward the reduction of the energy use (AT)	AT1	Saving energy in workplaces will help to protect the environment
	AT2	I typically perform energy-saving behaviours in my workplace
	AT3	During the winter, I performed these adaptive actions to make myself comfortable: Adjusting/switching off the heating system when feeling too hot
	AT4	During the winter, I performed these adaptive actions to make myself comfortable: Adding an extra layer of clothing when feeling cold
Knowledge about the energy consumption (KE)	KE1	I know how much energy the heater consumes
	KE2	I know how much energy the heating system consumes
	KE3	I know how much energy the air conditioning consumes
	KE4	I know how much energy the fan consumes
Perceived behavioural control (PBC)	PBC1	I believe that I have control over the amount of energy consumed at work
	PBC2	I believe that I can avoid unnecessary power consumption at work (i.e. closing the windows when the heating system is working)
	PBC3	Access is a main perceived impediment to interacting with the control system in my workplace
	PBC4	Other co-worker's needs are a main perceived impediment to interacting with the control system in my workplace

Tab. 1 *Main construct and indicators associated with TPB survey questions and related literature references: S. D'Oca et al. [15], A. Cibinskiene et al. [16].*

Lastly, the post-experimental questionnaire section included: comfort assessment and adaptive intention of interaction. The first part investigated thermal comfort parameters according to the standard UNI EN ISO 10551:2019 [17], as follows: Thermal Sensation Vote (TSV) from «very cold» to «very warm»; Thermal Comfort Vote (TCV) from «comfortable» to «extremely uncomfortable»; Thermal Preference Vote (TPV) from «much colder» to «much warmer». The second part focused on the adaptive strategies that subjects would have carried out to improve their comfort within the thermal environment. According to the TPB, the intention is assumed to be the immediate antecedent of the behaviour [18]; thus, the intention of interaction with a heater, fan, window, and air conditioning system was collected. Participants' choices were not displayed in the virtual office or implemented in the physical environment to show a real status change (opening/closing window, switching systems on/off, etc.).

A final section in the post-experimental questionnaire was included during the test in the virtual environment to verify the ecological validity of the model. In particular, the Slater-Usoh-Steed and the Igroup Presence Questionnaires (IPQ) were combined to evaluate the sense of presence and immersivity according to four indicators: Graphical Satisfaction (GS), Spatial Presence (SP), Involvement (INV), and Experienced Realism (REAL) on a seven-point scale (from «totally disagree» to «totally agree»). The Virtual Reality Sickness Questionnaire (VRSQ) was also added to assess motion sickness [19] on a five-point scale (from «not at all» to «very much»). Six symptoms were investigated: general discomfort, fatigue, eye strain, difficulty in focusing, headache, and vertigo.

In the real office environment and the virtual pre-experimental phase, the questions were submitted through an online platform to minimise interactions with the researcher avoiding any influence on the subject's answers.

For completeness, Appendix A reports the overall questionnaire.

2.4. EXPERIMENTAL PROCEDURE

Figure 3 shows the details of the experimental procedure. On each visit, participants were randomly assigned

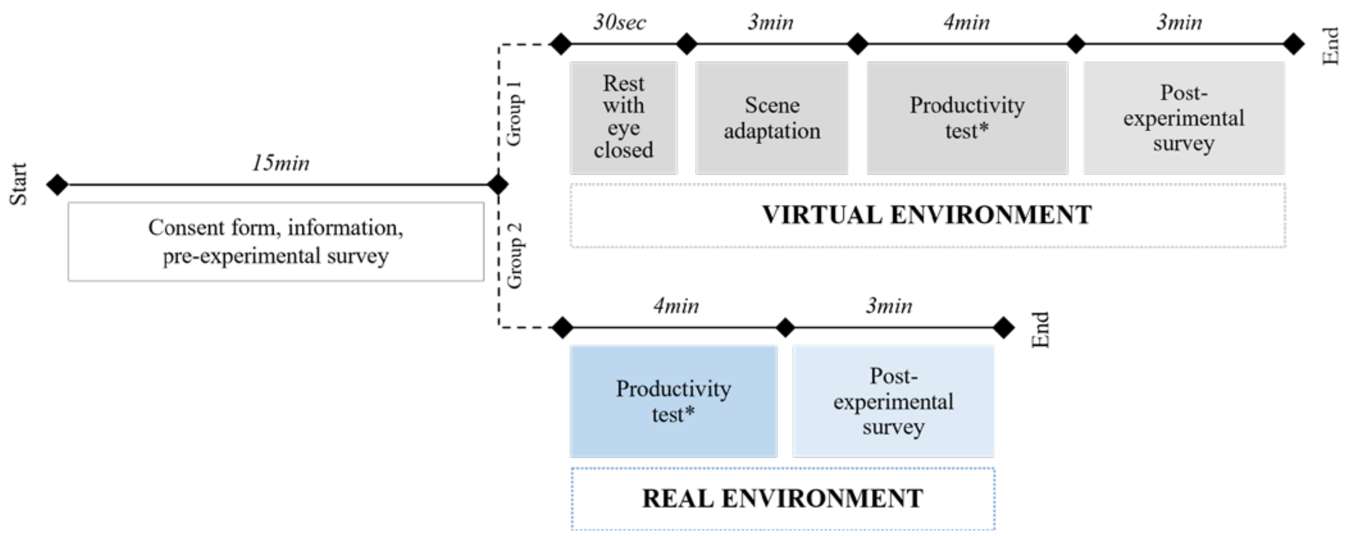

Fig. 3. *Experimental procedure in a real and virtual environment (*no performance analysis).*

to experience the real (group 1) or the virtual environment (group 2).

At the beginning of each test session, all participants signed a consent form and received information about the test. Later on, a pre-experimental phase (15 minutes) was carried out to allow them to get used to the environmental conditions and complete the pre-experimental questionnaire. After that, in both RE and IVE sessions, participants performed a productivity task (3 minutes) to stay focused and simulate a traditional working scenario during the test session. However, no task performance assessment was later carried out in this study. Then, they answered a post-experimental survey.

In particular, in the IVE experiment, participants wore and adjusted the head-mounted display before the operative phase, rested with their eyes closed for 30 seconds and adapted to the virtual scene for 3 minutes. In this way, any psychological fluctuations related to the virtual environment exposure were reduced, and immersion was facilitated. Responses to the productivity test and questions displayed on the virtual computer monitor were given by voice and recorded by the researchers.

Each test session lasted about 20-25 minutes to reduce overall fatigue and exposure to the virtual environment.

3. RESULTS AND DISCUSSIONS

In the following sections, the analysis of the two datasets (RE and IVE) is presented to investigate the ecological validity of the virtual model and establish the suitability of IVE in the behavioural research domain. Concerning the second point, the authors carried out a strict methodological step-by-step process to ensure the reliability of the results: the comfort parameters and the number and type of interaction were at first compared between the RE and IVE, then the ability of TPB integrated within the IVE to predict behavioural intention was analysed looking for any eventual difference with the RE.

3.1. PARTICIPANTS

The sample of 104 participants had a well-balanced male-female ratio (50-50%) and it was mainly composed of young people as follows: 48% between 20 and 25 years old (μ=23.2; SD=1.3), 35% between 26 and 30 (μ=27.5; SD= .6), 21% between 31 and 39 (μ=33.3; SD=1.9) and only the 6% over 50 years old (μ=40.7; SD=2.9). Most subjects were already graduated from university (45%), 40% were selected among university students, and 14% had a higher educational level (PhD, graduate school). 58% of participants had had at least one previous experience with VR technology. 42% of the sample had eyesight problems (myopia and astigmatism), but all of them wore corrective lenses during the tests to achieve a good model visualisation and correctly perform the test. The authors computed a power analysis (effect size 0.50, α=0.05) through the G*Power software [20], confirming that the sample size was adequate to detect significant effects due to a statistical power equal to 0.81.

3.2. ECOLOGICAL VALIDITY

The ecological validity of the created virtual environment was evaluated through the self-reports on the sense of presence and immersivity indicators (Graphical Satisfaction, Spatial Presence, Involvement, Experienced Realism) and the cybersickness disorders from group 2 performing the IVE experience.

In order to verify the immersivity level and the effectiveness of the study, the four indicator scores were compared with the ones from existing literature using the VR tool in the same research domain [21–24]. The type of adopted scale (i.e. Likert, five-point, seven-point) for each question may vary depending on the experiment. Thus, the average scores obtained were rescaled to a five-point scale. The mean scores are reported in relevance order in Table 2. The values are generally higher than a moderate level (i.e. 4) on a five-point scale ranging from 1 to 5. In particular, the participants appreciated the graphics of the model (GS), experienced a very good realism (REAL) and felt involved within the virtual environment (INV). In addition, a very good spatial presence was reported as the mean value for *SP* is 4.47, which is higher than [21] (3.39), [23] (3.68), [22] (3.74), and almost similar to [24] (4.24). Due to a negligible difference equal to 0.03, the virtual environment offered the users an excellent sense of presence and immersivity.

According to the Virtual Reality Sickness Questionnaire results, no subject has suffered from vertigo since the test was conducted in static conditions. General discomfort, fatigue and headache symptoms were negligible since between 92% and 100% of the subjects assigned a score of «not at all» and «slightly». Moreover, 10% of them reported «moderate» eye fatigue due to a «difficulty in focusing» (25%) caused by the slightly blurred images presented by the head-mounted display.

3.3. COMFORT AND INTERACTION ANALYSIS

The authors looked for a good agreement between the real and virtual experiments by qualitatively comparing the outcomes of the thermal comfort votes and intention of interaction.

At first thermal comfort (TSV, TCV, TPV) was assessed (Fig. 4). The average value of the indoor air temperature during the test sessions was 24.45°C (SD = 0.52). Figure 4 shows the participants' percentage of votes across the real and the virtual experiments. As expected, the temperature significantly influences TSV in both environments: at least 94% of the subjects felt from «slightly warm» to «hot». Therefore, the thermal condition was evaluated as not fully comfortable (from «slightly uncomfortable» to «uncomfortable») by 66%-83% of the subjects, respectively, because the selected temperature set-point was +4°C away from the usual winter thermal comfort temperature (20°C). Thus, according to the TPV, the majority (between 79% and 90%) of the subjects would have wanted to feel at least «slightly cooler» and «cooler».

Secondly, the authors analysed participants' number and type of intention to interact with typical thermal control systems (heater, fan, window, air conditioning) within both environments. Generally, only one intention per participant was recorded in both the real and virtual settings: between 77% and 85% of participants would

Classification		Year	*GS*	*REAL*	*INV*	*SP*
This study		2022	4.58	4.47	4.15	4.21*
Previous studies	[19]	2019	3.65	2.73	3.23	3.39
	[20]	2019	-	3.21	-	3.74
	[21]	2019	-	3.75	-	3.68
	[22]	2020	-	3.54	4.11	4.24*

Tab. 2. *Comparison of scores on a five-point scale of the four indicators: Graphical Satisfaction (GS), Experienced Realism (REAL), Involvement (INV), Spatial Presence (SP).*

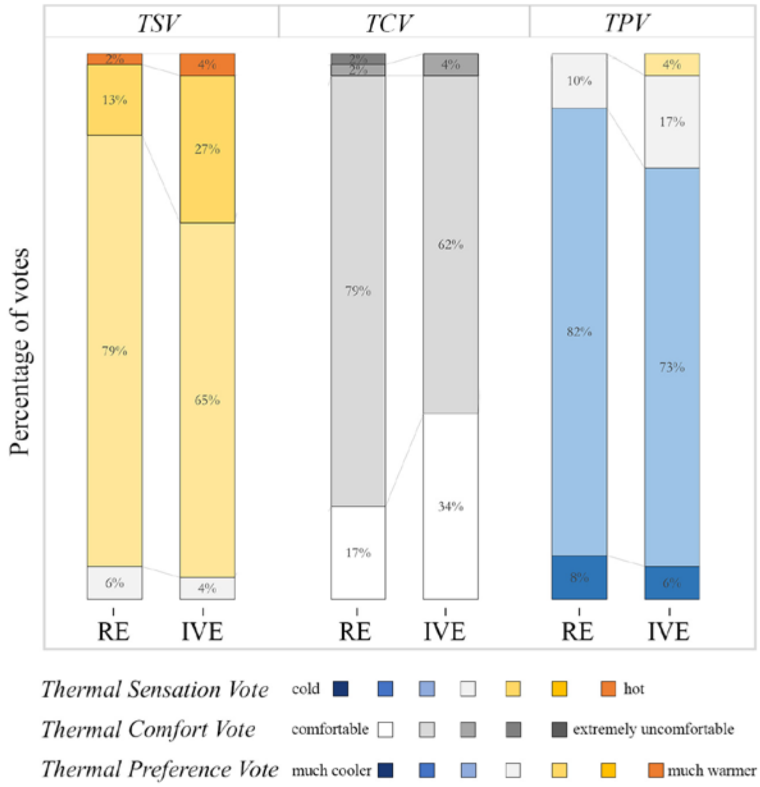

Fig. 4. *Percentage of votes for the thermal comfort parameters.*

have modified their thermal condition by interacting with one of the highlighted components. This result is in agreement with the TPV scores. The type of interactions was also compared. The qualitative analysis (Fig. 5) did not highlight a difference between RE and IVE: between 71% and 81% of subjects highlighted opening the window as the best strategy to improve their thermal sensation, decrease the indoor temperature and enhance air change. As a result, the authors concluded that the virtual reality tool performs well because no significant differences were discovered across thermal comfort and interactions. The results allowed the authors to conclude that VR properly performs because no significant differences were detected in terms of thermal comfort and intention of interaction between the real and the virtual environment, in line with previous studies (i.e. [12]).

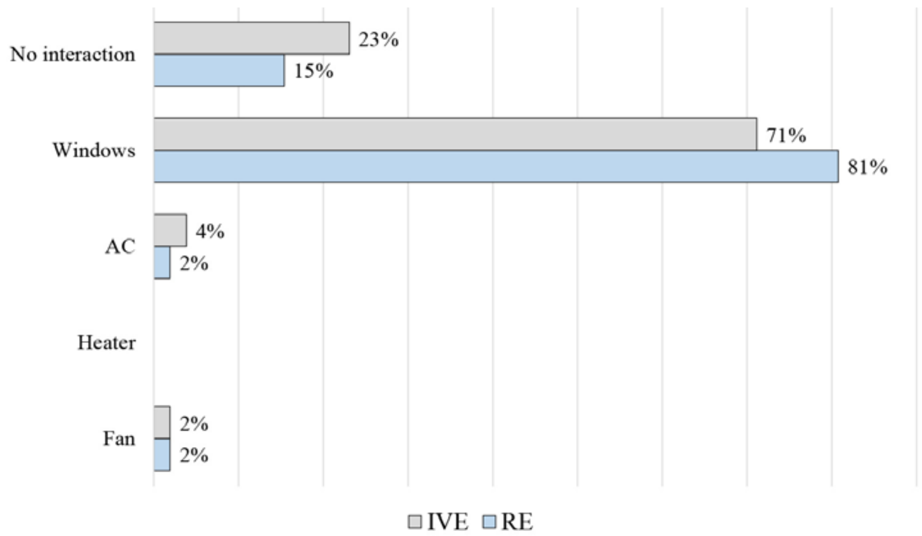

Fig. 5. *Type of intention of interaction within the two tested environments.*

3.4. TPB ANALYSIS

Finally, once the perfect match between RE and IVE in terms of thermal comfort parameters, number and types of interactions was demonstrated, the suitability of integrating TPB within an immersive environment was explored. Thus, as part of the validation process, the authors looked for a correspondence between the RE and IVE in terms of the ability of TPB constructs to predict behavioural intention.

First, this paragraph presents an overview of the data via qualitative analysis. Secondly, it was necessary to carry out a specific factorial analysis to ensure that the dataset of the four constructs (AC, AT, KE, PBC) is suitable to analyse the intention of interaction. Lastly, after ensuring the adequacy of the dataset for the research purpose, the results of the VE were compared to the real one via regression model to detect if TPB integrated within an IVE can adequately predict the same behavioural intention as in RE.

At first, a qualitative analysis of the TPB self-reports on the overall sample size (n=104) was conducted. All the subjects agreed that energy-saving in workplaces would lead to a positive outcome (AT1, 99%). Even if only 20% to 35% of them know how much energy the surrounding electric appliances (heater, heating system, air conditioning, fan) consume (KE), they confirm to carry out an energy-saving behaviour during the winter (AT2), such as adjusting or switching off the heating equipment when feeling hot (AT3, 100%) or adding an extra layer of clothing when feeling cold (AT4, 91%). Access (PBC3) and other co-workers' needs (PBC4) were perceived as the main impediment (100% and 95%, respectively) to interacting with the control system. Thus, less than 50% believed to have control over the amount of energy consumed (PBC1) and avoid unnecessary power consumption at work (PBC2). Despite that, at least 95% were aware of the consequences of interacting with the control systems in terms of comfort, energy consumption and productivity (AC).

Secondly, a Confirmatory Factor Analysis (CFA) was computed to evaluate the model's internal consistency and validity and ensure that the dataset is reliable. At first, two items, marked with an asterisk in Table 3, were dropped (AT4, PBC4) due to factor loadings (indicating the correlation between the item and the construct) lower than the threshold value for a sample of 100 respondents. Other lower values (AC1, AT3, italics font) were retained because it is recommended to have at least three items measuring each construct and their elimination neither

		Construct validity	Model-fit				
Construct	Item/ questions	Factor loading	Chi-square to the degree of freedom	Comparative Fit Index	Tucker Lewis Index	Root Mean Square Error of Approximation	Standardized Root-Mean-Square Residua
Awareness of consequences (AC)	*AC1*	*0.50*	1.89 ($\chi2$ = 106.28, df = 61)	0.93	0.91	0.08	*0.10*
	AC2	0.68					
	AC3	0.83					
Attitude toward energy-saving (AT)	AT1	0.92					
	AT2	0.55					
	AT3	*0.30*					
	AT4*	0.003*					
Knowledge about the energy consumption (KE)	KE1	0.83					
	KE2	0.96					
	KE3	0.96					
	KE4	0.83					
Perceived behavioural control (PBC)	PBC1	0.83					
	PBC2	0.77					
	PBC3	0.67					
	PBC4*	0.30*					
Threshold values		≥ 0.55 [23]	≤ 3.00 [24]	≥ 0.90 [24]	≥ 0.90 [24]	≤ 0.08 [24]	≤0.08 [24]

Tab. 3. *The result of the main standardised factor loadings, reliability and convergent validity according to the cut-off values ([25, 26]).*

increase nor decrease the reliability of the model itself (see next steps). As a result, the overall measurement items have significant construct validity. An adequate fit of the data was then confirmed according to the chi-square statistics, and four of the five fit indices respected the threshold values but fell short of the recommended cut-off for the SRMR.

The Composite Reliability (CR) and Average Variance Extracted (AVE) values were all greater than the recommendation, thus supporting the reliability and convergent validity of the model (Tab. 4).

Moreover, the square root value of the AVE of each construct (Tab. 4, bold font) was greater than the correlation among the constructs in the same row and column. According to the Fornell-Larcker criterion, the discriminant validity was established, confirming that each construct is unique and truly distinct from the others [27].

In conclusion, the measurement model (CFA) confirms that the overall AC, AT, KE, and PBC contribute to analysing the intention of interaction with the building systems of the total sample size (n=104).

Finally, after verifying the suitability of the measurement model, a stepwise multiple linear regression analysis (α=0.05) was undertaken to explore the ability of TPB constructs to predict behavioural intention based on the four constructs (AC, AT, KE, PBC) in both tested environments. The analysis was carried out in both groups separately (n=52), and then the results were compared. The constructs were entered into the model in the following order: awareness of consequences, attitude toward energy saving, knowledge about the energy consumption of the equipment, and perceived behavioural control. The significance level was set equal to 0.05 (5%). Table 5 shows that only when knowledge about energy consumption is combined with the awareness of consequences and attitude toward energy-saving (Model #3) does the predictive power (R^2) of the regression model increase. According to the R^2 value, Model #3 accounted for about 17% of the intention in interaction in both RE and IVE. Perceived behavioural control did not substantially improve the previous result (Model #4). Thus, a final regression model (Model #5) with knowledge about energy consumption as the only predictor shows a significant relationship in both cases. The authors concluded that no difference was detected across the two environments concerning the ability of the TPB constructs to predict the intention of interaction, thus supporting the adequacy of VR. Knowledge about energy consumption alone accounted for approximately 12% of the variation in the intention of interaction. However, only a few subjects knew how much energy the electric appliances (heater, heating system, air conditioning, fan) consumed.

Construct	Reliability	Convergent validity	Discriminant validity			
	Composite Reliability	Average Variance Extracted	AC	AT	KE	PBC
Awareness of consequences (AC)	0.71	0.51	**0.71**			
Attitude toward energy-saving (AT)	0.64	0.50	0.68	**0.69**		
Knowledge about the energy consumption (KE)	0.94	0.81	0.10	0.64	**0.90**	
Perceived behavioural control (PBC)	0.80	0.64	0.21	0.23	0.04	**0.80**
Threshold values	≥ 0.60 [25]	≥ 0.50 [25]				

Tab. 4. *The result of the reliability, convergent and discriminant validity.*

Model #	Predictors	R^2		F-statistics		p-value	
		RE	IVE	RE	IVE	RE	IVE
1	AC	0.02	0.03	0.33	0.35	0.45	0.44
2	AC + AT	0.10	0.09	0.87	0.82	0.52	0.57
3	**AC + AT + KE**	0.17	0.17	1.96	1.95	**0.04**	**0.04**
4	**AC + AT + KE + PBC**	0.17	0.17	1.96	1.95	**0.04**	**0.04**
5	**KE**	0.12	0.11	3.33	3.34	**0.01**	**0.01**

Tab. 5. *Multiple linear regression analysis in RE and IVE: significant p-value (<0.05) are in bold font.*

4. CONCLUSIONS

Understanding the factors affecting individuals' behaviour and attitude to saving energy is beneficial to encouraging behavioural changes and reducing energy consumption in workplaces. In this study, the Theory of Planned Behaviour was integrated for the first time with an office virtual environment to understand individuals' energy-related intentions of interaction with the building systems. A total of 104 participants, divided into two balanced groups, were recruited to answer questionnaires (TPB, comfort, intention of interaction, sense of presence, and cybersickness). Each group randomly performed one test session at a constant indoor air temperature (24°C): an in-situ experiment was compared with the virtual counterpart of an office room. The data were analysed to verify the adequacy of IVE in adaptive behaviour research: ecological validity, thermal comfort and number and type of interactions comparison, and the ability of TPB integrating within the IVE to predict behavioural intention in both tested environments.

In particular, the analysis and the comparison with past studies of the four indicators (graphical satisfaction, experienced realism, involvement, and spatial presence) revealed that the virtual environment created an excellent level of presence and immersivity, and most subjects did not report high disorder levels.

Secondly, a good agreement between the real and the virtual environment was discovered in terms of thermal comfort and the number and type of interactions. In both environments, the temperature has a significant influence on thermal sensation (at least 94% of the subjects felt from «slightly warm» to «hot»), and the selected temperature condition was evaluated as not fully comfortable because the set-point was +4°C away from the usual winter thermal comfort temperature (20°C). Thus, the majority (between 79% and 90%) of the subjects would have wanted to feel at least «slightly cooler» and «cooler». Therefore, opening the window was highlighted as the best strategy to improve the thermal sensation by decreasing the indoor temperature and enhancing air change in both RE and IVE.

After establishing a good model-of-fit (CFA analysis), multiple regression models of the environments were compared to evaluate the suitability of the TPB in IVE in predicting participants' intention of interaction. The comparison of the results did not reveal differences between RE and IVE, thus, supporting the adequacy of the integration of TPB within the VR technology. In particular, the analysis identified the knowledge of energy consumption as the main predictor, even if only a few subjects knew how much energy the electric appliances consumed. This implies that a higher knowledge about this topic could significantly positively affect energy-related behaviour, allowing individuals to interact correctly with the building equipment to make them comfortable while saving energy in the workplace.

In conclusion, the suitability of the virtual environment could offer an effective tool for decision-makers and researchers to develop strategies aimed at designing more comfortable, liveable and less energy-consuming buildings. However, future studies should be conducted after adjusting the TPB survey to include other predictors in the model, such as personal and social norms, habits in energy-saving behaviours, and time availability. Thirdly, the data were collected on a hundred subjects, which may restrict the generalizability of the results, but the findings may be effective in the university-specific contest where individuals are mainly students with limited access and knowledge about the building systems. Lastly, an educational strategy to improve people's awareness to use and save energy efficiently while creating more liveable and comfortable spaces should be carried out and then make a comparison between non-trained occupants and trained ones in terms of the intention of interaction and energy-saving practices.

Authors contribution

A. Latini: investigation, formal analysis, writing - original draft, writing - review & editing. E. Di Giuseppe: conceptualization, methodology, writing - original draft, writing - review & editing. M. D'Orazio: supervision, funding acquisition, conceptualisation.

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Appendix A

Factor	*Question*	*Rating scale*
Pre-experimental questions		
Demographical information	Please specify your: ● Gender ● Age ● Height ● Weight	Short open-ended questions
Educational level	Please select your educational level ○ Not graduated from university ○ Graduated ○ PhD, post-graduate school	
Health status and eyesight problems	● Do you suffer from body temperature-altering illness? ● Do you suffer from visual defects? If yes, do you have corrective lenses?	yes - no
Activity	A half-an-hour ago, you were: ○ Playing sport ○ Walking ○ Seating ○ Standing	
Garments	Please tick all the clothes you are wearing during this test □ Undershirt □ T-shirt □ Shirt □ Sweater □ Jumper/Hoodie □ Coat □ Tights □ Socks □ Short skirt □ Long skirt/trousers □ other …	
TPB: Awareness of consequences (AC)	Interacting with the control systems to make myself comfortable in my workplace will influence ● my comfort ● energy consumption ● my productivity	totally disagree/totally agree
TPB: Attitude toward the reduction of the energy use (AT)	● Saving energy in workplaces will help to protect the environment ● I typically perform energy-saving behaviours in my workplace ● During the winter, I performed these adaptive actions to make myself comfortable: adjusting/switching off the heating system when feeling too hot ● During the winter, I performed these adaptive actions to make myself comfortable: adding an extra layer of clothing when feeling cold	totally disagree/totally agree
TPB: Knowledge about the energy consumption (KE)	● I know how much energy the heater consumes ● I know how much energy the heating system consumes ● I know how much energy the air conditioning consumes ● I know how much energy the fan consumes	totally disagree/totally agree
TPB: Perceived behavioural control (PBC)	● I believe that I have control over the amount of energy consumed at work ● I believe that I can avoid unnecessary power consumption at work (i.e. closing the windows when the heating system is working) ● Access is a main perceived impediment to interacting with the control system in my workplace ● Other co-worker's needs are a main perceived impediment to interacting with the control system in my workplace	totally disagree/totally agree
Post-experimental questions		
Intention	Would you interact with the highlighted building systems to improve your well-being? If yes, please state your willing interactions	yes - no
Thermal comfort	● *TSV* How do you judge this environment? ● *TCV* Do you find this..? ● *TPV* Please state how would you prefer to be now.	very cold/very warm comfortable/ extremely uncomfortable much colder/ much warmer
Graphical satisfaction (GP)	I appreciate the graphics and images of the virtual model	totally disagree/totally agree
Spatial presence (SP)	● I perceived the office space as a place I visited rather than a photo I saw ● During the experience, I felt present in the office space ● I perceived the virtual model as immersive	totally disagree/totally agree
Involvement (INV)	During the experience, I was not aware of the real world around me	totally disagree/totally agree
Experienced realism (REAL)	● I perceived the objects inside the virtual office as proportionally correct (i.e., they had about the right size and distance from me and other objects) ● I had the feeling of being able to interact with the office space (e.g. grab objects) ● How realistic did you find the virtual model of the office space?	totally disagree/totally agree

CONSTRUCTION PRODUCTIVITY GRAPH: A COMPREHENSIVE METHODOLOGY BASED ON BIM AND AI TECHNIQUES TO ENHANCE PRODUCTIVITY AND SAFETY ON CONSTRUCTION SITES

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TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

DOI: 10.30682/tema090008

Abstract

The construction sector is characterised by distinctive issues, such as product uniqueness, the reluctance to introduce innovation, player fragmentation leading to a low productivity level and a related high level of risk intended due to the increased likelihood of damages and injuries, and the consequences on construction productivity. The common European Union regulatory framework provides strict regulations about on-site working activities, but there is still no standard for the environmental and social sustainability of construction sites. Productivity assumes a crucial role in reducing the environmental impact of construction and positively influences workers' safety due to higher levels of organisation, reducing time, costs, resource consumption and wasted time. This paper presents a methodology developed by augmenting BIM systems capabilities using Agent-based simulation techniques to simulate and optimise on-site work. The augmented BIM model allows analysis of site conditions in terms of space utilisation and resource allocation, resulting in the 'Construction Productivity Graph – CPG'. This graphic representation synthesises the results obtained, making it possible to visualise the work progression in different working areas with the resources employed, allowing for the management of productivity rates and the verification of work safety conditions.

Keywords

Project Construction Management, Agent-based modelling and simulation, Health & Safety Management, Location-Based Management, LBM, Business Process Modelling, BPM.

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1. INTRODUCTION

In light of recent geopolitical events, we are undoubtedly facing a sudden paradigm shift in the whole global production system. In the European Union – EU context, the challenges are related to the ecological transition, compromised but accelerated by the ongoing energy crisis, and a new awareness of the quality of life and social cohesion. Therefore, it is necessary to reflect on how these challenges affect the construction sector, which, among the manufacturing industry, has always had structural peculiarities and limitations that result in low productivity associated with high-risk factors [1]. The paper encompasses the research field of lean construction and health and safety management and presents a methodology for increasing productivity and the correlated reduction in risk exposure, ethical missions that point to the broader goal of process sustainability.

From an environmental perspective, construction management focuses on minimising construction-related energy consumption, which is very impactful in terms of the energy used [2]. Much of this consumption, however, is due to construction sites taking longer than expected, inefficiencies in the supply chain [3], and reworking activities because of variations, which can also result from design errors [4]. Since the 1990s, the manufacturing field has introduced lean methodologies to limit inefficiencies, but nowadays, these methodologies are not widespread. This limitation is due to structural inefficiencies in the industrial sector, such as the fragmentation of construction companies and design firms. These, being too small, do not have the economic leverage to impact production processes with investments necessary for innovation [5]. Despite this, an important diffusion of the BIM methodology, due to its collaborative vocation, allows even the smallest realities to upgrade towards digital innovation.

The efficiency of productivity in construction has a proportional relationship with the level of site safety. Notably, construction sites that are not very productive – and therefore poorly organised – physiologically have a higher level of accidents [6] because of the poor predictability of risky events in uncontrolled environments. The increase in the adoption of BIM gives the actors in the process the opportunity to use a shared database on which we can activate a whole series of data analyses that can impact the increase in productivity and, consequentially, the improvement of safety levels.

The proposed methodology relies on a BIM model linked to an Agent-based simulation – ABS environment. Therefore, each component of the BIM model is represented as an autonomous agent, which makes the model reactive to continuous design improvements and modifications, activating self-verification processes related to the satisfaction of the requirements arising from the demanding framework of the construction project. Once the characteristics of the project have been defined, the agent model activates the so-called 'Master Actor', who activates agents representing the work teams related to the tasks to be carried out in the assigned working area (i.e., location). The Agent system defines the duration and number of required resources based on the dynamic productivity library, which describes the task timing. The graphic result is the representation of the construction productivity graph – CPG, a synthesis of the computational processes aimed at explaining the location of tasks and the number of crews. This model shows high adaptability to changing boundary situations, with the possibility of having a quick visualisation of scenarios of the site organisation. In the current conditions, a ductile methodology can help the process' actors manage delays or site interruptions because of health quarantines, material shortages, or the rationing of energy sources.

This paper is structured as follows: Section 2 presents the background, focusing on the advancements of lean thinking in construction, the impact of the Industry 4.0 paradigm on safety in the construction sector, and the achieved level of synergy between computer sciences and construction management. Section 3 describes the methodology and describes the development of a case study. Section 4 offers a discussion of the findings, focusing on future developments. Section 5 presents the study's conclusions.

2. BACKGROUND

2.1. RECENT APPLICATIONS OF LEAN THINKING IN CONSTRUCTION

The lean construction approach focuses on methods and practices that aim to improve the result continuously through waste containment, respect for people, and work ethics. It achieves this by focusing on increasing productivity and quality, reducing costs, and generating maximum value. The extant literature shows synergies between the lean method and sustainable construction [7], also considering social sustainability as increasing the workers' quality of life in construction processes, and reducing accidents at all levels.

Further insights revealed that among the various categories of methods and techniques used to implement the principles of lean construction, the most widely used practices are just in time, total quality management, and the last planner system, besides a growing interest towards agile driven by the pandemic experience, during which even a very 'hardware' field such as construction had to improve the dematerialisation of its production processes [8]. The growing spread of BIM has led to the development of specific prototypes, such as KanBIM, created to link BIM and lean [9]. The principal goal of KanBIM is to control workflow and visualise process parameters through 3D models in which BIM entities represent the information database. A similar product is VisiLean, another BIM–lean integration IT tool resulting from a research project [10].

However, an analysis of the comparative tests produced on these tools revealed the main issue as the link between the BIM entity and the production of the optimised process diagrams according to lean logic [11]. After 30 years of introducing these techniques, it is now possible to consider the outcomes of these methodologies. Regarding the positive ones, there is undoubtedly greater control over aspects such as space management, logistics chain effectiveness, and greater centralisation of decision-making and control processes, optimising both production times and those related to planning and change management. However, from a cognitive point of view, we can notice a possible lack of attention and responsibility by workers, resulting in a visible loss of autonomy and consequent exposure to risk in the event of working conditions that are not explicitly foreseen [12].

2.2. IMPACT OF INDUSTRY 4.0 ON HEALTH AND SAFETY IN BUILDING PRODUCTION

The construction sector is among the most accident-prone in the manufacturing field [13]. Most of these accidents result from a lack of coordination and interference at the construction site, incorrect use of machinery and equipment, and a series of human errors combined with the factors mentioned above. Not only is this problem typical of developing countries, where, for reasons also linked to a different approach to prevention, there is a high number of serious accidents, but also in the European Union [14]. From the point of view of the worksite, introducing the new Industry 4.0 production paradigm has the capacity to improve the digital connection of all the elements that make up the production ecosystem. The aim, therefore, is to transform work traditionally understood as the sequential transformation of raw materials into products according to processes of a purely mechanical nature to production managed by computerised data and the potential that these data, once inserted into management and analysis systems, can provide to forecast, production, and simulation of the results [15]. From site optimisation and safety management perspectives, it is necessary to weigh the pros and cons of this type of technology.

A current application of the Internet of Things – (IoT) technique in construction sites is the use of smart devices and wearable technologies. They have proven to be highly effective in the construction context, although there are problems with the Information and Communication Technology – (ICT) infrastructure associated with the use of these technologies. However, especially when working on buildings made of shielding materials (i.e., thick walls, etc.) or in areas that are not adequately served by broadband, there is a risk of inefficient service. This inefficiency could overestimate the positive contribution given by the system and expose the workers to underestimating the risks and correct procedures due to losing signals from the Internet of Things systems when out of the range of the data connection. A pertinent goal could be defining a standard for temporary information and communication technology infrastructure installation for construction sites to ensure continuous data exchange between real and digital environments.

2.3. COMPUTATIONAL APPROACH TO CONSTRUCTION SITE MANAGEMENT

The goal of an Agent system is to predict the emerging behaviour of the model [16]. This model is composed of agents' rules and behaviours, which are understood as the actions that enable the agent to comply with the rules and goals [17]. Of course, agent modelling is not the only way to introduce predictions into the decision-making process, as there are a series of methodologies that serve the same purpose, many of which have been tested in manufacturing and considered for the construction sector [18]. These include Discrete Event Simulation (DES) and System Dynamics (SD), which follow a top-down approach in which a system is built at the macro level at the beginning. Hypotheses are then proposed, and their validity is measured. The process is deeply based on empirical analysis and is thus affected by the implicit knowledge of the technician setting the model parameters. Agent modelling follows the bottom-up approach, in which the basis is the agents and the choices made to achieve their objectives in a heterogeneous or homogeneous/consequential manner, as is the case when pursuing swarm behaviour.

Another key feature of ABS is its potential to explore an efficient solution to a multi-optional problem. [19]. The ability of ABS to differentiate each individual agent leads to the generation of almost any scenario. The difference that makes ABS so close to building production lies in agent heterogeneity. Thus, whereas other simulation techniques commonly represent a system as homogeneous as well as standardised and are the properties of the elements that populate the simulation model, the ABS allows the modelling of the rules individually and verifies the behaviour of the agents both as a reaction of the individual to external stress, with the possibility of verifying how the entire system can react and coordinate during external stresses (Fig. 1). However, ABS, following a bottom-up approach, can establish the interactive properties and characteristics of agents from the level of simple, reciprocal interactions, and thus produce an emergent result at the macro level. This characteristic makes ABS a preferable solution for activating *what-if* computational processes without relying heavily on empirical analysis, excessive assumptions, or directing the model in a preordained and biased direction [20]. Therefore, considering that ABS does not need to set rigid boundary conditions, we can test the same conditions in different environments, with clear benefits when used for H&S management [21]. This feature opens up interesting perspectives from the point of view of change management and maintenance, especially when performed during the facility's operability.

3. METHODOLOGY

The proposed methodology was developed to increase site productivity by complying with safety regulations using a sustainable approach. Both productivity and safety aspects are regulated by the efficiency of coordination and the accuracy of forecasts, so better improvement of synergies between the detailed progression of work and risk evaluations is needed. The optimisation of these aspects consents to evaluating, at a proper level of reliability, the reduction of the waste of resources from an ethical perspective of sustainability [22], due to the reduction of resources required, the diminution of time needed for the site completion, and the related decrease of emissions created by machinery and transportation of material and workers inside and outside the site. The first step to optimisation is based on a reliable model of the available areas, and related work to be performed there.

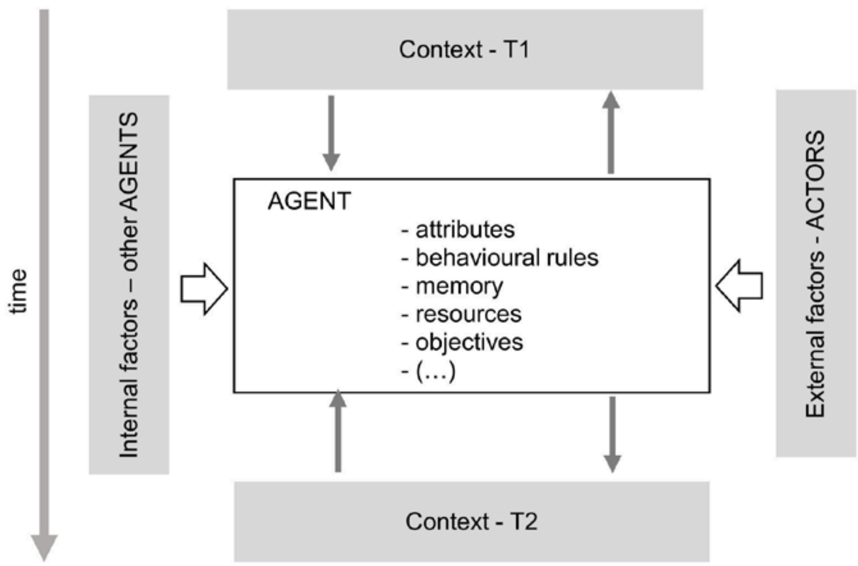


Fig. 1. *The inner structure of a simple agent.*

To address this first issue, the presented methodology uses the BIM model as a holistic box of all the components that make up a construction project.

BIM modelling for construction requires recursive checking that ensures the viability of the project itself. This implies the involvement of several design specialists who collaborate to improve design quality. To manage the level of collaboration, the fluidity of the data flow, and the speed of communications, a Business Process Management (BPM) system is presented. Thanks to the digital BPM orchestrator, this system can manage BIM data flows, activate microservices like sub-methodologies and tools activated to process a specific task, and communicate among professionals through push messages or digital file updates. Following this approach, it is possible to validate the model and obtain a viable set of building information intended as building objects. These are grouped as Work Breakdown Structure (WBS) items, corresponding to the tasks to be performed by workers in a defined location [23]. The location is the functional unit of the construction site, that is, a set of locations encompassing homogeneous work where resources can be allocated. Tasks are organised in locations by an ABS system, with the scope of maximising efficiency in using resources and considering safety regulations. Once the work to be carried out into locations has been organised, the system automatically starts checking the propaedeutic and proximity to the horizontal and vertical communication methods of the construction site to reduce wasted time and interference that may arise from the mere transit of materials through the site. Finally, the results are graphically shown overlapping a series of information, such as the occupation of the location, the crowding of nearby locations, and the productivity of the workers involved.

3.1. BIM MODEL VALIDATION PROCESS THROUGH MICROSERVICES AND DEFINITION OF RESOURCES INVOLVED

In order to guarantee the efficiency of the proposed methodology, it is necessary to gain a BIM model with an appropriate level of development (LOD) level as a reference. The proper level for these applications is LOD 400 (in the US scale, comparable to the Italian UNI 11337–LOD E), since the process flow feeds itself with the information of each element to be processed and their complex interrelationships. Therefore, the more the BIM objects are detailed, the more the data that feed the process are reliable for an ongoing and automated validation process since the early phases of construction design.

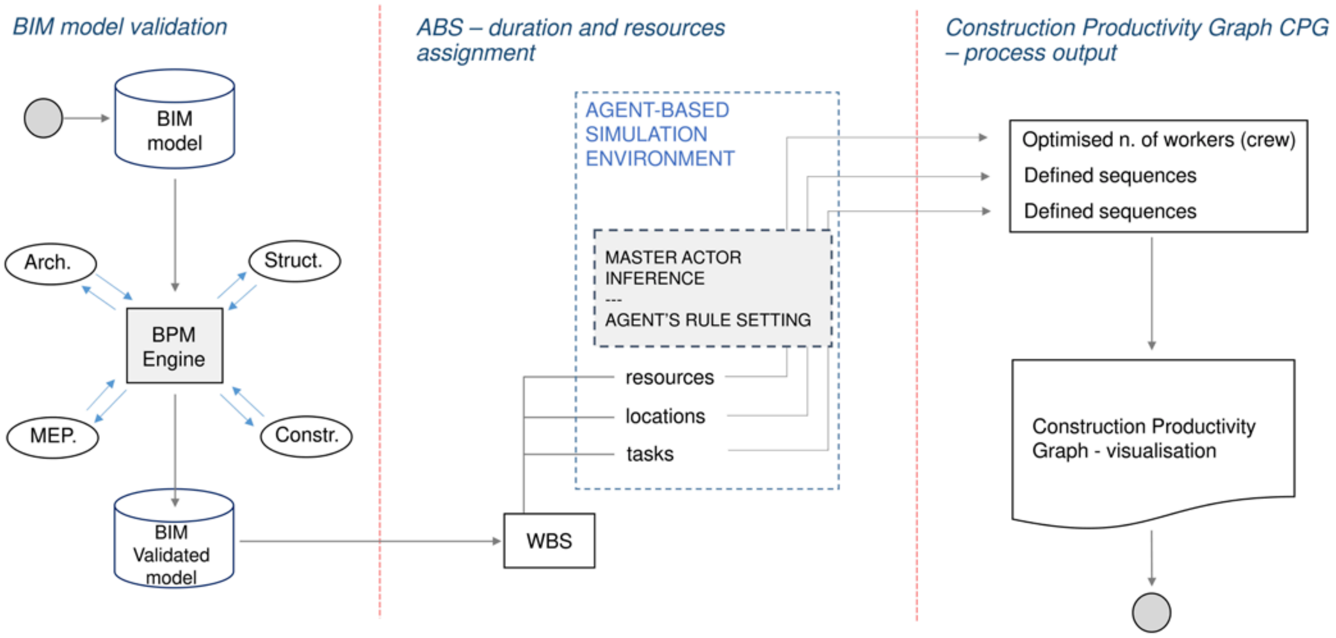


Fig. 2. *The general framework of the CPG methodology.*

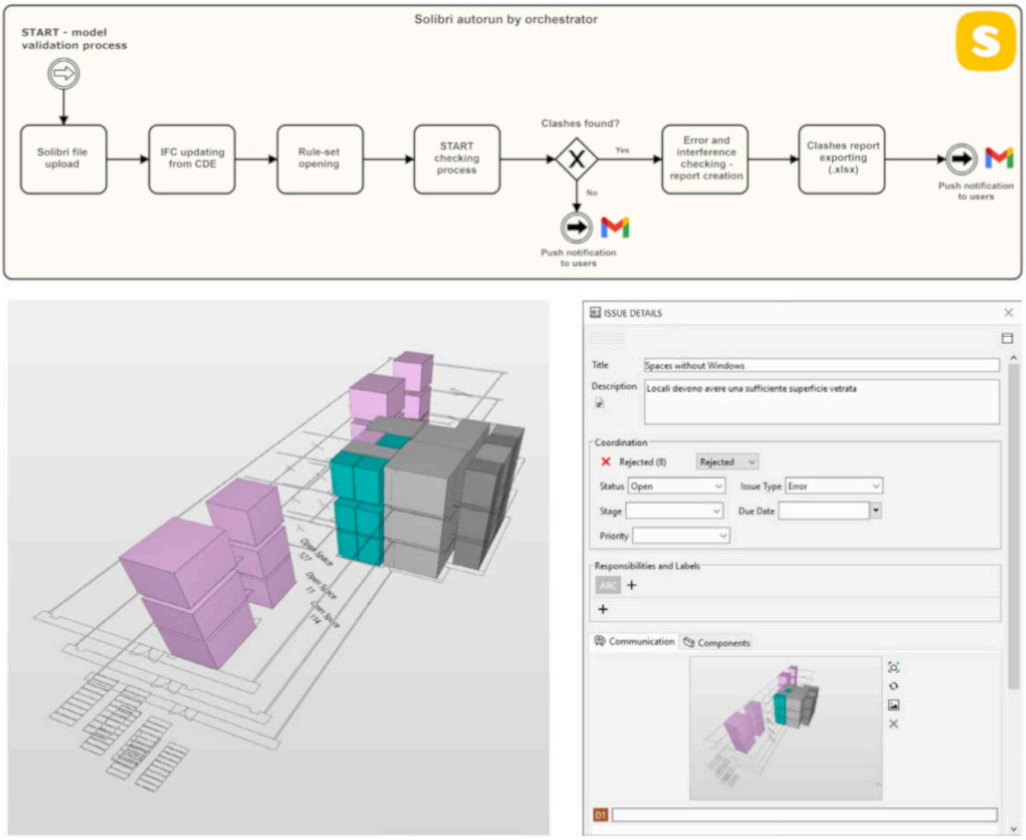
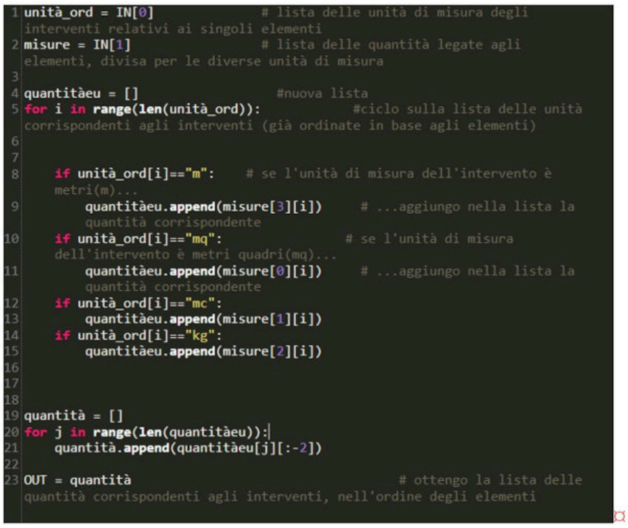


Fig. 3. *Model validation path from importing an IFC file inside a model checking tool (Solibri™). The activation of the process (micro-service) and the communication through the actor are managed by the orchestrator.*

This validation phase requires the involvement of several actors working on an evolving model. Therefore, to avoid data inconsistencies, overlapping, and low global efficiency in sharing data, it is necessary to manage this information flow inside a BPM system. It consists of a middleware system that manages the definition and orchestration of business processes [24]. To achieve our goal, we compared two approaches to BPM. The first was the use of a centralised orchestrator who gained information and sent actions to do from a unique endpoint application; the second consisted of a choreography of microservices, where data were exchanged in a circular approach but constantly supervised by the orchestrator. The workflow engine used was Camunda®, a Java-based BPM orchestrator. The results of the comparison showed that for our purposes, it was preferable to set a centralised micro-services orchestrator to clearly define the communication method among the various microservices and the actors appointed, following a 'waterfall' process framework made of consecutive validation for updating the BIM model via the direct API connection with the other microservices. For project validation, a microservice is activated (Fig. 3). The scope of the orchestrator in this phase is to manage communications and actions among the different consultants involved in the process and to monitor the completion rate of tasks.

Therefore, at this first process level, the building object to be used can be addressed, and a detailed WBS can be established. We found two main methods to develop the project WBS: the first relies on the activation of another microservices, in this case, Autodesk Navisworks®, where the designer can set a group of elements and assign them both to 4D and 5D analysis as WBS. The second method involves the use of the embedded visual programming plug-in of Revit, Dynamo®. This offers a quantity take-off organised for a group of elements representing a simple WBS activity. This method warrants direct and dynamic correspondence between the model and related quantities, raising the level of reliability and dynamicity of the analysis (Figure 04). These quantitative analyses are the basis for the development of the resource assignment phase.



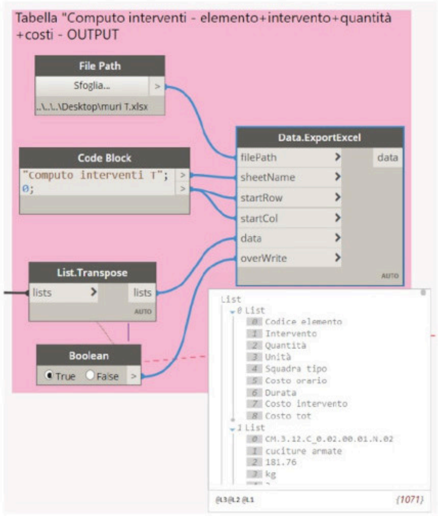


Fig. 4. *On the left is an excerpt of the script that enables the relationship between tasks and the quantities of raw material related to the building object included in the task; on the right is the Dynamo node that manages the 'task/building object/quantities/costs' *.xls output, to be transferred by the orchestrator to the subsequent process phases.*

By starting with quantities, it is necessary to account for them in relation to costs. These could be established both by public pricing indexes and by a specific cost analysis produced by the designer. These prices encompass costs related to raw materials, rental charges, company income, general expenses, and workforce costs. Thus, when the cost of the activity is known, the cost related to the workforce can be derived and divided by the imposed number of work team members, as described in the following formula:

$$T = \frac{C(A)\ x\ Wr\ (\%)}{w_t \times C\ (Dw)}$$

where:

T = time to achieve a WBS-defined activity

C = costs

A = activity, as defined in the WBS analysis

Wr = Workforce rate incidence inside the global cost of the defined activity

Wt = number of teams involved in the activity

Dw = daily wage for each worker involved in the team member, considering the different amounts related each worker's various roles and skills.

Here, it is possible to determine for each activity defined in the WBS the related time and the number of workers included in a single team, or the need to employ more than one team to accomplish the analysed activity. This development can also be useful for managing of the construction site supply chain, another important problem in terms of resource optimisation and, globally, the whole sustainability of the Construction Site.

3.2. AGENT MODEL TO ASSIGN DURATION AND NUMBER OF WORKERS TO LOCATIONS

Once the checking regarding the consistency of the model with the standards of the construction design and execution and the congruence of the WBS with the categories of work to be performed are completed, the conditions for activating of the optimised agent system for construction are addressed. This system is governed by a Master Actor (MA), who manages workflows according to the quantities and grouping rules set out in the WBS. Thus, we model the WBS themselves as agencies, that is, systems that contain other agents representing components and simple elements within them. Rules set up by the user characterise these WBS, concerning the reference location and the correct sequence for the other working phases. Precisely, the MA can send messages to agents to activate them, create temporary agents to cope with specific issues, and generally manages the cue of the agent's action or their idling status. Each process of the presented methodology starts with an MA action and is concluded by a final MA message that determines the conclusion of the process when it reaches a satisfacto-

```
/// <summary>
/// This method creates an actor for each instance of the input category inside the BIM model.
/// </summary>
/// <param name="bimCategory">The Revit category of the new actors to set up.</param>
public static void NewActorsSetup(BuiltInCategory bimCategory)
{
    switch (bimCategory)
    {
        case BuiltInCategory.OST_Doors:
            {
                // get all door instances in the model
                FilteredElementCollector bimWorld =
                    new FilteredElementCollector(Doc).OfCategory(bimCategory)
                        .OfClass(typeof(FamilyInstance));

                // extract properties and populate an ActorSetup message
                foreach (var bimElement in bimWorld)
                {
                    ActorSetup actorSetup = new ActorSetup()
                    {
                        BimElementCategory = BuiltInCategory.OST_Doors,
                        BimElementName = bimElement.Name,
                        BimElementId = bimElement.Id,
                        BimElementUniqueId = bimElement.UniqueId,
                        LocationPoint = bimElement.Location as LocationPoint,
                        ParameterSet = bimElement.GetOrderedParameters(),
                    };

                    // tell the master actor to create a child with each set of properties
                    MyMasterActor.Tell(actorSetup);
                }
                break;
            }
        case BuiltInCategory.OST_Rooms:
            {
                // get all room instances in the model

                FilteredElementCollector bimWorld =
                    new FilteredElementCollector(Doc)
                    .WhereElementIsNotElementType()
                    .OfCategory(BuiltInCategory.OST_Rooms);

                // extract properties and populate an ActorSetup message
                foreach (var bimElement in bimWorld)
                {
                    ActorSetup actorSetup = new ActorSetup()
                    {
                        BimElementCategory = BuiltInCategory.OST_Rooms,
                        BimElementName = bimElement.Name,
                        BimElementId = bimElement.Id,
                        BimElementUniqueId = bimElement.UniqueId,
                        LocationPoint = bimElement.Location as LocationPoint,
                    };
```

Pseudo-code summary of the crowd rule

```
When MA activates location ()
    Agent () append tasks in
    location ();
For each task () init workers list
    If location () is >> 1 room,
    then invoke agent (room 1, room
    2, room n ….);
    elif == 1 room then invoke
    dimension ();
    If dimension () is >= 100 mq,
    then invoke workers crew [0,1,2
    … n];
    elif << 100 mq then invoke
    workers crew [0,1,2];
For each task, if the workers crew
    >> 1, set max 20 sqm for each
    crew;
    elif workers crew ==1 set max 4
    workers/crew;
```

Pseudo-code summary of protection from falling object hazards

```
When MA activates location ()
    Agent () append tasks in
    location ();
    For each task () == [4,5,6,8]
    Then stop works in location ()
```

Fig. 5. *Parts of the ABS system: The left panel shows the creation of actors for each instance of the input category inside Revit and agents that represent rooms. On the right are two examples of rules imposed by the user.*

ry condition. Generally, the scope of the system in this process phase is to determine objects inside the model, localise and quantify them, and distribute the working teams to accomplish the works in a determined time, as explained in Section 3.1. As this phase is completed, the system starts by checking the agent's behaviour with the imposed rules, such as the crowding of locations, the risk related to the presence of workers and task-related hazards, and other rules set up by the user. The inner library of values and parameters used by the ABM system is managed by the experience of the human designer to add the implicit knowledge and experience of designers into the model and to keep contact on the effective resources available, which could be updated by a *.xls user interface linked to the agent system. This *.xls allows actors to constantly update the availability of workers, equipment, and raw materials.

The output of this iteration is the average time and number of resources that could be used to accomplish a task under the determined conditions. The results are represented in tables (Fig. 6) that link tasks, locations, and duration without graphical references. These will be automatically produced with a further automatised process, as described in Section 3.3.

Starting Date		1	2		2	3		3	4		4	5
09/11/2021 8.00	Location 1 (2h)	Location 1 Start	Location 1 Finish	Location 2 (2h)	Location 2 Start	Location 2 Finish	Location 3 (2h)	Location 3 Start	Location 3 Finish	Location 4 (2h)	Location 4 Start	Location 4 Finish
Task 1	32	9/11/21 8.00	11/11/21 13.20	32	11/11/21 13.20	16/11/21 10.40	32	16/11/21 10.40	19/11/21 8.00	32	19/11/21 8.00	23/11/21 13.20
Task 2	38	24/11/21 8.00	25/11/21 12.40	38	25/11/21 12.40	29/11/21 9.20	38	29/11/21 9.20	30/11/21 14.00	38	30/11/21 14.00	2/12/21 10.40
Task 3	105	26/11/21 8.00	30/11/21 13.00	105	30/11/21 13.00	3/12/21 10.00	105	3/12/21 10.00	7/12/21 15.00	105	7/12/21 15.00	10/12/21 12.00
Task 4	25	7/12/21 8.00	9/12/21 8.40	25	9/12/21 8.40	13/12/21 9.20	25	13/12/21 9.20	15/12/21 10.00	25	15/12/21 10.00	17/12/21 10.40
Task 5	50	10/12/21 8.00	15/12/21 9.00	50	15/12/21 9.00	20/12/21 10.00	50	20/12/21 10.00	23/12/21 11.00	50	23/12/21 11.00	28/12/21 12.00
Task 6	72	27/12/21 8.00	29/12/21 8.00	72	29/12/21 8.00	31/12/21 8.00	72	31/12/21 8.00	4/1/22 8.00	72	4/1/22 8.00	6/1/22 8.00

	5	6		6	7		7	8		8	9
Location 5 (2h)	Location 5 Start	Location 5 Finish	Location 6 (2h)	Location 6 Start	Location 6 Finish	Location 7 (2h)	Location 7 Start	Location 7 Finish	Location 8 (2h)	Location 8 Start	Location 8 Finish
32	23/11/21 13.20	26/11/21 10.40	32	26/11/21 10.40	1/12/21 8.00	32	1/12/21 8.00	3/12/21 13.20	32	3/12/21 13.20	8/12/21 10.40
38	2/12/21 10.40	3/12/21 15.20	38	3/12/21 15.20	7/12/21 12.00	38	7/12/21 12.00	9/12/21 8.40	38	9/12/21 8.40	10/12/21 13.20
105	10/12/21 12.00	15/12/21 9.00	105	15/12/21 9.00	17/12/21 14.00	105	17/12/21 14.00	22/12/21 11.00	105	22/12/21 11.00	27/12/21 8.00
25	17/12/21 10.40	21/12/21 11.20	25	21/12/21 11.20	23/12/21 12.00	25	23/12/21 12.00	27/12/21 12.40	25	27/12/21 12.40	29/12/21 13.20
50	28/12/21 12.00	31/12/21 13.00	50	31/12/21 13.00	5/1/22 14.00	50	5/1/22 14.00	10/1/22 15.00	50	10/1/22 15.00	13/1/22 16.00
72	6/1/22 8.00	10/1/22 8.00	72	10/1/22 8.00	12/1/22 8.00	72	12/1/22 8.00	14/1/22 8.00	72	14/1/22 8.00	18/1/22 8.00

Fig. 6. *The output of the agent-based simulation showing tasks, locations, and time needed.*

These duration analyses are critical for the management of time and resource optimisation, given that a large part of the optimisation conditions derives from the possibility of using a date number of locations in parallel, managing interference and the possibility of using shared logistical conditions to reduce the areas of transit and handling of loads on the site, conditions characterised by a high risk of accidents. This activity also helps in the evaluation of the wasted time of transport within the site; thus, the goal is to maximise the work planned in areas close to the loading verticals and horizontal handling paths on the floors.

3.3. LOCATION AND CREW VISUALISATION

Once the number of workers is obtained from the ABS in relation to the work to be carried out for each location, a new microservice is activated for the graphic visualisation and checking of interference in relation to the activities expected for each location and the number of workers used. Simple spreadsheets in accessible and widespread formats, such as *.xlsx, were used to define these graphs. In the first part of graph development, the location-based structure (Fig. 7) is set up so that the duration of work, the maintenance of the optimal workflow average [25], and any overlaps can be fully visualised.

The first graphical result (Fig. 8) combines the graphical ease of the Gantt diagram with the staff presence line graph. This representation, which is unique for each location, makes it possible to verify both the sequence of activities (Gantt) and the simultaneous presence of people (line graph), to monitor the crowding of areas, any issue related to the activities and the number of workers present, and to constantly verify the adequacy of worksite facilities (e.g., toilets, canteens, etc.) in relation to workers' expected number. This kind of representation is the output of CPG. Once the congruence of data of the individual locations has been verified, the results related to the entire worksite are inputted into the system for a complete overview of the optimised consecutiveness of the works.

We represent these according to the Gantt technique, whereas the line graph shows the co-presence of workers. This analysis verifies the worksite and areas' occupancy rate, and the most critical one is analysed. From a conceptual point of view, this graphical methodology is a decomposition of the well-known location-based management technique, which, displayed in another view, allows a constant overview of productivity and the occu-

```
LBM_DB - 1

Sub LBM_DB()

    Dim L, T As String
    Dim i, j, NLocations, NTasks, NTeams As Integer

    Worksheets("Locations Table").Activate
    Range("A2").Select
    NLocations = Range(Selection, Selection.End(xlDown)).Row
    Worksheets("Tasks List").Activate
    Range("A2").Select
    NTasks = Range(Selection, Selection.End(xlDown)).Rows.Cc
    Range("B1").Select
    Worksheets("Teams List").Activate
    Range("A2").Select
    NTeams = Range(Selection, Selection.End(xlDown)).Rows.Cc
    Range("B1").Select
    Worksheets("LBM Database").Activate
    Cells.ClearContents
    With Cells.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With
    For j = 0 To NLocations - 1
        Cells(2, 3 * j + 2) = Worksheets("Locations Table").
        Cells(1, 3 * j + 3) = Worksheets("Locations Table").
        Cells(2, 3 * j + 3) = Worksheets("Locations Table").
        Cells(1, 3 * j + 4) = Worksheets("Locations Table").
        Cells(2, 3 * j + 4) = Worksheets("Locations Table").
    Next
    Rows("2:2").Select
    Selection.RowHeight = 30
    With Selection
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = True
        .Orientation = 0
        .AddIndent = False
        .IndentLevel = 0
        .ShrinkToFit = False
        .ReadingOrder = xlContext
        .MergeCells = False
    End With
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .ThemeColor = xlThemeColorAccent4
        .TintAndShade = 0.6
        .PatternTintAndShade = 0
    End With
    With Rows(1)
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
    End With
    Range(Columns(2), Columns(NLocations)).ColumnWidth =
    Sheets("Tasks List").Select
    Range("B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Range("B1").Select
    Sheets("LBM Database").Activate
    Range("A3").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    With Selection.Interior
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .ThemeColor = xlThemeColorAccent5
        .TintAndShade = 0.6
        .PatternTintAndShade = 0
    End With
    Columns("A:A").EntireColumn.AutoFit
    Cells(2, 1).Select
    ActiveCell.Offset(-1, 0).Value = "Starting Date"
    ActiveCell.Value = Date + 8 / 24
    ActiveCell.NumberFormat = "dd/mm/yyyy h.mm;@"
    With Range("A1:A2")
        .Borders(xlDiagonalDown).LineStyle = xlNone
        .Borders(xlDiagonalUp).LineStyle = xnlNone
        .Borders(xlInsideVertical).LineStyle = xlNone
        .Borders(xlInsideHorizontal).LineStyle = xlNone
        With .Borders(xlEdgeLeft)
            .LineStyle = xlContinuous
            .ColorIndex = xlAutomatic
            .TintAndShade = 0
            .Weight = xlMedium
        End With
        With .Borders(xlEdgeTop)
            .LineStyle = xlContinuous
            .ColorIndex = xlAutomatic
            .TintAndShade = 0
            .Weight = xlMedium
        End With
        With .Borders(xlEdgeRight)
            .LineStyle = xlContinuous
            .ColorIndex = xlAutomatic
            .TintAndShade = 0
            .Weight = xlMedium
        End With
        With .Interior
            .Pattern = xlSolid
            .PatternColorIndex = xlAutomatic
            .ThemeColor = xlThemeColorAccent3
            .TintAndShade = 0.6
LBM_DB - 2

            .PatternTintAndShade = 0
        End With
    End With
    With Range(Cells(NTasks + 5, 1), Cells(NTasks + 5, 2)).Int
        .Pattern = xlSolid
        .PatternColorIndex = xlAutomatic
        .ThemeColor = xlThemeColorAccent6
        .TintAndShade = 0.6
        .PatternTintAndShade = 0
    End With
    Cells(NTasks + 5, 1) = "Teams Name"
    Cells(NTasks + 5, 2) = "Members"
    Sheets("Teams List").Select
    Range("A2:B2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Range("B2").Select
    Sheets("LBM Database").Activate
    Cells(NTasks + 6, 1).Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Cells(NTasks + 6, 3).Formula = "=+A2"
    Cells(NTasks + 6, 4).Select
    For j = 0 To NLocations - 1
        L = Worksheets("Locations Table").Cells(j + 2, 2).Valu
            For i = 1 To NTasks
                T = Worksheets("Tasks List").Cells(i + 1, 2).\
                Cells(i + 2, j * 3 + 2) = Worksheets("Tasks Pi
            Next
        Next
End Sub
```

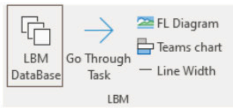


Fig. 7. *Source code for plotting the productivity graphs.*

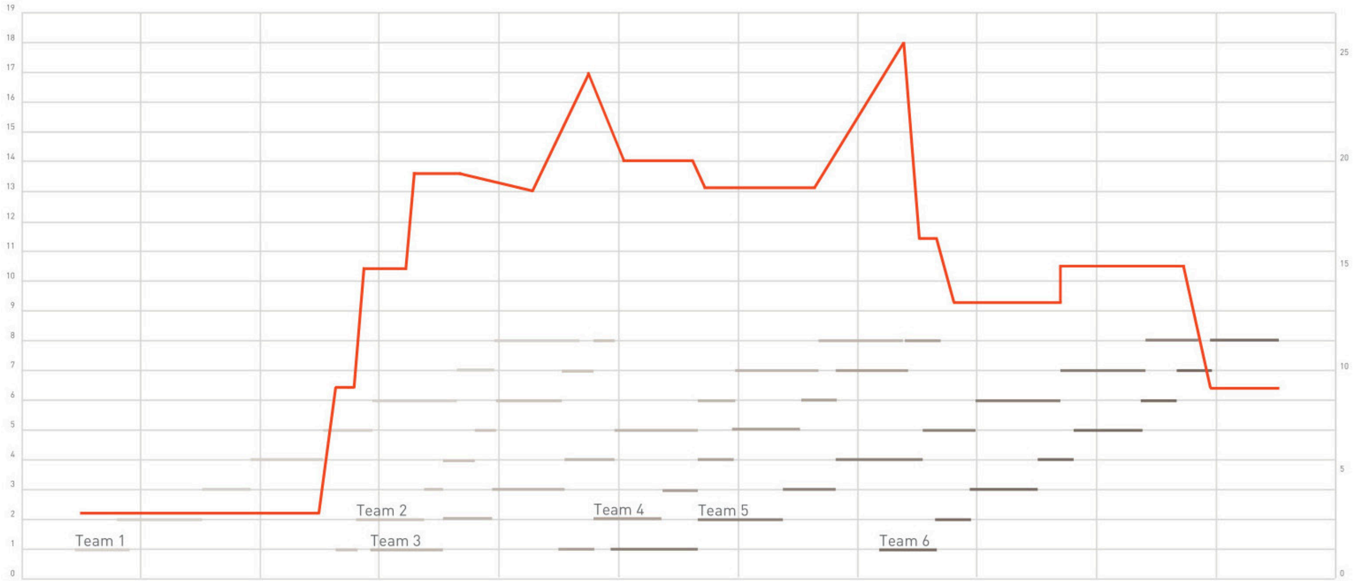


Fig. 8. *A construction productivity graph: The red line shows the number of workers; the greyscale lines show the tasks; The teams involved are also shown. Analysis conducted for a single location.*

Fig. 9. *An extended view of CPG line of balance, derived from the ABM process.*

pancy of working areas (Fig. 9). These in-depth process services are linked to the BIM model, which, thanks to the continuous exchange of data made possible through the API, updates the technical elements displayed at each stage, thus having a bi-univocal link between the graphic representation of the production processes and the construction site BIM model.

4. CONCLUSION AND DISCUSSION

The proposed methodology faces the strictly related efficiency and sustainability construction sites' request. The papers present a methodology that grounds on BIM, BPM and ABS that allows to define a system able to define processes finalised to improve efficiency and sustainability. The methodology produces a BPM process that starts from a BIM model that contains information for CPG definition. The BIM model data are validated through the involvement of checking tools and involved specialists, automatically activated by a BPM network. An ABS system uses validated information to define the resources to employ to accomplish working tasks. The final balanced results are represented in overlaid graphs that describe the location crowding, the productivity of workers' crew and, globally, the construction management metrics. This information flow, guaranteed by the

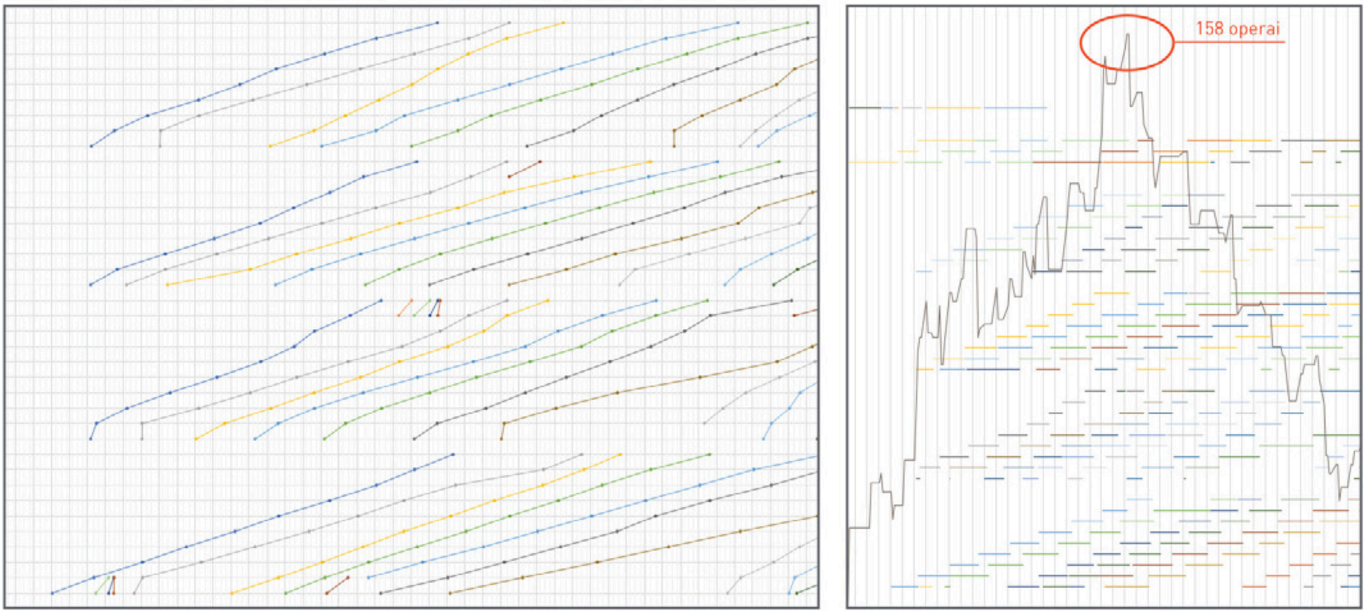


Fig. 10. *An overview of the line of balance of the site and the issue highlighted in the productivity graph.*

service orchestrator and managed via APIs, opens interesting perspectives of the further method's evolutions. Thus, other microservices could be added to the workflow to make the results increasingly accurate while accept a reduction in the modelling and simulation speed of execution. From the point of view of Industry 4.0, wearable technologies connected to the simulation environment could be implemented. This could have two results. The first comprises immediate communication between the system and the worker, who could be constantly warned about the activities to be carried out in the predetermined workplace; the latter instead concerns a continuous collection of data, to create an extensive database for subsequent machine learning applications.

The results' efficiency and accuracy depends both from on the LOD level and the BIM model, and also from the completeness of rules' definition inside the ABS environment. Considering that LOD is referred to an object and not for the whole model, this methodology could face inaccuracies if the model were populated by building objects with a lower LOD level than necessary because of the possible lack of information required to excerpt reliable quantities and tasks' details. However, the methodology reserves particular attention to offering users an easy and ready-to-use interface, providing results in a usable standard *.xlsx dashboard for inputting data and read outcomes. From the point of view of safety this methodology allows for better coordination of the presence of workers and the crowding of areas. For example, in the case study, due to the methodology implemented, we observed an underestimation of the productivity reduction factor due to peak occupancy and overcrowding in some areas that are also at high risk, such as the roofing structures (Fig. 10).

Considering the analysis of the background, the CPG could be fully integrated into lean methodologies for the capability to save time and resources through organisational improvements, such as the better definition of resources required, which reflects a more efficient supply chain to reduce wasted time, occupancy of site soil to host waiting material, and the logistic impact within the site and on the neighbourhood. Furthermore, these aspects reflect a lower pollution production because of the shorter duration of site operation and a smaller impact on urban mobility, where sites are located inside urban centres. Finally, in view of these findings, the following issues present opportunities for future work:

- Scalability of the system: Considering the large amount of detail required for BIM and agent modelling, there are major limitations regarding the machine's ability to process such large data volumes relatively quickly. It could be interesting to evaluate the development of digital meta-models, which will show representative values of the project, in order to carry out rapid assessment, creating a new design level named 'constructive feasibility'.

- Forecast accuracy: For an adequately accurate forecast model, it is necessary to feed the database of similar events with a good amount of data, as is for the 'big data' approach. This consideration may face many practical obstacles, since the construction plans of construction sites, execution methods, and metrics of realised projects could be classified proportionally to the intended use of the building itself and sometimes problematic to share (e.g., justice facilities and airports). Similarly, it is difficult to create a shared common data environment from the point of view of the production process of construction companies, which have part of their capitalisation and value in the construction and maintenance of best practices and standardised procedures. Therefore, it would be interesting to consider a free digital platform of references in this sense, produced by public institutions that, depending on the type of intervention carried out and the sensitivity of the building, could make available on an open platform with all the information necessary to train data libraries dedicated to the construction elements of the building, and the related agents and rules.
- Auto-generative knowledge: An interesting research effort would be to gather the experiences gained on the building site itself as a basis for improving the decision-making process for the following construction phases. This could allow for solving the need to manage a knowledge strongly related to a single case, as experienced in building construction.

Acknowledgments

Case studies and implementations of the proposed methodology were developed during the 'Construction Site Management' thesis workshop, academic year 2020/21. Students: Edoardo De Santis, Caterina Spoletini, Nehir Surel.

Authors contribution

The authors both participated equally in writing the article.

Funding

This work was supported by the Ministry of Education, University and Research – PRIN 2017 prot. 2017EY3ESB.

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TEMA
Technologies
Engineering
Materials
Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

A GENETIC ALGORITHM-BASED APPROACH FOR THE TIME, COST, AND QUALITY TRADE-OFF PROBLEM FOR CONSTRUCTION PROJECTS

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DOI: 10.30682/tema090012

Abstract

Quality identifies the overall level of performance of the desired building facility or civil infrastructure. Quality can include safety and sustainability requirements, and planning the desired quality level is paramount in construction projects. Nevertheless, two other significant project management Key Performance Indicators (KPIs) must be considered in construction project management: time and cost. Project Managers always perform a trade-off between these three KPIs, but it is known that the relationship between these three indicators can be difficult to understand. Therefore, a multi-objective Genetic Algorithm (GA) has been proposed to develop a comprehensive approach to optimize project performance in construction. The proposed multi-objective GA can be used as a decision support system for the detailed design stage of a construction project to detect better and alternative detailed design and construction solutions. A GA is an Artificial Intelligence application (AI) that develops an evolutionary learning optimization process that discards worse solutions and re-introduces better solutions with an iterative process. Therefore, the most suitable solution can be found by performing a trade-off between the three indicators. The research aims to demonstrate the availability of AI applications to understand and perform the Time-Cost-Quality trade-off for construction projects. The developed procedure has been tested on a simple pilot study of a building renovation project, and the best-found optimized results have been detected with Solver® and discussed. Future research work will be aimed at improving the procedure's efficiency so that it can be implemented in larger projects.

Keywords

Construction, Project management, Genetic Algorithm, Detailed design, Time-Cost-Quality Trade-off.

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1. INTRODUCTION

Quality identifies the overall level of performance of the desired building facility or civil infrastructure, therefore, quality includes all design and technical requirements to be fulfilled by a construction project. Nevertheless, traditional project control techniques focus on time and cost constraints, meaning that the project baseline is built upon the project time schedule, which indicates the total project duration and the timing of work packages, along with the schedule of rates and the bill of quantities that compute the cost of work packages and the total cost of the project. The Earned Value Method generally addresses the integrated project control of time and cost. Nevertheless, time, quality, and cost create the well-known *Iron Triangle* of Project management [1], meaning that a Project Manager must balance these three constraints to reach the project's objective. Therefore, construction project managers are used to selecting a combination of construction technologies and resource usage that minimizes cost and time while maximizing quality. This project management process is termed the Time-Cost-Quality Trade-off problem (TCQT) [2]. In construction projects, quality is complex and meaningful. Quality can be defined as the level of accomplishment of a product or a process to a set of performance requirements [3]. ISO standards define quality as the degree to which a set of inherent characteristics fulfil requirements. Quality assessment in construction can be divided into three main components: quality of products, quality of design, and quality of processes. The quality of products can be understood primarily as a technical quality, whereas the quality of design is about meeting the needs of clients and end users successfully. The quality of processes refers to all activities throughout the construction project's life cycle.

Artificial Intelligence is playing a core role in the Fourth Industrial Revolution, providing significant productivity improvements via analyzing large datasets quickly and accurately, and the optimization of construction management problems via Genetic Algorithms (GA) has been largely addressed by literature. GA methods have been used by many researchers in literature as an optimization technology to address Architecture, Engineering, and Construction (AEC) optimization goals, as for instance construction scheduling and cost optimization. Most of the Artificial Intelligence techniques used in the AEC sector are GAs [4].

Construction Engineering and Management benefits from GAs because of intelligent optimization, meaning searching for the optimal solution to minimize or maximize an objective function subject to a set of constraints. This problem can be divided into two versions. The simple version is the single objective optimization to identify a single optimal alternative. At the same time, the complex one is multi-objective optimization, which simultaneously optimizes more than one objective function with a set of feasible solutions [5].

A GA can be used for project-controlling purposes, assisting decision-makers in identifying optimal or near-optimal solutions concerning project implementation and management processes addressing a project's planning, scheduling, and controlling functions. A GA is an AI application that can be used to optimize construction management problems. GA, indeed, creates a learning-based optimization process because better solutions are re-introduced in the iterative optimization process while worse solutions are discarded. Therefore, an optimized solution can be found in a reasonable amount of time, i.e., the algorithm converges to better solutions, even if sub-optimal [4].

Since in construction projects, the relationship between quality, cost, and time is usually unknown, and a dependence function between these factors can be challenging to detect, an AI application has been proposed to demonstrate that AI applications can help project managers perform project management processes concerning trade-off between time, cost and quality objectives.

The paper is structured as follows. The research background section presents an analysis of the state-of-the-art concerning TCQT and the related use of GA. The proposed method section presents a GA-based procedure to solve the TCQT problem, and an application to a pilot study follows. Then, the discussion and conclusion sections close the paper.

2. RESEARCH BACKGROUND

Few researchers focused on the problem of evaluating the global quality of a project or system using a quality indicator, and developing a time-cost-quality trade-off procedure is seldom the objective of research papers. The use of AI for construction management has been, instead, the aim of many research works. This section offers background on two different topics relevant to the current paper: the time-cost-quality trade-off and the related GA application. Construction project managers must deal with clients' objectives, and clients' general requirements concerning time, cost, and quality can be evaluated and weighted with a value management approach. Rwelamila and Hall [6] argued that despite time, cost, and quality being the most important issues for the clients of the construction industry, the vast majority of projects are procured by competitive bidding with the lowest cost or lowest cost plus project duration criteria. This traditional approach can lead to extensive delays, cost overruns, and serious problems in quality. Critical system thinking and the total systems intervention approach are proposed to balance these project management factors via a "problem-solving" approach. Quality is defined as the value for money from the client's point of view.

Babu and Suresh [7] suggested that project quality may be affected by project crashing for minimal cost search. Time-cost trade-offs can affect quality; therefore, a TCQT is needed. Linear assumptions are used to develop a simple methodology that links each project schedule activity's time, cost, and quality attributes. Time is considered the independent variable, and quality can be computed with cost constraints. Khang and Myint [8] tested the Babu and Suresh approach with a case study of the construction of a cement factory in Thailand, highlighting key problems and difficulties faced. A significant limitation of the method is that only a very small portion of the overall quality of a work package has a direct relationship with time and cost performances. Only labor-dependent quality is affected by time and cost constraints in the execution process.

Atkinson [1] introduced the project manager's iron triangle concept, meaning the need to integrate time, cost, and scope, or quality project objectives. These are also the most critical criteria available to measure project performance. It is suggested that a more realistic and balanced indication of project success should consider the project output, namely the technical strength of the resultant system and the benefits to the resultant organizations and the stakeholders. The "Quality–Based Performance Rating System" for contractors' qualification of the American National Cooperative Highway Research Program (NCHRP) [9] introduces the concept of Quality Breakdown Structure (QBS) of the project. Quality can be measured through a global quality Key Performance Indicator (KPI), termed Quality Index, based on the project's QBS. QBS aims to evaluate the final quality of the products for the construction process with a performance-based approach. Therefore, quality indicators are detected to assess the final product quality.

Many researchers tackled the resource-constrained project scheduling problem with AI applications, mostly with GAs. Ono, Yamamura, and Kobashi [10] proposed a procedure for Job-Shop-Scheduling Problems with GAs. The proposed approach used a job sequence matrix and introduced crossover and mutation operators. The proposed procedure seems very effective, though the method is not construction-oriented. A neural dynamic model for schedule and cost optimization was proposed by Adeli and Karim [11] for construction projects composed of repetitive and non-repetitive tasks. As network-based schedules have proven to present several shortcomings, linear planning charts are proposed for construction project scheduling. In addition, a robust neural dynamics model was developed to optimize the cost-duration relationship of the project.

Marki, Fischer, Kunz, and Haymaker [12] focused on the optimization of 4D building process planning using GA and developed an interactive 4D-modeling toolbox for the 4D modelling of buildings. The model consists of the following four tools: a 4D model builder that supports the identification of building components and the definition of structural dependencies between them; a discrete event simulator for the automated sequencing of activities into a network plan; a genetic algorithm process optimization (GAPO) that enhances project schedules in terms of time, cost and resource management; a 4D player for the visualization of the building processes. Later, Dong et al. [13] proposed a new GA-based method that automates look-ahead schedule generation in the finishing phase of complex construction projects to minimize project duration or cost. Intending to improve construction quality, El Rayes and Kandil [14–15] presented a multi-objective optimization model that supports decision-makers in creating an optimal resource optimization plan that minimizes construction cost and time while maximizing its quality. The *MACROS* automated optimization system for construction resources was implemented [14–15], and GA developed the TCQT algorithm. Following this research line, El Razek et al. [16] addressed the TCQT problem by implementing a Java programming code, AMTCROS, based upon a GA. Long and Ohsato [17] developed a project scheduling method for repetitive construction projects with several objectives, such as project duration minimization, project cost minimization, or both. A GA is used to find a set of suitable durations, and the method also considers resource work continuity and different relationships between direct costs and durations of activities. San Cristobal [18] proposed an Integer Programming model to meet quality output standards and time and cost objectives. Even in this case, the research aims to develop a method to search for an optimal/near-optimal resource utilization plan that minimizes construction cost and time while maximizing quality. The need to develop a trade-off algorithm arises because governmental agencies want to increase long-term returns on public-investments by using new types of contracting methods.

Zhang and Xing [2] addressed AI applications and presented a fuzzy-multi-objective particle swarm optimization to solve the TCQT problem. Solving a TCQT problem involves determining an optimal combination of construction methods for all activities in a project to achieve an optimal balance of time, cost, and quality. Zhang and Xing argue that the project performances, such as time, cost, and quality of construction activity, are measured with no precise numbers, i.e., they are uncertain, especially the quality. Therefore, uncertainty, vagueness, imprecision, and subjectivity are present in the performance measures of each project activity. A fuzzy multiple attribute utility method where fuzzy numbers describe time, cost, and quality is proposed to solve the TCQT problem about uncertainty.

Magalhaes-Mendes [19], instead, proposed a two-level GA for the multi-mode resource-constrained project scheduling problem for construction that minimizes project completion time and evaluates the quality of the schedule. The quality of the schedule is assessed by comparison with the best-known solution. Kim [20] proposed a GA-based decision support model that provides decision-makers with a quantitative basis for multi-criteria decisions related to the construction schedule. A multi-objective construction schedule optimization using a modified niched Pareto GA is presented [21] to minimize construction duration, construction cost, and variations in resource utilization during construction. Dong et al. [13] proposed a new GA-based method that automates construction schedule generation, intending to minimize time or cost, considering engineering and space constraints. Later, Faghihi et al. [22] developed a computer application that can automatically derive a statically stable construction schedule by data extraction from a BIM model using the concept of GAs.

In Information Technologies, Mishra and Mahanty [23] indicated that optimizing project cost, schedule, and quality for a software development project in an outsourcing environment can be studied with a system dynamics simulation approach. Kyriklidis and Dounias [24] addressed the resource levelling optimization problem with an evolutionary algorithm (GA) in the project management field, while in the specific construction sector, Monghasemi et al. [25] proposed a Multi-criterion decision-making approach that identifies all global Pareto optimal solutions by a multi-objective GA. Sorrentino [26] applied GAs to a time, cost, and quality optimization problem for project scheduling of road construction. Tiene et al. [27] investigated a similar application to select design alternatives for a building envelope. Liu et al. [28] presented a GA–based optimization for the Resource-Constrained Project Scheduling problem that enhances the evolution strategy by proposing modified operators for selection, crossover, and mutation. Hyun et al. [29] developed a multi-objective optimization tool for modular unit production lines based on GAs that assumes that the duration of activities on a production line in modular construction depends on the number of workers, and reducing construction duration and labour cost will be the optimization objectives. Soman and Molina-Solana [30] presented a novel Look-Ahead Schedule generation method that uses reinforcement learning algorithms and linked data-based constraint checking to help construction planners as a decision support system. The output schedule is compared with the manually generated one, with the critical path method, and with the modified GA by Liu et al. [28]. Therefore, a multi-objective GA can perform TCQTs that evaluate the effectiveness of various combinations, computing better solutions with an iterative process. At the end of the process, the most suitable balance between the three project targets can be selected between the outputs by project managers.

Though all the previous approaches seem complete and effective, the quality dimension of project outcomes is still missing in pertinent literature concerning the construction sector. The TCQT problem is difficult to solve in the construction sector because of the variability of the relationship between quality, time, and costs. In general, less expensive resources or technologies would lead to a longer duration to complete an activity, but with some exceptions. On the other hand, even time reduction can produce low-quality products and project outputs. In addition, increasing project costs because of more efficient workers or equipment, because of the increase in the number of workers or machinery, or because of overtime work shifts may lead to time reductions but with a non-balanced time-cost-quality output. With this background knowledge and context, the paper aims to contribute to understanding the TCQT problem in construction and to propose the application of GAs for its solution.

3. PROPOSED METHOD: A GA-BASED APPROACH

The construction industry is going through constant innovations via digitalization and Artificial Intelligence [5]. Artificial Intelligence is a branch of computer science that drives computers to understand and learn inputs like humans and implement processes that include perception, knowledge representation, and problem-solving. There are many applications of AI in specific sub-areas of the construction industry, such as structural engineering and construction management. These applications can be categorized into four major groups: expert systems, fuzzy logic, machine learning, and optimization algorithms. Optimization algorithms aim to search locally or globally for optimal results from a set of available alternatives. The use of GAs was introduced by J.H. Holland [31] as a research method based on the mechanics of natural selection and natural genetics of Darwin's Evolutionary Theory. Later, Goldberg [32] developed further the GA approach in the field of automation engineering. GAs have been implemented in many engineering, operations research, and optimization problems, such as the Travelling Salesman Problem [33] and Construction Project Scheduling [5]. A GA is a global and stochastic operational research method termed "genetic" because of the implementation of an evolutionary and iterative computational process that creates a set of possible solutions for each step, termed generation, using the terminology from genetics, a branch of biology. It is a probabilistic search procedure designed to work on large spaces involving states that can be represented by mathematical strings, i.e., genes or individuals. A GA is an evolutionary computation technique that automatically solves problems without a deep understanding of what needs to be done, i.e., without specifying the form of the solution.

GAs usually start by generating an initial population of possible solutions called "individuals". This generation of individuals is based upon a random approach, i.e., stochastic. Every individual in the population is coded as a string called a "chromosome". Then, each chromosome is assessed by calculating its fitness value by the objective function, and chromosomes are sorted depending on their fitness values. The best individuals are selected as parents, and therefore, a set of new individuals is created, and a sequence of new populations, termed "generations", is produced to be assessed again. It is an iterative process [31] [32]. Generation by generation, GA develops populations of better solutions, hopefully. This process is random, and it can never guarantee results.

Therefore, the basic structure of a GA involves cyclic operations that simulate the evolutionary process of a population. Each loop represents one generation, and better and better individuals form each new population generated. Four steps are considered in a GA: setting GA parameters, developing the initial population, evaluating against fitness function, and breeding a new generation [15] (Fig. 1).

A GA-based optimization problem has the task of detecting the optimal solution related to a specific objective function termed "fitness" under a set of constraints. There are two types of optimization problems: single-objective optimization, which identifies a single optimal alternative, and multi-objective optimization, which simultaneously optimizes more than one objective function and gives a set of feasible solutions as an output [5]. As identified by many researchers [5] [34], optimization-based scheduling can maximize project quality while minimizing project

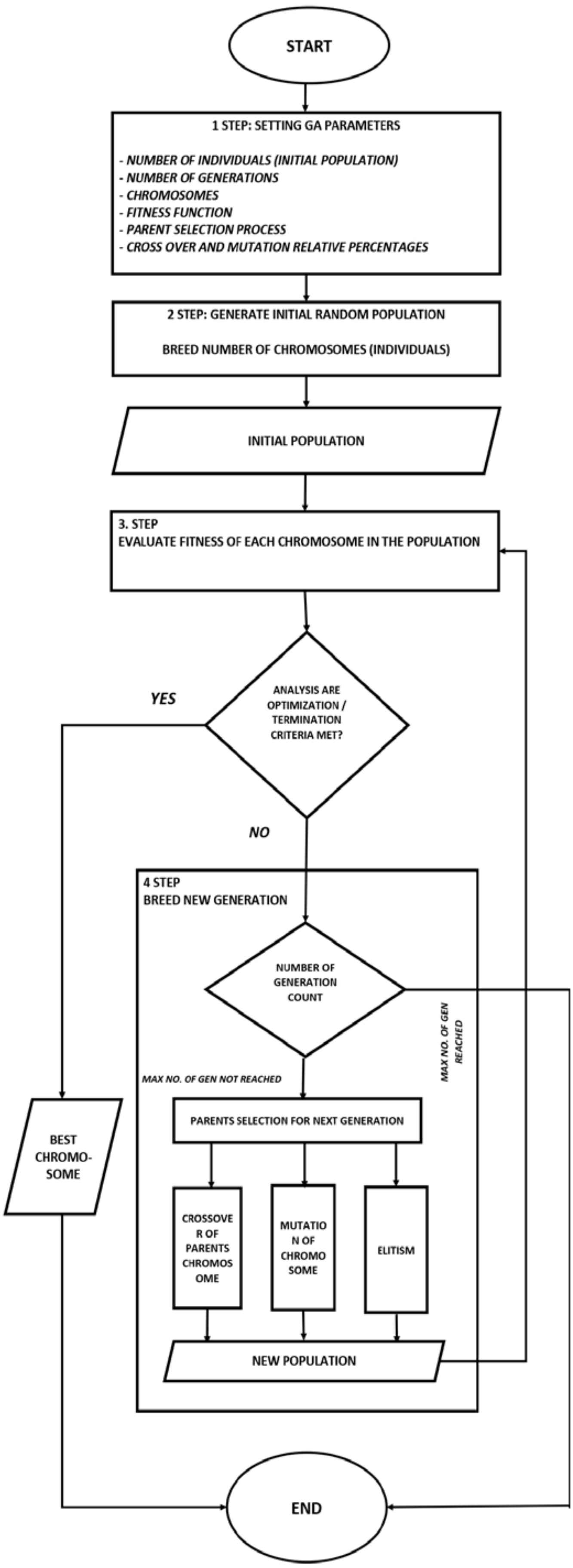

Fig. 1. *Steps of a GA.*

total cost and duration. In other words, the TCQT can be developed. The research work aims to optimize only one objective function to simplify decision-making.

3.1. PROPOSED GA COMPUTATION PROCEDURE

The proposed GA-based computation procedure aims to detect an optimized solution of the TCQT for a construction project. The proposed approach follows two stages: construction project identification and iterative population generation (Fig. 2).

3.1.1. STAGE 1: CONSTRUCTION PROJECT IDENTIFICATION

The construction project must be identified in terms of time, cost, and quality. Therefore, the database is the set of construction activities of the project and the Work Breakdown Structure (WBS) that identifies Work Packages (WP), their durations, their cost, and related quality indexes. Following these datasets, a network-based project schedule, a bill of quantities, and a QBS can be created [14]. Anyway, in the project's detailed design stage, some alternatives for WP and activity execution concerning activity description, building products, construction methods, and the number and type of resources (crew, equipment, production systems) can be evaluated. These WP alternatives produce different outputs regarding duration, quality estimate, price, and direct cost. Duration is the time needed to build, install the building component, or perform the activity. Quality is an intrinsic feature characterized by a relative concept because it consists of an objective and subjective part. Direct costs are related to the cost of materials or building products, labour, and equipment rental needed to perform the activity. If an official price list estimates the cost indicator, the cost index can also include markup and overhead costs. Therefore, it is much more challenging to quantify the quality performance of an activity than time and cost performances [26] [27]. Three possible activity alternatives have been considered (Tab. 1 and Fig. 2).

The project dataset is summarized by a table that lists for each WP the possible alternatives of duration, cost, and quality (Tab. 1). The following three KPIs have been defined for each (i) activity and WP: Quality indicator, Time indicator, and cost indicator.

Quality indicator Qi

A quality index Qi is identified for each (i) activity of the WBS. The quality index indicates a quality estimate developed by the designer, taking into account the complex set of performance requirements needed to perform the specific activity based on design and physical or functional requirements (for instance, thermal transmittance) [14].

Time indicator Di

The time indicator of each (i) project's activity is its duration. The duration of the activity can be computed based on labour hours and crew members of each activity [27].

$$Di = MHi / nm \qquad [1]$$

where Di = duration of the activity (i) in hours; MHi = total labor estimate of the activity (i) in man-hours; nm = the number of members of the working crew of the activity (i).

Cost indicator Ci

The cost indicator Ci for each (i) activity is the work package rate as detected from an official price list for public works or its direct cost, depending on the study perspective (i.e., from owner or contractor standing points). Each activity's design alternatives entail different initial products and building procedures, as indicated by the official price list. All design alternatives are suitable solutions for the final building products, meaning that the product alternatives generate activity alternatives consistent with building design and processes. The sum of the cost of each activity gives the total cost of the j project, TCj.

The following three KPIs have been defined for each (j) project alternative, depending on the chosen performing option of each activity and its different contribution to project execution: Total Quality indicator, Total Project Duration, and Total Cost indicator.

Total Quality indicator TQj

TQj can be found by the following equation:

$$TQj = \frac{\Sigma\, Qi}{n} \qquad [2]$$

where ΣQi is the total sum of quality indexes Qi of each i work package of the project (i = 1, 2, 3, ….n) for the generation j and n the total number of work packages of the project.

Total Project Duration TDj

TDj is the total project duration found by network diagramming and critical path computation for project j. TDj is the maximum duration found by critical path analysis comparing each total duration TDjk of a single path k of the project j composed of the work packages ik belonging to the k network path. Therefore, k species can be found in the project network, meaning each species is a single dataset for time-based network computation.

$$TDj = \max TDjk \qquad [3]$$

Total Cost indicator TCj

TCj is the total cost of the j project defined by the sum of the costs of the i work packages of the project:

$$TCj = \Sigma Ci \qquad [4]$$

where ΣCi is the total cost of each j project, found by adding the cost Ci of all the n work packages of the project (i = 1, 2, 3, ….n).

3.1.12. STAGE 2: ITERATIVE POPULATION GENERATION

Each project activity includes three possible alternatives. Each has its own different time, cost, and quality indicators; thus, a search space of thousands of possible solutions is created. An initial random selection of options for each activity is performed, a population of individuals – chromosomes are generated, and the corresponding objective function – fitness – is computed. Next, GA uses genetic operators to create a new population, or generation, in an iterative manner. The genetic operators are three: crossover, mutation, and elitism. "Crossover" divides two initial solutions, exchanging their chromosomes to generate new solutions, "mutation" simulates the effect of random errors, and "elitism" maintains the best individual in the next generation or substitutes the son with the parent if it gives better performance. The new solution is a set of new chromosomes, a new generation. The new generation is computed again, and the objective function results are compared with the previous ones. The best solutions are selected to improve the fitness function. Each solution has a fitness value different from the others, and the best solutions are chosen for future generations while worse solutions are set aside (Fig. 2).

The goal of the proposed procedure is to develop a chromosome or a set of them that will minimize construction total cost and construction entire duration while maximizing project quality, thus performing the TCQT problem automatically. The proposed GA procedure can use both direct costs or prices, including overhead costs and markup. Generally speaking, other lowest pricing strategies and bid-related considerations are not addressed in this paper.

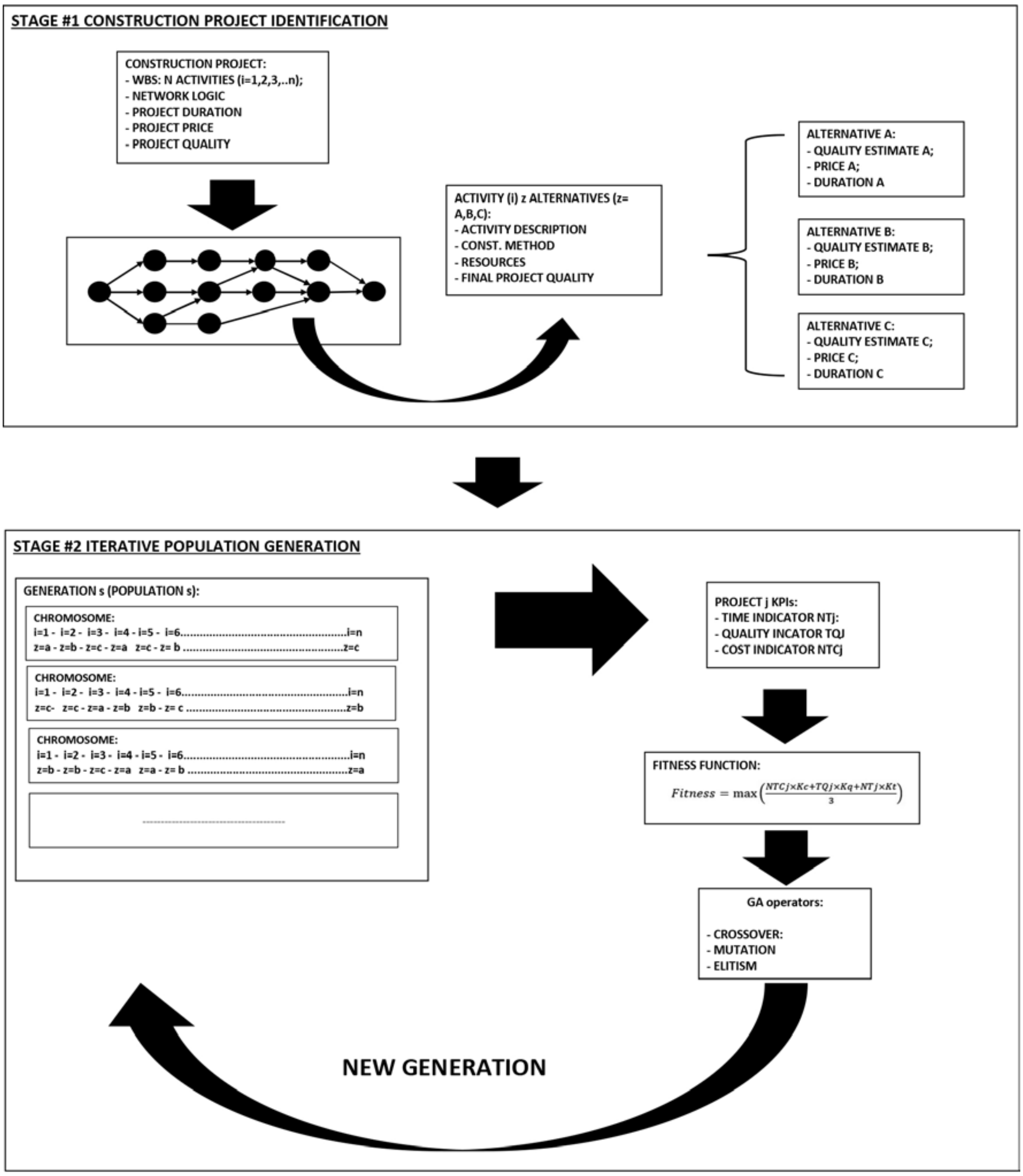

Fig. 2. *Stages of the proposed GA procedure.*

Therefore, the proposed fitness function depends on the three total project indicators – TQj, NTCj, and NTj – weighted (please note that j indicators refer to the whole project while i indicators to single activities). The following equation (4) is proposed:

$$Fitness = \max\left(\frac{NTCj \times Kc + TQj \times Kq + NTj \times Kt}{3}\right) \quad [5]$$

where NTCj is defined by the following:

$$NTCj = 1 - \frac{TCj - TCmin}{TCmax - TCmin} \quad [6]$$

in which TCj is the total cost of the project (j = 1, 2, 3, ….n). TCmin and TCmax are the project's minimum and maximum possible total cost values.

TQj is the total quality indicator of project j found with equation (1). TQmin and TQmax are the project's minimum and maximum possible total quality values.

NTj is the time parameter found for the j project, defined by the following:

$$NTj = 1 - Tj \quad [7]$$

where Tj is the normalized total duration:

$$Tj = \frac{TDj - TDmin}{TDmax - TDmin} \quad [8]$$

in which TDj is the total project duration found by network diagramming and critical path computation for the j project. TDmin and TDmax are the minimum and maximum possible values for the whole duration of the project.

The weighting parameters k_c, k_q, and k_t can range from 0 to 1 for cost, quality, and time, respectively. In order to balance the three parameters, the following values have been set: k_c=1; k_q=1; k_t=1. The final evaluation of the found solutions can be performed by comparison

WORK AND QUALITY BREAKDOWN STRUCTURE (1)

No. / WP alternatives	WBS	Work Package description	Quality Index Qi (%)	Cost Ci (€)	Duration (h) Di
1	**A.01**	**demolition and removal**			
A		demolition and removal works A	90%	€ 15.174,00	177
B		demolition and removal works B	100%	€ 15.345,85	177
C		demolition and removal works C	110%	€ 15.409,35	179
	A.02	**Brickwork**			
2	A.02.01	sew-unstich brickwork (indent repairs to masonry)			
A		solid bricks	100%	€ 18.225,22	248
B		old-style solid bricks semi-crafted	110%	€ 30.846,14	307
C		old-style hand-crafted solid bricks	90%	€ 35.972,56	308
3	A.02.02	partition walls perforated bricks cm 8 thickness			
A		six hole perforated bricks 8 x 14 x 28	100%	€ 592,08	8
B		ten hole hollow blocks 8 x 25 x 25	90%	€ 572,64	7
C		gypsum panels partition wall thickness 8 cm	120%	€ 738,24	8
4	A.02.03	partition walls perforated bricks cm 10 thickness			
A		six hole perforated bricks 10 x 14 x 28	100%	€ 1.540,59	19
B		gypsum panels partition wall thickness 10 cm	110%	€ 1.839,02	20
C		gypsum-clay panels partition wall thickness 10 cm	120%	€ 2.304,46	21
	A.03	**Concrete screed**			
5	A.03.01	lightened insulating screed			
A		lightened insulating screed with expanded clay quick	105%	€ 3.379,20	34
B		lightened insulating screed with natural cork	110%	€ 4.878,40	34
C		lightened insulating screed with expanded vermiculite	90%	€ 5.156,80	33
	A.04	**Plaster finish**			
6	A.04.01	Premixed plaster for interior wall coatings			
A		Interior plaster with lime - cement mortar	100%	€ 4.994,08	83
B		Interior plaster with lime mortar	110%	€ 4.877,60	82
C		Interior plaster with cement mortar	90%	€ 4.994,08	82
	A.05	**Floorings and sheathing/walls**			
7	A.05.01	ceramic floor blasted tiles			
A		ceramic floor blasted tiles 40 x 40	100%	€ 2.837,97	18
B		ceramic floor blasted tiles 60 x 60	110%	€ 4.874,85	14
C		ceramic floor blasted tiles 20 x 20	90%	€ 2.497,11	18
8	A.05.02	Ceramic wall cladding			
A		ceramic wall tiles 20x20 mono-coloured	90%	€ 6.261,71	49
B		ceramic wall tiles 20x20 marble-effect	100%	€ 3.632,72	49
C		ceramic wall tiles 10x10 stone-effect	110%	€ 7.433,79	60
9	A.05.03	Skirting board			
A		Stoneware skirting board 10x20	110%	€ 2.504,80	21
B		Clinker skirting board 8x24 glazed	100%	€ 1.700,00	17
C		Wooden skirting board - cherry 75x10mm	80%	€ 1.201,60	9

WORK AND QUALITY BREAKDOWN STRUCTURE (2)

No. / WP alternatives	WBS	Work Package description	Quality estimate Qi (%)	Cost Ci (€)	Duration (h) Di
	A.06	**Windows and doors**			
10	A.06.01	counter frame for sliding doors			
A		metal sub-frame for sliding doors	100%	€ 511,28	3
11	A.06.02	counter frame for hinged doors max width 11 cm			
A		wooden counter frame fir depth 2,5 cm width 11 cm	100%	€ 93,60	1
12	A.06.03	wooden hinged solid door			
A		Hinged solid interior door - tanganika walnut wood	90%	€ 2.412,84	8
B		Hinged solid interior door - walnut wood	120%	€ 3.855,00	7
C		Hinged solid interior door - oak wood	100%	€ 3.209,88	8
	A.07	**Electric system**			
13	A.07.01	Electric system for one apartment			
A		Electric system for one apartment	100%	€ 2.200,00	21
	A.08	**Plumbing and sanitary system**			
14	A.08.01	Supply and installation of vitreous china toilet bowl			
A		Vitreus china toilet bowl	100%	€ 473,50	5
B		Vitreus china wall-hung toilet bowl	110%	€ 629,10	5
C		Vitreus china wall-hung chrome finish toilet bowl	120%	€ 1.034,08	6
15	A.08.02	Supply and installation of vitreous china bidet			
A		Vitreous china bidet	100%	€ 469,26	4
B		Vitreous china wall-hung bidet	110%	€ 625,10	5
C		Vitreous china wall-hung bidet with chrome finish	120%	€ 1.030,08	6
16	A.08.03	Supply and installation of vitreous china wash basin			
A		vitreous china wash basin 70x55	100%	€ 687,84	5
B		vitreous china wash basin 65x50	95%	€ 643,20	5
C		vitreous china washbasin 70x55 pedestal basin	105%	€ 842,06	6
17	A.08.04	Sanitary waste water system			
A		sanitary waste water system for one bathroom PVC	100%	€ 629,12	8
18	A.08.05	domestic hot/cold water system			
A		domestic hot/cold water system polybutylene	100%	€ 967,00	9
B		domestic hot/cold water system galvanized steel	95%	€ 1.156,64	18
C		domestic hot/cold water system cross-linked polyethlene	105%	€ 1.366,44	17
	A.09	**Building assistance**			
19	A.09.01	wal assistance plumbing	100%	€ 640,00	11
20	A.09.02	wal assistance electrical system	100%	€ 880,00	15
	A.10	**Painting**			
21	A.10.01	Indoor water-based paint			
A		Indoor water-based breathable paint	95%	€ 3.648,20	55
B		Indoor water-based breathable / washable paint	100%	€ 4.077,40	60
C		Indoor palette knife effect resin-based wall coating	110%	€ 20.839,40	309

Tab. 1. *Pilot study data set.*

with the maximum and minimum set limits of the three parameters, termed TC_{max}, TC_{min}, TD_{max}, TD_{min}, TQ_{max}, and TQ_{min} (Tab. 1) (and Fig. 3).

4. PILOT STUDY APPLICATION

A GA-based algorithm has been implemented with Solver®, an add-in of MS Excel® [35]. This application can quickly explore the solution space and identify a set of optimal solutions. The purpose of the pilot study is to test the proposed GA-based procedure. The pilot study consists of a small building renovation project that has also been used in previous research works by the authors but with different procedures and computer applications. This paper constitutes an evolution aimed at increasing the procedure's efficiency. The pilot study consists of a refurbishment project of two small residential apartments with a superstructure of load-bearing masonry walls. Most activities were aimed at renovating the architectural finishes and the mechanical, electrical, and plumbing services. For each work package of the pilot study, three different commercial product options have been considered, and the corresponding activity durations, costs, and quality performances have been detected from a public works price list. Quality indexes have been evaluated straightforwardly as product quality and its suitability for use (Tab. 1). Therefore, the proposed TCQT procedure has been implemented using Solver®-based GAs to find a set of optimal solutions for the building construction project. The data found for each work package are presented in the following text.

No alternative permutations are possible between different species because of the structure of chromosomes, i.e., the number of WPs in each network path. The chromosome of a species is created by time, cost, and quality data of each chosen WP alternative belonging to a network path. The limit values of total project alternatives can be found by time-based computation of the critical path method (Fig. 3 and Fig. 4) and the total sum of the cost and quality data of the project (Tab. 1). Minimum and maximum total values of the three project parameters, time, cost and quality, can be found by manual computation of the corresponding alternatives of each WP (Tab. 2). The minimum total value of TDj was computed

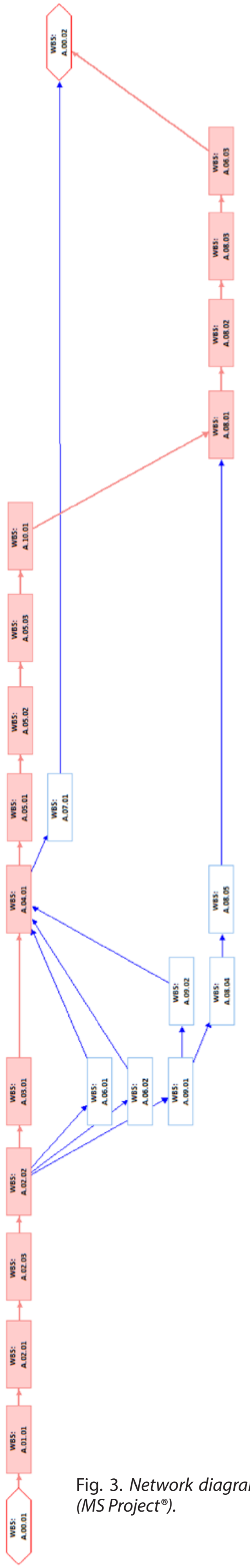

Fig. 3. *Network diagramming of the pilot study project (MS Project®).*

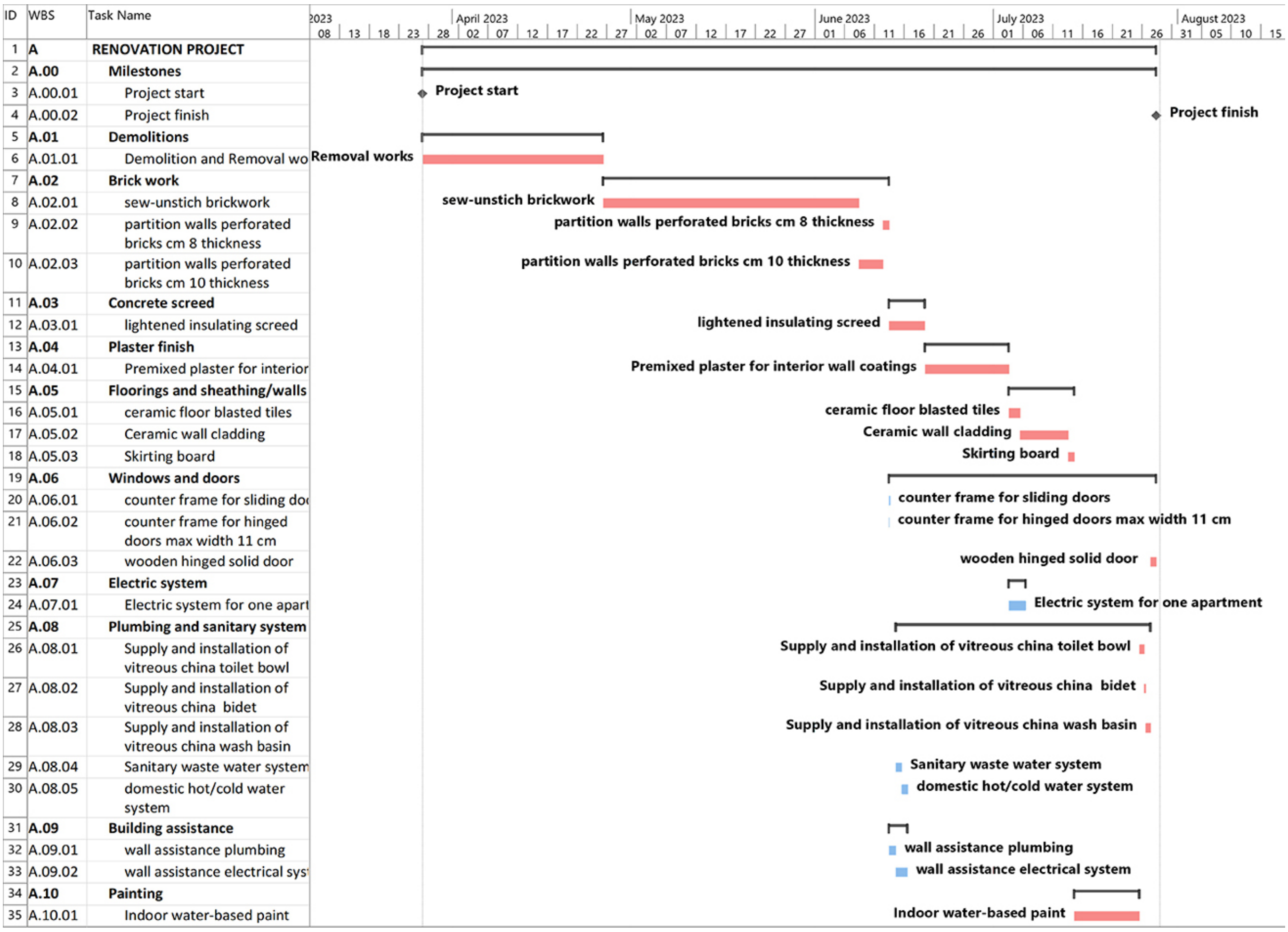

Fig. 4. *Gantt Chart of the pilot study project (MS Project®).*

selecting all the possible options of the dataset of table 1 with the minimum activity duration (Di), and then calculating the critical path. The minimum total values of TCj and TQj were found by adding all the possible alternatives in Tab. 1 with the minimum cost Ci and quality Qi. Maximum limits TDj, TQj, and TCj were computed similarly but using maximum values Di, Ci, and Qi of activities and WPs. Please note that the six limit values found in Tab. 2 belong to six different project alternatives. The aim of setting each indicator's min/max limits is to assess the boundaries that define the min/max performance of project alternatives indicated by the outputs computed by the GA-based procedure.

Therefore, using the evolutionary algorithm, the Solver® application has been set for the specific problem. The optimization engine has the following characteristics. Each WP has three alternatives, say A, B, and C, each with corresponding time, cost, and quality indicators. Each option is multiplied by a scalar coefficient ci that can be 0 or 1 depending on the value of the random variable xi given by the Solver and by the constraints of the spreadsheet (Fig. 5). The network diagram and the

Total project values	**Maximum limit**	**Minimum limit**
Total project duration TDj	TDmax = 1067 (h)	TDmin = 714 (h)
Total project cost TCj	TCmax = € 113.309,99	TCmin = € 64.668,68
Total project quality index TQj	TQmax = 109.1%	TQmin = 94.5%

Tab. 2. *Limit values of total project alternatives.*

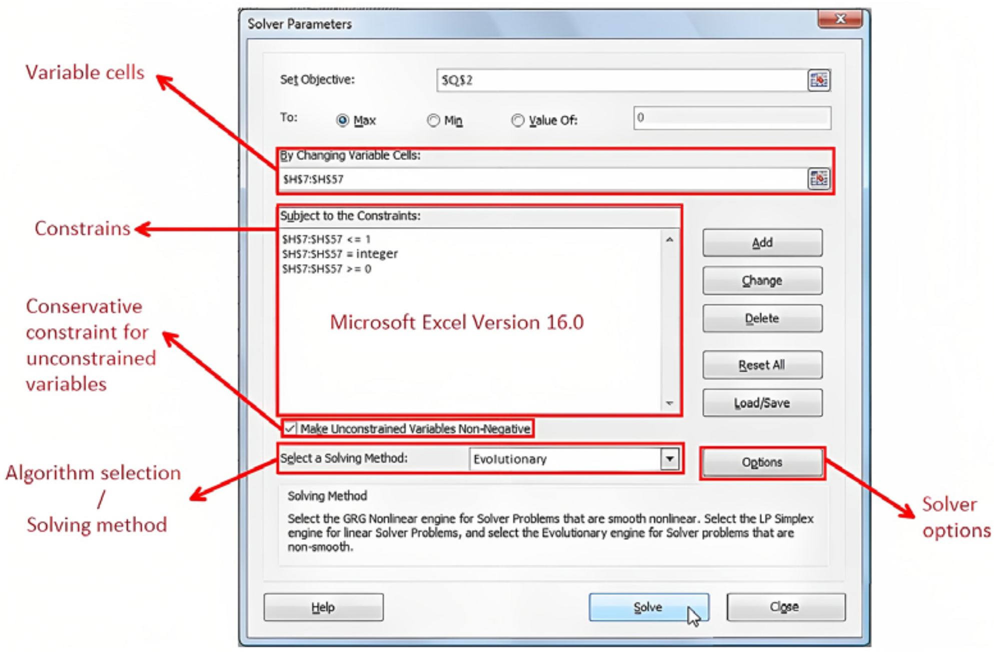

Fig. 5. *Setting of Solver® for the pilot study project (MS Excel®) (Pozzi, 2021).*

working options of the pilot study have been formalized in Microsoft Project (Fig. 3 and Fig. 4). The maximum number of generations has been set to 100 and the maximum time without improvements to 100 seconds. The best-found optimized result in the case of balanced weights (Kq=1, Kc=1, Kt=1) is the following: Fitness value=0.34853; Total project duration TDj=720 h; Total cost TCj=€ 64,668.68; Total quality index TQj=97.38%. The results are consistent with the limit values of total project alternatives in Tab. 2.

5. DISCUSSION

Solver® is an Excel add-in program that can be used for different optimization analyses of MS Excel®. It includes a GA, termed evolutionary Solver. The Solver guide [35] describes the following steps of the GA:

1. Start with a population of chromosomes randomly chosen that constitutes the first generation or first iteration;
2. Evaluate the fitness values of chromosomes;
3. Rank the chromosomes by their fitness;
4. Apply genetic operators: elitism, crossover, and mutation. All these operators are assigned a probability of occurrence;
5. Create a new generation from these chromosomes and evaluate their fitness;
6. Apply genetic operators again as before and iterate until the process is stopped;
7. End of the process when convergence is achieved or the maximum number of generations is reached.

The critical point of this process is setting constraints concerning the value of the variables and required path computation. The results are inside the possible maximum and minimum limit values of each project index representing TCQT, intending to find a solution that optimizes the time and cost with the lowest possible values and maximizes the quality of the project work packages. The time-related index addresses the total project duration TDj of the j project, found by critical path computation. The range of TDj values is from 714 h to 1067 h (Tab. 2). Solver found an optimized TD value of TD=720 h. The quality-related index addresses a designer's comprehensive score Qj of the project found as the mean value of the 21 Qi indexes of each "i" activity of the project. The range of Qj values is from 94.5% to 109.1% (Tab. 2). The optimized found TQj value is TQj=97.4%. The cost-related index is the total project cost TCj found by adding the cost Ci of each "i" activity of the project. The range of TCj values is from € 64,668.68 to €

113,309.99 (Tab. 2). Solver found as TCj value TC=€ 64,668.68, which is the minimum value. Actually, the proposed application found the project with the lowest cost value as the best result. This issue is of interest, as it could be the typical solution the owner's consultant found without any decision support system like the one described and implemented with Solver®. Also, the total project duration value is excellent, near the minimum value. The calculated quality value is 97.4% under all activities' 100% quality index target. However, as a compromise, a trade-off between the three values addressing time, cost, and quality can be considered a good result. This indicator can be enhanced by increasing the relative weight of Kq for quality. Limits of the proposed application is using a standard spreadsheet, which prevents the use of the procedure to large construction projects and small population sizes [36]. These limits will be tackled in future research work.

6. CONCLUSIONS

TCQT problem is of great importance in construction project management. Still, the complex relationship between these project KPIs varies from case to case, and no simple solutions are feasible in actual projects. In order to demonstrate that AI applications can address the TCQT problem, an innovative GA optimization has been developed and implemented with Solver®, a Microsoft Excel® add-in program. Actual data from a pilot study concerning each project activity's expected duration, quality index, and cost have been detected, and three possible performing alternatives of the WPs were developed. Therefore, the overall performance of the whole construction project, with the processing of all the WPs, was simulated, considering the possible alternatives of activity duration, cost, and quality. The time estimate was developed using a network-based activity network with Microsoft Project®, while the total cost estimate was the sum of the cost of all work packages, and the overall project quality index was estimated as the average quality index of all work packages. A GA-based procedure has been proposed, developed in two stages to find automatically (or semi-automatically) a balance between the time, cost, and quality project objectives via GA computation. In Stage 1 – Construction Project Identification, the WBS, QBS, BOQ, and project schedule logic are developed corresponding to the three possible activity alternatives. In Stage 2, the iterative population generation process is performed based on the fitness function evaluation and the selected GA operators (crossover, mutation, and elitism) after setting algorithm constraints. After 100 generations, the procedure is terminated, and the found results are evaluated. Actual data for a pilot study simulation of a building renovation project of a small residential building have been used to demonstrate the possibility of implementing a GA-based optimization of project objectives, and the found results are consistent with the initial assumptions in terms of ranges of time, cost, and quality values. Limits of the proposed application are the use of a standard spreadsheet that prevents the application of the procedure to large actual construction projects and the small population size. Nevertheless, researchers and practitioners can easily implement this simple application addressing the desired TCQT problem solution, even if it is sub-optimal. Future research work will be aimed at improving the procedure's efficiency so that it can be implemented in larger projects.

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MANAGING PEOPLE'S FLOWS IN CULTURAL HERITAGE TO FACE PANDEMICS: IDENTIFICATION AND EVALUATION OF COMBINED MEASURES IN AN ITALIAN ARENA

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TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

DOI: 10.30682/tema090004

Abstract

The management of people's health and safety in cultural buildings has been drastically changed in view of the COVID-19 pandemic. The combined effects of crowding levels and people's flows are now associated not only with emergency conditions (i.e., evacuation) but also with ordinary fruition issues, given the possible spreading of the virus. Cultural buildings, particularly cultural heritage, are critical scenarios for emergency and fruition issues because of their specific geometric and technical features. They suffered from COVID-19 restrictions mainly due to physical distancing measures. Protocols have been developed during the last two years to manage pandemics in such contexts, and the increasing number of vaccinated people is also pushing toward a full return to pre-pandemic rules. However, they should be carefully evaluated and tailored depending on cultural heritage conditions. This work identifies and evaluates combined measures to manage people's flows (access, movement, queue) depending on boundary conditions at the overall (building capacity) and individual levels (face mask; vaccinated/recovered; "green pass"). The effectiveness evaluation is performed by using a simulation model that jointly represents the virus spreading and the people's flow. An Italian historical arena is selected as a significant case study. Results show that a higher occupants' number can multiply the contagion spreading. Still, a more significant impact on its limitation can be achieved by controlling infectors' access (supporting body temperature control with rapid tests) and occupants' movement during queues and pauses. The methodology can help decision-makers to balance a proper combined application of management measures.

Keywords

Cultural heritage, Pandemics, People's flow, Simulation model.

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1. INTRODUCTION

The COVID-19 pandemic remarked that people's flows and activities can significantly affect the overall built environment safety, especially in spaces open to the public and characterized by long-lasting and critical crowd conditions [1]. The attractiveness of spaces with respect to their users can create ideal conditions for both emergency safety issues in buildings (e.g., fires, evacuation) [2] and ordinary fruition models in view of virus-spreading effects among building occupants [3]. Although pre-pandemic works underlined the impact of people's flows on individual health and safety in combination with management strategies and building systems use (e.g., ventilation) [4], the way the COVID-19 pandemic spread and the virus' effects on people (both from a physical and psychological perspective) magnified the importance of organizing effective risk-mitigation measures, especially in closed environments (thus both in buildings or also public transports) [5, 6].

In particular, cultural buildings and heritage, such as theatres, cinemas, public halls, museums and exhibition places, arenas and stadia, widely suffered from COVID-19. They were characterized by a high probability of hosting large numbers of people, for a significant permanence timing, interacting with each other, and also in possible overcrowding conditions, thus increasing the possibility of the virus spreading in case of poor safety management strategies [7, 8]. As an immediate response, these buildings were immediately closed because of the adopted widespread lockdown strategies, as for many other public indoor and outdoor spaces [9]. After the first lockdown phases, cultural buildings were reopened, and strict safety protocols were adopted according to World Health Organization (WHO) criteria to reduce proximity conditions, exposure time, presence of infectors, and their effects. Besides facial mask use by occupants, protocols mainly involved access and occupants' movement control, as well as physical distancing [10]. Nevertheless, occupants' limits for many cultural buildings were initially provided without connection to the building surface and layout [11, 12]. For instance, tens of people were allowed in this first response phase, whereas hundreds were hosted before the COVID-19 pandemic. In the following pandemic stages, regulations were modified to enable a reduction of occupants' capacity in percentage terms, with respect to the full (standard) capacity, thus moving towards a gradual return to normality. Meanwhile, large-scale experiments were performed to understand the effective impact of indoor/outdoor events and how to overcome these critical limitations [7, 8]. They revealed that the total number of contacts lasting several minutes was relatively low during the event and a higher number of contacts occurred during admission to the venue and during the breaks. Thus, measures should combine occupants' capacity limitations to the management of attraction areas in the built environment [9], including collective (e.g., access control; possible infectors' detection, also via body temperature control; sanitizing actions; air flows) and individual (e.g., mask-wearing) strategies Similar strategies have been widely applied in a large number of building intended uses, and mainly in public and work spaces [9, 13, 14].

The progressive introduction of vaccines in several countries, the consequent reduction of infection rates and hospitalizations, and the parallel adoption of screening campaigns (e.g., "green pass" adoptions) have been encouraging a discussion on how the adaptation of COVID-19 measures can overcome occupants' capacity limits for public cultural events [9]. However, the possibility of applying measures and their effectiveness depends on the following:

- the type of event, the attractiveness of architectural spaces, and the social response of people during it. For instance, before the pandemic, proximity during festival and music events was not experienced as an invasion of personal space but as sharing 'social identity space', and therefore, something tolerable or even positive [9];
- the geometrical and technical characteristics of the building hosting the events. This factor is a fundamental factor in the building heritage and generally affects the sustainable use and adaptation of cultural heritage over time [15], especially in connection with safety issues and crowd conditions [2].

In the context of such historical buildings, arenas and theatres are still used to host theatrical, musical, and opera events, representing one of the most significant scenarios. According to the consolidated proximity, exposure-time and ventilation-based criteria for COVID-19 transmission [10] as well as to the aforementioned experimental results on public concert venues [7, 8], their risk for contagion spreading is significant mainly because:

- the audience contemporarily occupies the same closed built environment, which hosts both the parterre and the tiers, thus exposing, to the same conditions, a number of occupants that is generally higher than other conditions (including public transports);

- possible overcrowding conditions can appear over time also in the narrow and complex spaces to reach this audience space (i.e., entrance/exit queue, people's flows during breaks or towards internal attraction area, e.g., bar, foyer, toilets). General fruition conditions thus imply the overlapping of static use (i.e., in the audience space) with dynamic use (i.e., occupants moving and socializing before, during, or after the breaks).

Furthermore, these cultural buildings also generally imply the circulation of occupants in other community facilities that are external to the buildings themselves due to leisure activities in view of the venue [7, 8]. Tailored safety protocols should be provided and evaluated for such historical buildings, considering (1) the possibility of maximizing the occupants' number while (2) improving the final users' satisfaction, (3) the possible revenues for all the stakeholders, and (4) directly managing complex spaces with low impact solutions, as for general reuse, adaptation, and safety issues [2, 15, 16].

Simulation tools could be useful to effectively set up sustainable solutions from these perspectives [1, 13, 17]. A similar approach is shared by other safety-related issues in the cultural heritage (e.g., evacuation safety) [2] and was also applied by previous studies on airborne disease mitigation [4]. Some simulation approaches have been provided to evaluate the COVID-19 spreading in closed environments been performed for public spaces and closed built environments [1, 17, 18]. However, the development of measures was generally assessed separately [14]. Limited efforts to evaluate the effectiveness of safety protocols have also been provided [19], and thus, joint optimization issues were not carried out according to structured approaches and by including vaccine effects. Furthermore, to the authors' knowledge, no works were performed in the context of cultural buildings, such as arenas and theatres, and specifically considering historical buildings because of their aforementioned intrinsic limits affecting risk.

This study aims to develop an approach to identify combined measures for contagion-spreading mitigation in the context of building heritage used for cultural purposes and then verify their joint effectiveness to define efficient and tailored protocols against COVID-19. The approach relies on the joint simulation of people's flows, virus-spreading rules, and specific health and safety protocol measures. A simulation model developed and validated by previous research group works [19] has been modified to ensure its application in the cultural heritage context. Considered measures are consistent with Italian Government regulations (https://bit.ly/3Eb96CE, checked: 14/04/2022), as well as with national and international guidelines (including the ones of WHO) [14, 20], and mainly comprise people's flows management tasks such as access, queue, and movement control, in respect to occupants' capacity at the overall level and individual features. The approach capabilities are shown using a significant case study, the "Arena Sferisterio" (Macerata, Italy), a famous historical arena with a capacity of 3000 people, used to host operas, concerts, and other theatrical events for over 100 years. The model predicts the effectiveness of safety protocol measures in terms of the probability of new contagions at the end of an event. Thus, such results can help the decision-makers evaluate the best combination of strategies to be adopted in the theatre.

2. METHODS

This work is organized into 3 steps: 1) the identification of combined measures in the cultural heritage context by focusing on theatres and arenas and their implementation in a simulation model [19] in synergy with the virus spreading and people's flows rules (Section 2.1); 2) the definition of criteria to perform and analyze simulation results (Section 2.2); 3) the application to the selected case study by tailoring measures according to the current scenario and decision-makers choices (Section 2.3).

2.1. COMBINED MEASURES IDENTIFICATION AND MODELING APPROACH

Measures to manage health and safety against COVID-19 in cultural buildings can be arranged into 3 different classes, according to national decrees and national/international guidelines the decree requires (e.g., https://bit.ly/3Eb96CE, [14, 20]): 1) people's flows management, in terms of minimum physical distancing (≥1m) and other control actions, such as ticket booking and access supervised and regulated by dedicated personnel (i.e., body temperature control, <37.5°C; "green pass" control); 2) overall control measures, focused on maximum building capacity, body temperature check, and sanitizing measures; 3) measures at the individual level, i.e., face-masks use (independently by the mask type), being vaccinated, having a "green pass". These measures are combined in order to be represented in a multi-agent simulation model, which can hence evaluate the effectiveness of measures in the safety protocol, depending on people's flow, behaviors, and interactions induced by the event organizers, the geometry of the cultural building and the attractiveness of its composing spaces.

According to previous works of the research group [19], the model considers that each individual in the environment can: 1) be an infector or a susceptible person; 2) wear a face mask of a certain type; 3) can have a "green pass" and/or being vaccinated or not. On such bases, the model jointly represents: 1) the position of each individual in the areas of the arena, over time, depending on the environment layout, its use, the event organization, and adopted measures (Section 2.1.1); and 2) the virus transmission between people depending on their positions and according to a probabilistic approach (Section 2.1.2).

2.1.1. LAYOUT, USE, AND COMBINED MEASURES

The simulation environment is composed of: *"waiting areas*" that are placed near the entrance gates, *"sectors"* where the audience attends the event, and "*other attraction areas*" such as common spaces and toilets. People can spend time in such areas according to the event schedule. In addition, inaccessible areas and main obstacles to occupants' presence (i.e., the stage) are also taken into account. Thus, the environment surface *A* [m^2] is defined as the sum of the surfaces of such areas.

The number of simulated *initial people* [pp] depends on the specific occupants' capacity according to the considered safety protocol scenario. A specific status (infector/susceptible, "green pass"/vaccinated or not, face mask type) is assigned at the start of the simulation to each simulated individual [19]. The model considers that people just enter the environment at the beginning of the event and can leave it at the end.

Initially, people are randomly distributed in the "*waiting areas*", respecting the minimum physical distancing requirements (1m). They can move into their "*waiting area*" while respecting the physical distancing. This distancing assumption is also compatible with real-world behaviors retrieved in public buildings [21], where only a marginal number of people (up to <20%) seem to assume lower distance values in building fruition and movement. After a *queue time*, people move to the "*sector*" corresponding to their "*waiting area*". A random position is attributed to them respecting the criteria of minimal safety distance (1m) between seats, which is consistent with seat occupation criteria in the case study (compare Section 2.3). The "act" phase starts when the event begins, and all agents remain in their assigned seats without moving. Only a limited number of people has been characterized by the ability to move (arbitrarily assumed equal to 5%, thus representing a marginal impact of such behaviors during the "acts") towards specific "attraction areas" (i.e., toilets). At the end of each "act", that is, during the pause, each individual can move towards the "attraction areas", depending on his/her possibility of "moving at pauses". According to an example of typical opera acts' scheduling (e.g., considering the Sferisterio organization and most represented operas [22]), this work considers a simulation step equal to 15 minutes. This work considers three "acts" (30 minutes each) and two pauses between the acts (15 minutes each). At the end of the last "act", people return to the entrance gate where they were initially placed to leave the building, depending on the *queue time*.

People's position modeling is aimed at representing the overall contagion-spreading effects on the whole population, depending on the attractiveness of the space, with a time discretization of 15 minutes as a consistent threshold for the increase of contagion probability [13, 23].

2.1.2. VIRUS TRANSMISSION

Consolidated *proximity and exposure-time-based rules* represent high-risk and close contact between the occupants. Considering a distance between a susceptible occupant and an infector <2m, the probability of being infected P_C [%] (Eq. 1) increases with: 1) the infector's transmission efficiency of the virus i_{eff} [-], calculated as the ratio between the current time from the virus contagion and the virus incubation time (capped at 1); and 2) the exposure time Δt [h]. P_C can be hence reduced by: 1) the mask filter of the infector ($prot_i$) and of the susceptible occupant ($prot_j$) for each individual depending on the EN 149:2009 classification [19] (maximum protection when $prot_i$=$prot_j$=1; and 2) the antibody efficacy V_{eff} [-], for vaccinated/recovered people [24]. P_C is capped at 100% (maximum probability). This approach has been validated according to real-world experimental data [19].

$$P_C = i_{eff} \cdot \Delta t \cdot \left(1 - prot_j\right) \cdot (1 - prot_i) \cdot V_{eff}\,[\%] \quad \text{(Eq. 1)}$$

According to the Wells-Riley approach (Eq. 2), given the number of susceptible people S [pp] in the environment, the probability of being infected because of *ventilation-based rules* P_V [%] depends on the number of infectors C [pp] and the quantum generation rate produced by each of them q [h^{-1}], on the pulmonary ventilation rate of a susceptible occupant p [m^3/h], on the exposure time Δt and on the ventilation rate of the environment Q [m^3/h]. In Equation 1, one quantum q represents "a collection of pathogen particles that can infect susceptible people", and the q values derived for the COVID-19 context range from 14 to 48 h^{-1} [17].

$$P_V = \frac{C}{S} = 1 - e^{-\frac{q \cdot p \cdot \Delta t}{Q}}\,[\%] \quad \text{(Eq. 2)}$$

Transmission modes due to surface contamination also have been not considered because of the constant sanitizing activity [20].

For each susceptible occupant, P_C and P_V are calculated at each simulation step, and his/her infection probability is associated with the maximum value between them. Then, the infection probability is compared to a random number (varying from 0 to 100%), and the susceptible occupant is stochastically infected when the infection probability is equal to or greater than this random number. It is also considered that this newly infected occupant cannot infect other people because his/her i_{eff} tends to zero while remaining in the environment (see Eq. 1).

2.2. SIMULATION SETUP AND RESULTS EVALUATION CRITERIA

The multi-agent NetLogo platform (version 6.2) [25] is used to implement the model. The space is divided into squared patches, whose sides are equal to 1m. The model running is performed through a script in R programming language (version 4.0.5), in particular using the NLRX package to ensure repeated tests according to the probabilistic approach (https://cran.r-project.org/web/packages/nlrx/index.html). More than 300,000 simulations have been performed, including different simulation setup organizations on the case study, as reported in Table 1, according to Section 2.3 assumptions. All the simulations consider that infectors are asymptomatic persons who are not revealed by controls before the event (e.g., by swabs) or at the building access by body temperature control.

At the end of each simulation, results have been organized to evaluate the contagion spreading reduction due to combined measures, considering a single event. Thus, the contagion spreading after each event is expressed through the final infected people percentage dI [%], which depends on the final S_f [pp] and initial S_i [pp] number of susceptible people according to Eq. 3 [19]:

$$dI = \left[1 - \frac{S_f}{S_i}\right]\% \quad \text{(Eq. 3)}$$

dI ranges from 0 (no new infections at the end of the event) to 100% (all the susceptible people become infected at the end of the event). Successful measures should minimize dI. dI<5% is also assumed as a reasonable threshold for contagion spreading discussion. dI values are mainly correlated to:

- the combination of measures on *initial people* (to consider the maximum number of allowed occupants), *init-infectors-percentage* (to assess the effectiveness of access control procedures), *moving-at-pause* (to evaluate the internal displacement possibility for the audience by the staff members' control);
- and the contextual factors at the national level in terms of *vaccinated/recovered percentage.*

dI values are traced according to 2D Kernel Density, thus pointing out the *dI* probability depending on the parameter range. Results are organized by first discussing the impact of each aforementioned parameter condition by itself and then combining them. In this sense, the median *dI* is assumed to be a risk index to compare the effectiveness of each measure.

2.3. CASE STUDY APPLICATION

The Arena Sferisterio (or just the "Sferisterio") of Macerata is one of the most prominent architectural structures of the late European Neoclassical Style in the Papal State and betrays a Palladian influence [26, 27]. Built in the '20s of the 19^{th} Century by Salvatore Innocenzi and Ireneo Aleandri, the Sferisterio is characterized by an open-air semi-elliptic layout (Fig. 1). Since the end of the '80s, it has regularly hosted the international "Macerata Opera Festival" during the summer. Most of the audience is hosted in the parterre, placed at the ground level, assigned to two main sectors and several sub-sectors, with fixed seats divided by corridors. The C-shaped building comprises several levels hosting: at the ground floor, a portico to grant space for people waiting to enter the arena, artists' rooms, toilets, and corridors to the parterre; at the 1^{st} level, the terrac-

Parameter by typology	Unit of measure	Values range in this work	Notes
Environment and global parameters			
A	m^2	4500	The overall surface of the Arena Sferisterio (see Section 2.3)
Δt	exposure time as the simulation step	1 step = 0.25h (15 minutes)	Simulation step provided according to critical exposure-time values in consolidated proximity-based criteria for contagion spreading, to typical opera scheduling and to the queue time according to the case study application (see Section 2.3)
Individual's features			
i_{eff}	-	0 to 1	infector's transmission efficiency of the virus, randomly assigned to each infector
Vaccinated/recovered percentage	%	30 to 70%	Percentage of vaccinated/recovered occupants who can enter the building
V_{eff}	%	85% to 95%	Effective coverage of the antibodies from the infection; randomly assigned to each individual; evaluated starting from vaccine-related data
init-infectors-percentage	%	0.2 to 4	How many individuals could be infectors at the start of the simulation
$prot_i = prot_i$	-	0 to 1	Uniform mask types distribution is considered for the individuals, based on the criteria from EN 149:2009 on maximum aerosol drops penetration percentage. Limits of each type refer to: FFP3≥98%, FFP2 95-98%; FFP1 80-95%; surgical 54-88%; community masks and no-protection limit<54%.
Safety protocol			
initial people	pp	600 - 1100	Number of people in the environment ranging from about 2/3 of the maximum COVID-19 capacity to +20% of the maximum capacity. Although 842 people (see Section 2.3) is the maximum allowed capacity for the case study stakeholder, the maximum number of people has been increased to better stress the capacity effects on the contagion spreading.
Moving-at-pause	%	5 to 100%	Maximum number of people moving during the pause phase between two consecutive acts
Queue time	-	1 or 2	entrance and exit queue time: 1 stands for 15 minutes-long queue; 2 stands for up to 30 minutes-long queue

Tab. 1. *Model parameters setup for simulation.*

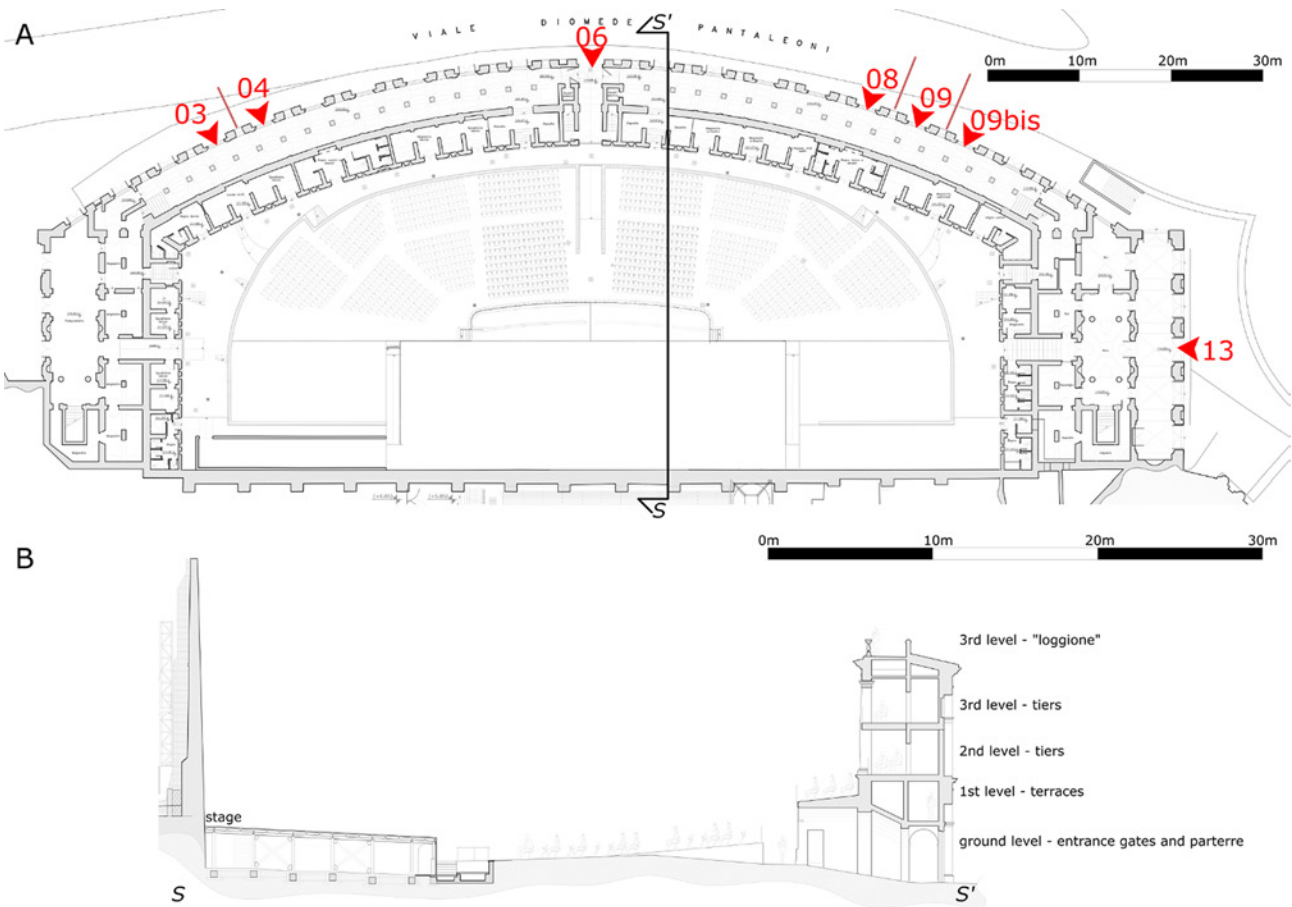

Fig. 1. *Arena Sferisterio layout: A-. plan view of ground level, showing the parterre, the main portico, and the main entrance gates; B- section view (S-S') showing the 4 levels of the open-air theatre. The entrance gates' codes are shown according to COVID-19 safety, as shown in Table 2. Courtesy of "Sferisterio Arena Association".*

es, with fixed seats, which are served by a long corridor, toilets, and technical rooms; at 2nd and 3rd levels, tiers (4 to 6 seats for each tier), divided into boxes, which are served by a long corridor as for the first level; at the last level, the building flat roof hosting the "loggione", without seats.

The following simulation scenarios are based on the tailored protocols adopted by the Sferisterio managers in the 2021 seasons (starting in June), to consider more restrictive conditions and pursue a conservative approach to regulations applications. Thus, infectors' data affecting individual measures refer to the same period (i.e., end of May 2021).

People's flow management and overall control measures are based on the audience's division into 6 sectors and subsectors, as in Table 2. The number of people in each area is defined depending on the seat position (which is fixed at the ground) and number (to grant the minimum physical distancing). Furthermore, the access to each sector/sub-sector is associated with a specific entrance gate, which is graphically shown by the codes and the red arrows in Figure 1-A (compare Tab. 2 for the same codes). Only 7 gates were left open. This type of organization was introduced to reduce the interactions between people while moving to seats assigned in different sectors, as well as to limit the queue while entering. Two values for the *queue time* (15 and 30 minutes) are considered thanks to the support of 60 staff members, who were assumed in 2021. The queue time is due to the staff's ticketing service and support for automatically checking people's body temperature via infrared cameras. The staff additionally: 1) controls and reduces people's flow and interactions during the queues and the event; 2) assists people and grants a constant sanitizing activity (seats, doors, toilets, etc.). From an individual level, people are obliged to wear a face mask. Still, no

Sector name	People	Entrance gate code (Figure 1) – sub-sector name: number of people [pp]
Parterre	388	06-central: 224 pp; 08-lateral left: 82 pp; 04-lateral right: 82 pp
Terraces	172	09-lateral left+journalist tribune: 92 pp; 03-lateral right: 80 pp
Tiers (I order), divided into boxes	120	09bis-lateral left: 60 pp; 09bis-lateral right: 60 pp
Tiers (II order), divided into boxes	114	13-lateral left: 60 pp; 13-lateral right: 54 pp
"Loggione"	48	13-unique sub-sector: 48 pp
Total	*842*	

Tab. 2. *Maximum number of people for each sector/sub-sector and association with the entrance gates.*

limitations for the type of mask (surgical, FFP, etc.) are considered in this work to verify the effects of different protection levels on the spreading of the contagion.

Since the model is based on 15 minutes-long simulation steps, 8 simulation steps correspond to the 3 acts-2 pauses structure, while the duration of the overall event depends on the queue time (10 steps for 15 minutes-long queue; 12 steps for 30 minutes-long queue). Preliminary simulations were performed to assess the impact of *ventilation-based spreading* with respect to the *proximity and exposure-time-based rules*. P_C is assessed as the prevalent transmission mode in case of more than 4 complete air changes per hour, which seems in line with previous works [17]. Therefore, since the arena is an open-air environment, the influence of the ventilation can be reasonably excluded.

3. RESULTS AND DISCUSSION

Figure 2 shows *dI* depending on the number of *initial people* attending the event, according to a 2D kernel density (0-1 scale) visualization. This 2D kernel density value expresses the probability of having a specific *dI* value depending on the *initial people* value. As expected, the number of people attending the event impacts *dI* in a direct manner. For instance, the probability of maintaining *dI*<5% decreases when the *initial number of people* increases: up to 700 people, 90% of probability; between 700 and 850 people (actual maximum capability), 80% of probability; over 950 people, 70% of probability.

Figure 3 shows the 2D kernel density of *dI* vs. the initial infectors percentage. The comparison of Figure 2 and Figure 3 demonstrates that the initial infectors percentage seems to assume a more important rule to reduce

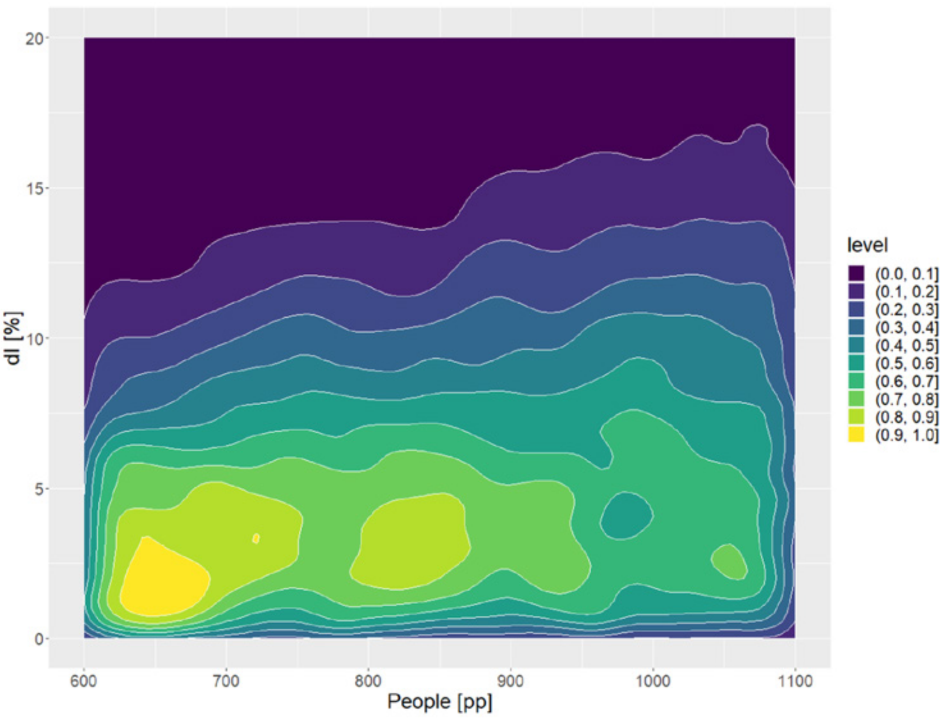

Fig. 2. *dI versus the number of initial people: color represents the 2D kernel "density" (adjusted density on a scale of 0-1).*

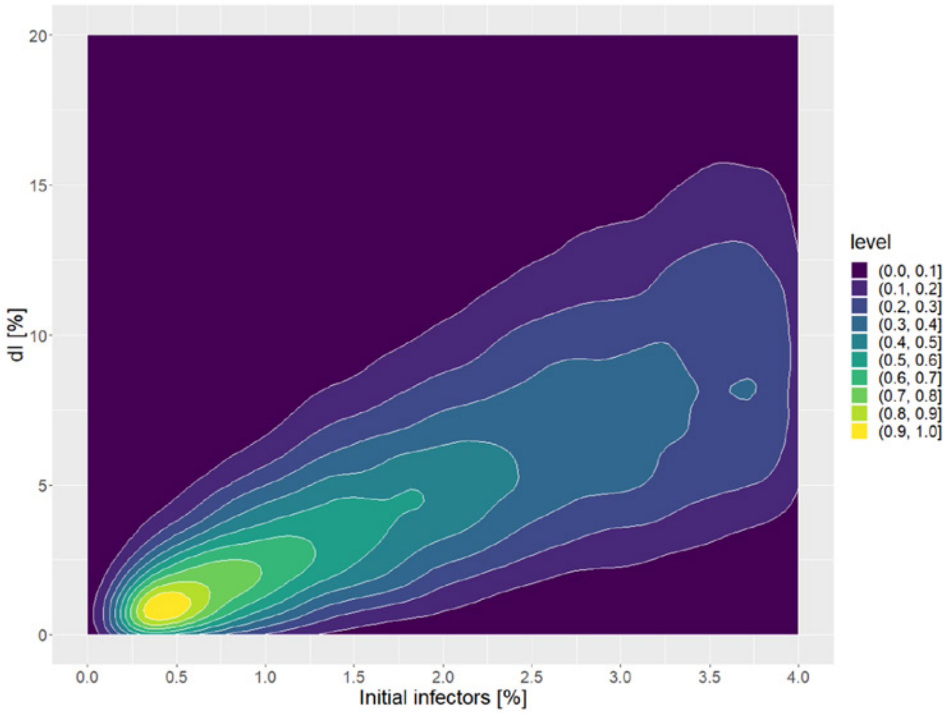

Fig. 3. *dI versus the initial infector percentage: color represents the 2D kernel "density" (adjusted density on a scale of 0-1).*

contagion spreading. Maintaining the number of initial infected people <0.5% (see Section 2.3) gives a 90% probability of limiting *dI*<5% (Fig. 3).

Figure 4 shows a 2D kernel density of *dI* depending on the percentage of people allowed to move during each pause to reach "*other attraction areas*" (e.g., bar, toilets). The probability of maintaining *dI*<5% ranges from 60 to 80%. The general *dI* trend is close to the one due to the *initial people* values (Fig. 2), as shown by the shape and width of the 2D kernel density areas.

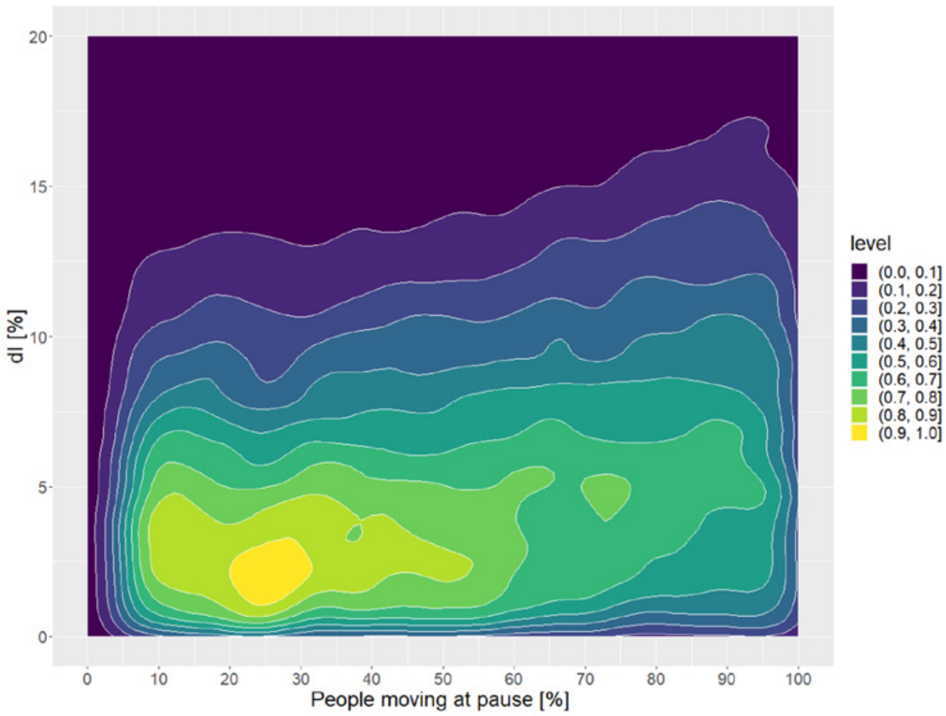

Fig. 4. *dI versus the percentage of people moving at the pauses (moving-at-pause): color represents the 2D kernel "density" (adjusted density on a scale of 0-1).*

Figure 5 shows the significant influence of the *queue time* (15 and 30 minutes) on the probability of a contagion spreading, depending on the *initial people*. For queue time equal to 15 minutes, the probability of having *dI*<5% always varies between 80% (lower *initial people*) and 60% (*initial people* tending to 1100 pp). On the contrary, when the *queue time* increases, the probability decreases to 50% for more *initial people*.

Although the queue is organized by dividing people into different groups depending on entrance gates/"waiting areas" and assigned sectors, the *queue time* appears to be the most critical aspect to control due to the possible interactions between people while waiting. This result is mainly confirmed by data for extreme *initial people* values, which can amplify these contagion-spreading interactions.

Let's assume a marginal probability of 10% in *dI* values (moving to dark blue areas in Fig. 5) to point out a contagion spreading threshold with lower confidence but not negligible. When *initial people* tend to 1100pp, *dI* tends to 1) 15%, for queue time is equal to 15 minutes; 2) 20%, for queue time equal to 30 minutes. The same 10% probability always describes critical *dI* values for maximum parameters conditions that are lower than those of the queue time-related impact:

- for maximum values of *initial people* (Fig. 2) and initial infector percentage (Fig. 3), *dI* up to about 16%, regardless of the other measures;
- for maximum values of *moving-at-pause* (Fig. 5) implies *dI* up to about 18%.

The combined increase of the percentage of *moving-at-pause* and the *queue time* could hence lead to severe risk levels. Figure 6-A compares the combination trends for *queue time* equal to 15 minutes (left) and 30 minutes (right). *dI<5%* can be achieved only if limited movement is allowed. When considering values of *moving-at-pause* <60%, the probability of having *dI>5%* increases by about 10 to 20% when *queue time* is equal to 30 minutes (density of about 0.7) with respect to 15 minutes (density of about 0.5), as shown by the 2D kernel "density" representation. The free movement towards different Sferisterio areas is the second critical risk factor, thus underlining how access, queue, and movement control should be strictly ensured. Such results can allow identifying the thresholds for the related safety protocol strategies to be guaranteed by the Sferisterio staff members.

Figure 6-B represents the influence of contextual factors at the national level in terms of *vaccinated/recovered*

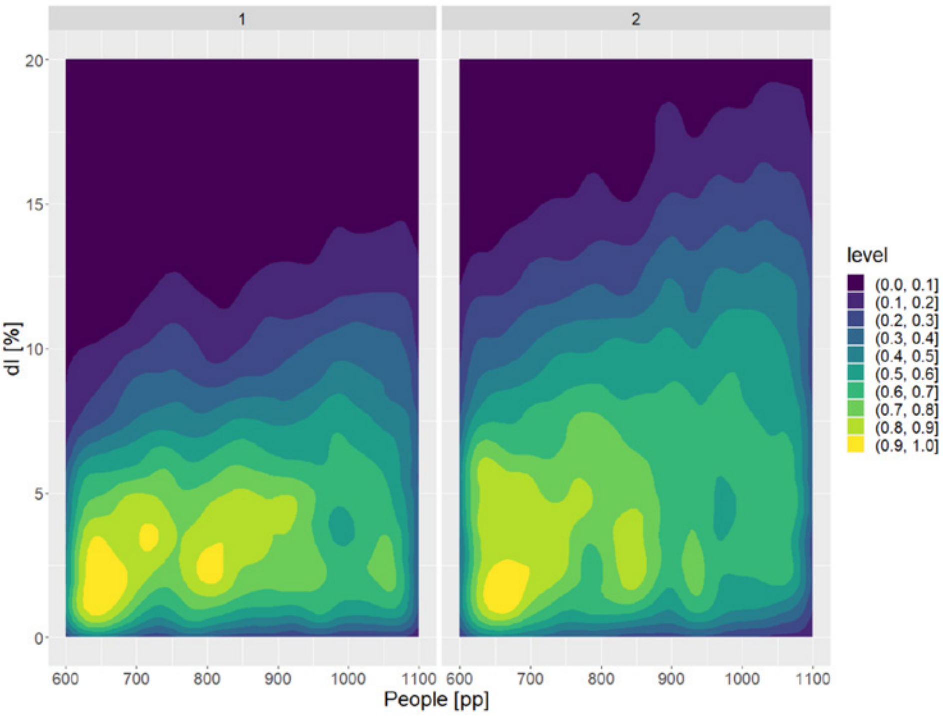

Fig. 5. *dI % versus number of initial people, depending on the queue time: 1-15 minutes; 2-30 minutes. Color represents the 2D kernel "density" (adjusted density on a scale of 0-1).*

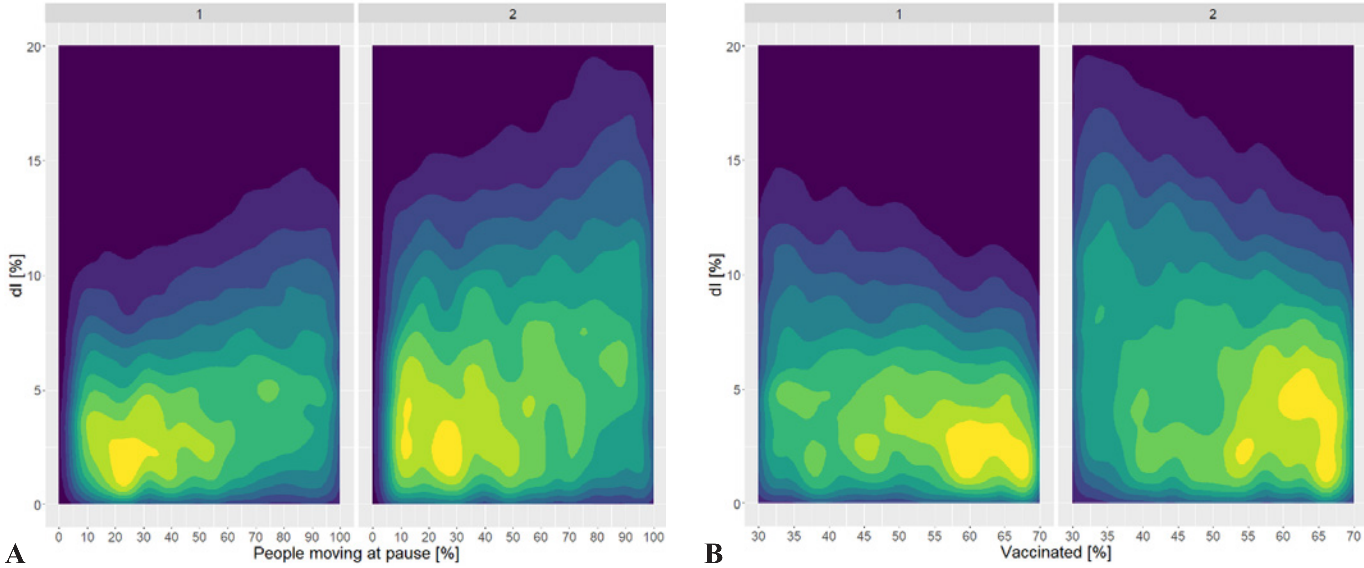

Fig. 6. *dI versus: A- moving-at-pause; B- vaccinated/recovered percentage. Values are offered depending on the queue time: 1-15 minutes; 2-30 minutes. Color represents the 2D kernel "density" (adjusted density on a scale of 0-1 on the right).*

percentage, thus also considering the vaccine campaign advancement by distinguishing *queue time* trends of 15 minutes (left) and 30 minutes (right). As for the *moving-at-pause* trend, it is possible to observe the strong influence of the *queue time* on the contagion spreading, especially with a limited vaccinated/recovered population (e.g., for values of 40% and *queue time* of 30 minutes, maximum *dI* values for the residual probability of 10% can be equal to about 20%). Although the protocol cannot manage this factor because it mainly depends on the national context and the vaccination campaign, these results underline the importance of widespread vaccination of the population to restart cultural events safely, adapting the current regulation-based measures [9].

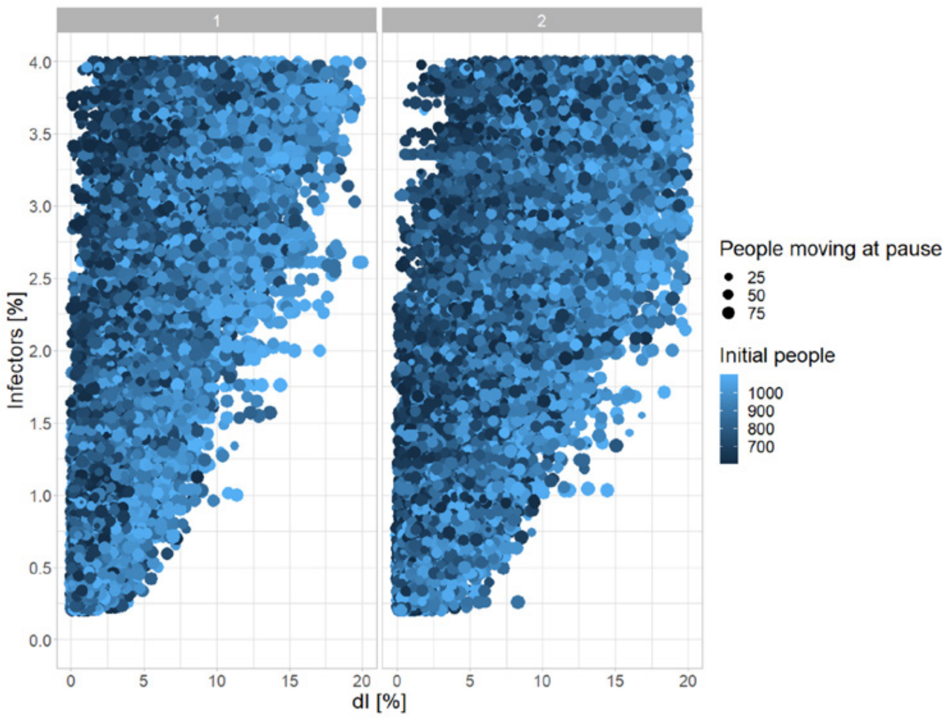

Fig. 7. *Scatterplot of dI versus initial infectors percentage depending on the queue time: 1-15 minutes; 2-30 minutes. The point size represents the percentage of people moving during the pauses (divided into 3 groups, up to the percentage values in the legend), and the color represents the number of initial people.*

Figure 7 resumes the combined effects on dI due to init-infectors-percentage, depending on queue time (left: 15 minutes, right: 30 minutes), moving-at-pause, and initial people since these input parameters conditions can be effectively managed by the safety protocol measures.

Results related to combined conditions confirm the outputs of each parameter condition. When the number of *initial people* tends to maximum values and *moving-at-pause* is over 75%, *dI* sensibly shifts (+5-10%) towards higher values while moving from 15 to 30 minutes of *queue time*. Limiting the *init-infectors-percentage* certainly appears to be a significant measure since it can reduce the overall scattering of the *dI* range and so the possibility that critical interactions among infectors and susceptible people can appear in the Sferisterio. In fact, *dI* ranges from about 0% to 5% for *init-infectors-percentage* tending to 0.2%, while it ranges from about 2% to 20% for *init-infectors-percentage* tending to 4%.

3.1. INSIGHTS ON THE EFFECTIVENESS OF THE COMBINED MEASURES

Table 3 resumes the effectiveness of the alone and combined measures in the Sferisterio, showing the median value of *dI* and distinguishing two different intervals of related input parameters. Interval 1 in Table 3 traces the more limiting but more powerful conditions. Table 3 also resumes some possible proposals on improving each measure's effectiveness to move towards Interval 1 results. Moreover, the last column of Table 3 calculates the difference between *dI* in Interval 1 and Interval 2 conditions. This approach allows for obtaining simple but reliable feedback from the decision-makers.

The *init-infector-percentage* control is the most useful measure to minimize the median *dI* value. Actions aimed at body temperature control should be supported by rapid tests (e.g., swabs relating to "green pass") to be performed before the event access (e.g., the day before) due to the possible presence of a significant number of asymptomatic people. As remarked by experiments performed on concerts, e.g., RESTART-19 [7, 9], such rapid tests seem to represent a compensative measure to support the increase of maximum occupants' capacity.

Considering each of the other measures by themselves, the second measure in importance order is the *queue time* control, which implies the limitation of free interactions between occupants while standing up in the "*waiting areas*", thus confirming previous works' results [9].

Limiting the maximum number of allowed people seems to have a smaller significance with respect to the possibility that the occupants can move during pauses. According to Table 3, the *dI* in Interval 2 for *moving-at-pause* is higher than that of *initial people*, while the difference of *dI* (interval 1 – interval 2) is almost the same. During the event, people's physical distancing can be

Input parameter	**Proposal on how to improve the effectiveness of the related safety protocol measure**	***dI* (input parameter range)**		**difference of dI (interval 1 – interval 2)**
		Interval 1	**Interval 2**	
Init-infector-percentage	supporting body temperature control with rapid test results	2.62 (0- 2%)	8.08 (2%-4%)	-5,46
Q - Queue time	staff members' control, possibility of evenly spaced access (e.g. event ticket with access time), and exit by the audience	4.95 (15 min)	6.67 (30 min)	-1,72
M - Moving-at-pause	staff members' control, higher level of internal division of common spaces/toilets by sectors	5.00 (≤50%)	6.55 (>50%)	-1,55
I - Initial people	n.a.	4.72 (600-750)	6.28 (750-1100)	-1,56
Combined (Q,M,I) depending on the init-infector-percentage	see above	3.59 (see above)	8.09 (see above)	-4,5

Tab. 3. *Impact of each safety protocol measure and their combination in terms of the median value of dI. For each measure, the input parameter in the simulation and the possible proposal on how to improve each measure's effectiveness are offered (n.a.= no additional details because of a simple measure to be implemented).*

ensured by the seats fixed at the ground, thus limiting the interaction between them, especially in case of higher building capacity. Thus, interactions at the pauses (when physical distancing cannot be ensured) become critical.

The combination of these measures amplifies the effects on *dI*, as shown by the last row in Table 3. The number of *initial people* has an obvious multiplier effect, but controlling infectors' presence, access time, and movement at the pauses reduces the spreading of contagion.

4. CONCLUSIONS

Managing the safety of people in cultural buildings during pandemics means identifying and deploying effective measures to mitigate contagion risks while ensuring the proper fruition of the cultural facilities. Cultural heritage is a critical scenario in this sense, in view of its peculiar management and physical (including the layout of attraction spaces) features. Measures should be better tailored depending on these specificities, so approaches to support decision-makers in evaluating their effectiveness are also needed to better prepare for future critical conditions.

To this end, this work provides a methodology to identify, organize and evaluate combined measures to manage people's flow (access, movement, queue) depending on boundary conditions at the overall (building capacity) and individual levels (face mask; vaccinated/recovered; "green pass"). The attention is focused on historical theatres and arenas as significant scenarios.

The effectiveness evaluation is performed by using a simulation model that jointly represents the virus spreading and the people's flow, and that allows the calculation of a risk index expressing the probability that the contagion spreads during an event hosted in cultural buildings. This risk index calculates the newly infected people with respect to initially susceptible people by using a probabilistic simulation tool based on a multi-agent approach.

A case study application, the Arena Sferisterio (Macerata, Itay), one of the most famous Italian historical open-air arenas hosting operas during the summer, is chosen to evaluate the effectiveness of the safety protocol introduced to restart the cultural activity of the arena. According to the results of more than 300,000 simulated events, limiting the maximum number of allowed people in the arena has little significance, despite the rules adopted in Italy and other countries. The number of people can multiply effects, but a higher impact on the contagion limitation can be achieved through the control of infectors' access as well as of the interactions between people during the access/exit queues and the pauses between acts. However, it is worth noticing that results could be influenced by the behavioral modeling assumptions of users, including physical distancing (actually based on 1m distance protocols). To this end, the next works could test the effect of other minimum physical distancing values on the contagion spreading and include a random model of preferred distancing. In this sense, the model could also be varied to assume other simulation steps that would represent different dynamics of crowd and fruition modes, especially if moving towards a finer granular representation of the simulation time [8].

In conclusion, considering the economic impact of measures, the approach can help to find the optimal solution combining safety, practical and economic aspects in the specific situation. This approach can be easily applied or adapted to other historical arenas and theatres, to other historical buildings characterized by possible overcrowding conditions, and to other future critical conditions due to pandemics in intense crowd spaces (by varying the virus transmission rules, if similar to the ones assumed to this model).

Acknowledgment

The authors would like to thank the Arena Sferisterio Association and its President, Luciano Messi, for the availability of the material used in this work.

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ON SITE DATA GATHERING BY A COLLABORATIVE NETWORK TO ASSESS DURABILITY, RELIABILITY, SERVICE LIFE, AND MAINTENANCE PERFORMANCE

TEMA
Technologies
Engineering
Materials
Architecture
e-ISSN 2421-4574
Vol. 9, No. 2 - (2023)

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DOI: 10.30682/tema090011

Abstract

Any maintenance service could benefit from automatic and intelligent fault detection and diagnostics (intelligent AFDDs) to monitor building systems. Here, a system for FCUs (fan coils) is tailor-made to take full advantage of Collaborative Networking 4.0. Big data is collected by interconnected Internet of Things sensors and transferred to the cloud after local intelligence has identified which data is really significant for cloud transmission: to avoid network overload, anomaly detection and fault diagnostics are entrusted to local intelligence, cloud sending only out-of-range data and a very low-frequency sampling for standard data.

By feeding the network with only the relevant processed data and sharing the information at each level, the resulting AFDD system becomes a collaborative network capable of extending the diagnostic process to the entire building, making it accessible through integration into an appropriate BIM model.

Real-time data monitoring is vital to managing the facility maintenance service sustainably, but collecting big data on a wide scale enables other possibilities. For example, component service life rating (to support a procurement service) and maintenance effectiveness by comparing the after-service values with the data recorded at the component's acceptance.

Keywords

BIM modelling, Big data, Automated Fault Diagnostic, Fan Coil Unit, Smart sensors.

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1. INTRODUCTION

Nowadays, new possibilities in terms of cognitive and decision-making processes for building facilities management are supported by the latest technological advances as well as the development of emerging paradigms such as collaborative networks 4.0 (CN 4.0), Internet of Things (IoT) platforms and Big Data management [1].

In particular, facility maintenance service (FMS) could benefit from an integrated approach between facility managers (FM) and decision-makers (DM), provided that this type of method is based on data collection and immediate integration and interoperability.

IoT platforms allow FMs, FMSs and facility managers to share the same open IoT environment that enables the convergence of various technologies (building management systems, sensors and connectivity), resulting in more sustainable building management [2]. Furthermore, the adoption of IoT enables FMS, DM and FM operators to recognise and apply new state-of-the-art techniques. Indeed, the idea of an IoT platform is growing rapidly, as it can provide a single, integrated framework for data management, provided that operators, and the FMS in particular, accept and collaborate on the concept of centralising data.

For instance, according to Katipamula, S. & Brambley [3], poorly managed and degraded machinery wastes between 15% and 30% of the electricity used in commercial building systems, and we can suppose a similar impact in the other kinds of buildings. However, most of this waste could be avoided if state-based automated maintenance requests were adopted on a large scale. Most of the research on AFDD is focused on heating, ventilation and air conditioning (HVAC) systems or, more specifically, air handling units (AHU) and fan coil units of buildings. Over the last few decades, extensive study in the field of AFDD has been undertaken to classify various techniques that are appropriate for building HVAC and AHU systems by authors of [4–6], considering physical redundancy, heuristics or statistical bands, including the control chart approach, pattern recognition techniques, and innovation-based methods or hypothesis testing on physical models to detect faults. For fault isolation, the authors use information flow diagrams, expert systems, semantic networks, artificial neural networks, parameter estimation methods, and various AFDD software and hardware that have been produced as study results. However, assessing the reliability of various AFDD systems is a challenging task, and developing a more reliable AFDD system for building facility management involves professionals and practitioners from different areas working in collaboration [7].

Basically, AFDD is intended to help with facility maintenance service (FMS). So far, we have not had any significant spillover into the design process or procurement phase. Expected Service Life data in real working conditions could actively support the decisional process, e.g., which components are the best choice.

This paper illustrates the design of a collaborative network AFDD system intended for building facility maintenance, its preliminary testing on a fan-coil, and the potential long-term extension of the use of the acquired data in statistical terms to feed a possible national database on the reliability of individual components in specific usage situations. The paper is organised as follows: after introduction, faults detection methodology on local sensor node is introduced, and then the IoT & BIM-based fault diagnostic approach is outlined, and a possible statistic fallout towards a national ESL rating and maintenance rating are summarised. The collected data from sensors are integrated into the BIM model and linked in real-time to a dashboard for trend visualisation. The BIM model is used to visualise the location of the element and get an overview of the building; in the future, it could also be used to verify the ESL history of any specific component or technology choice, checking the effectiveness of procurement after the fact, and the efficacy and effectiveness of the maintenance intervention.

2. WHAT FOR SMART & DISTRIBUTED FAULT DETECTION?

The research first focused on the need for an effective failure and performance degradation detection system.

Two strategies were possible.

The first, typical of building management sensing, would have employed sensors specific to indoor environmental control to monitor the evolution of environmental parameters, whose deviation from design values would have identified the fault condition or, rather, the effect of the fault condition on the environmental system.

The second, typical of machine control in industry, would have required dedicated sensing to monitor the component behavior (FCU), with the advantage of having an AFDD system embedded in the component and autonomous from the building. In addition, the system can directly detect the actual fault condition on the component and not its impact on the internal environmental parameters.

In this way, the influence of environmental conditions is all but eliminated, and detected anomaly conditions (e.g., the FC does not heat) do not interfere with any management anomaly conditions (e.g., insufficient room temperature for FC off or open windows).

The second option has been set as a goal to design the AFDD system.

Facilities' elements must be equipped with sensors to detect faults in building systems automatically. One of the most common components in building structures is the fan coil unit (FCU), which is part of the heating, ven-

Sensor node	Sensor name	Location and variable names on the fan coil	Max. and Min. Measuring ranges	Accuracy	Units
RPIZCT4V3T2 (Raspberry Pi Zero W and Arduino MCU)	Current (SCT-013-000)	i1, i2,i3	0-100A	±3	Ampere(A)
	Voltage (77DE-06-09)	v1,v2,v3	0-230 (50Hz)	±5	Volt(V)
	Temperature DS18B20	T1,T2,T3,T4	0°– 90°C	±0.5	Celsius(C)
	Temperature RTD(PT100)	T5	-200° to 550°C	±0.05	Celsius(C)

Tab. 1. *Implemented sensor board and sensors specifications.*

tilation and air conditioning (HVAC) system and uses a water coil and fan to heat or cool rooms. A fan coil unit with motor model FC83M - 2014/1 in 3-speed version (high, medium and low) was used as a case study. At maximum speed, the FC motor runs at 1100 revolutions per minute (RPM) counterclockwise. In addition, the FC is equipped with a single cooling/heating coil and filters to protect the blower and coil from dust clogging.

Specific sensors are required to develop a sensor-based fan coil monitoring for an automatic fault detection system. The measuring parameters and measuring ranges of the sensors vary depending on the internal components of the fan coil. Considering these features, specific sensors and sensor boards that host all sensors are selected for this project and described in Table 1.

In addition, sensor sampling rates are important so as not to lose key features, while the storage of incoming data in the database is tailored to avoid overloading the system by reiterating stable and redundant parameters. Configured data acquisition sampling frequencies of each sensor are listed in Table 2.

Sensors	Frequency	Sensor allocation
T1	180"	water in
T2	180"	water out
T3	180"	air intake
T4	180"	air outlet
T5	10"	motor case
v1, v2, v3	0,1"	motor voltage (speed I, II, III)
i1, i2, i3	0,05" / 3"	Motor currents (speed I, II, III)

Tab. 2. *Sampling frequencies of sensors.*

T1, T2 and T4 sensors (see Fig. 1) measure temperature in the range between 0 ÷ 90°C. T3 is applied to measure the air temperature in the range 0 ÷ 50°C and T5 is devoted to monitoring the motor case temperature in the range between 0° to 200°C. Voltage and current sensors are connected to the fan coil's power line to monitor the motor's behaviour at each of the three speeds. The RPIZCT4V3T2 board is programmed so that coming data from sensors are sorted according to the importance of the data and locally stored or delivered to the cloud database.

The RPIZCT4V3T2 board is equipped with an Arduino microcontroller (MCU) and connected to the temperature sensors. Current and voltage sensors are connected to the MCU through an amplifier and analog-to-digital converter (ADC). Additionally, on the RPIZCT4V3T2 board, MCU is connected to the Raspberry Pi (Rpi) Zero W via general-purpose input-output (GPIO) pins. RPi Zero W is a single-board computer with an integrated Wi-Fi module. The board is programmed to collect raw data from sensors, and then the MCU processes the necessary values and sends the final computation to the Rpi Zero W using the Universal Asynchronous Receiver-Transmitter (UART) serial port.

A Node-Red is installed on the Rpi Zero W, providing real-time access to the sensors' data through serial protocols and displaying them on local dashboards. MQTT flow on the Rpi Zero W is intended to send (Publishing) a message to the cloud server, which will act as a receiver (Subscriber) using Message Queue Telemetry Transport

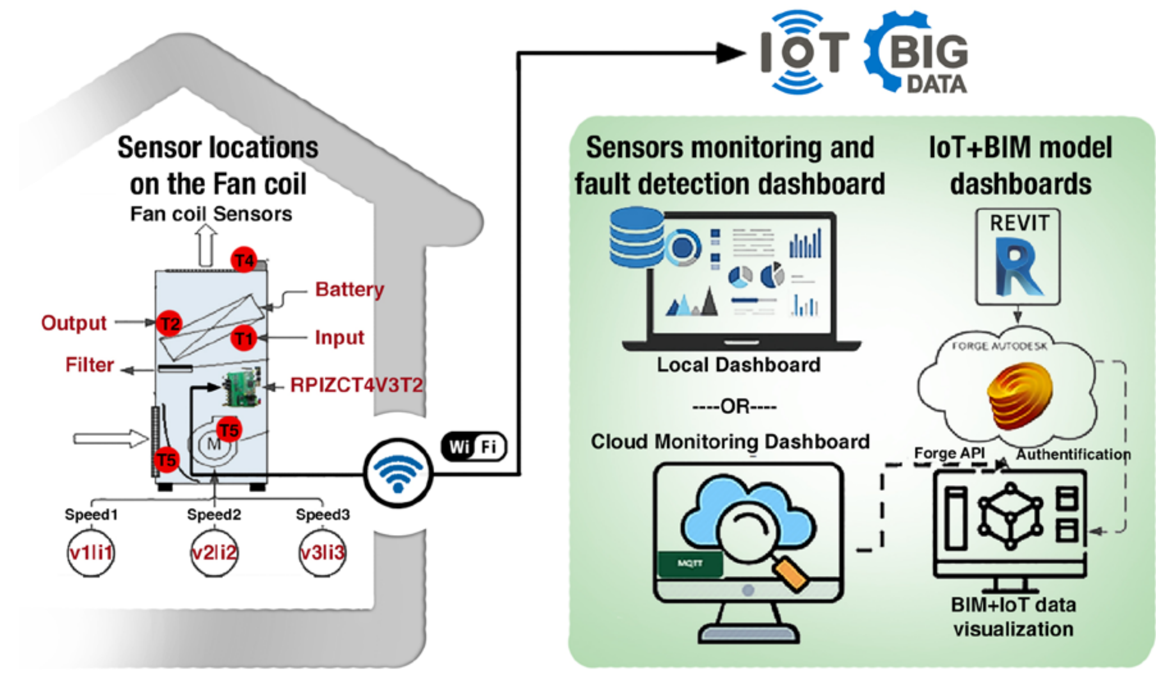

Fig. 1. *From distributed local smart sensors to cloud monitoring and BIM 3D model integrated dashboard.*

(MQTT) protocol, an OASIS standard messaging protocol for IoT (so light that is ideal for connecting remote devices with a small code footprint and minimal network bandwidth [8]).

Moreover, DNSmasq free software is installed to use the Rpi Zero W as a router, providing a communication bridge between internal sensors and external components by protocol (IP) addresses.

MySQL database, PHP interpreter, and Apache web server are utilised to store sensor data locally on the Rpi Zero W. The Connection diagram between components and sensors of the local fault detection system based on the RPIZCT4V3T2 board is summarised in Fig. 2.

While running the system, all sensors start to collect data from the FCU, and the accounted end-user can access the Rpi Zero W using the static IP address of the board. On the board, Node-Red and MQTT provide access to the external devices. Moreover, MySQL database flow is installed and configured to the PHP interpreter to store collected data locally using the Apache web server. By powering the Rpi Zero W, MySQL gets the IP address, opens the configured port, and waits for Node-Red to send data that must be collected and allocated to the linked tables. Collected MySQL data can be connected to the BIM using a data-driven approach or directly using Forge nodes on the Node-Red.

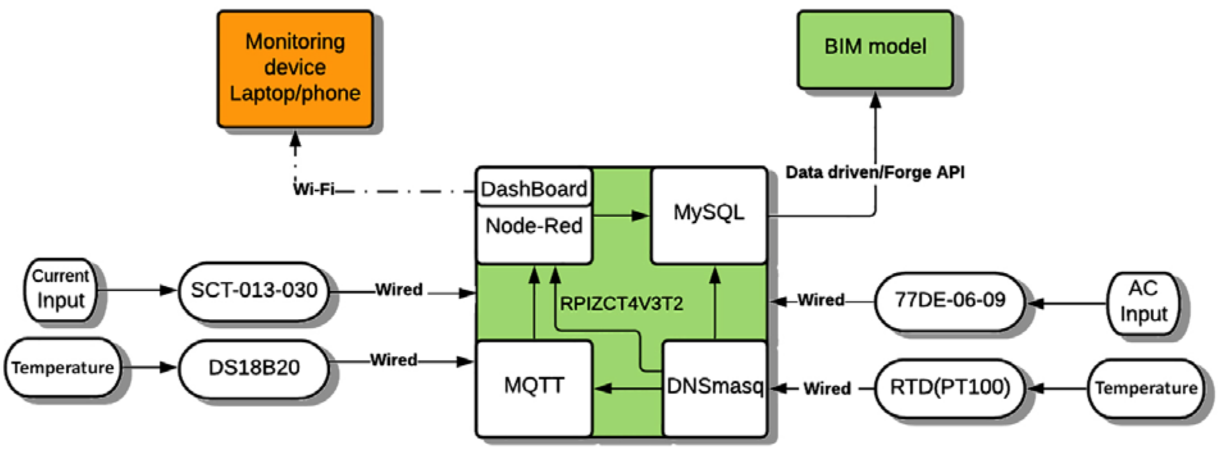

Fig. 2. *Anomalies detection network: local and cloud monitoring [9].*

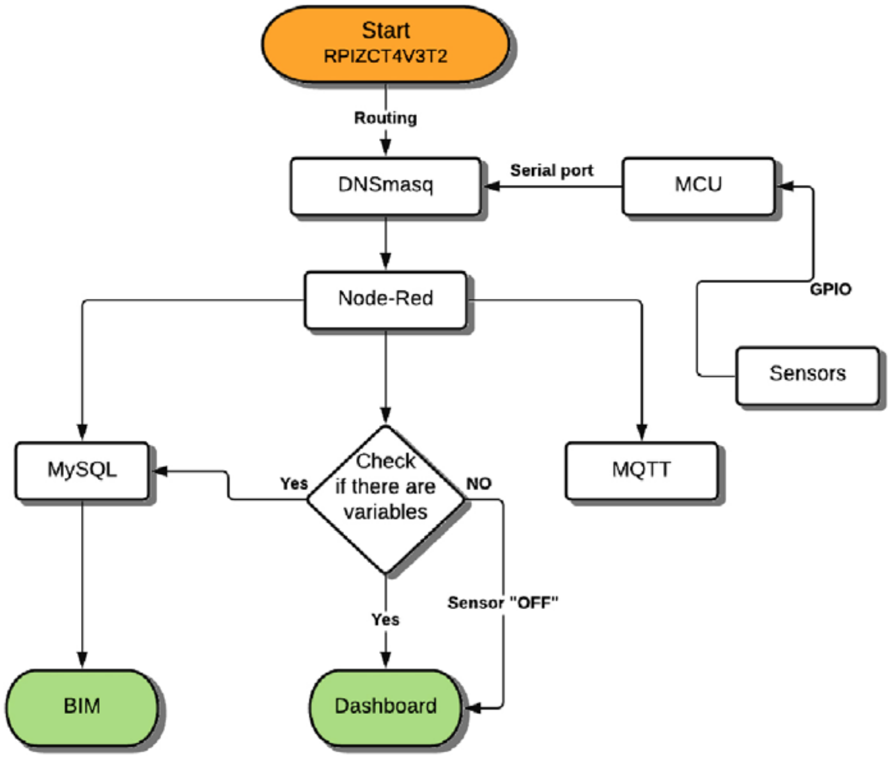

Fig. 3. *Functional diagram of the data acquisition system [9].*

The research work developed customised add-ons on the Visual Studio Code for Autodesk Forge Viewer so that collected IoT data and the 3D building model of Revit can be visualised together on the Forge Viewer using URL and PORT provided by Forge API. The fault detection system connectivity diagram with sensors and related components is shown in Fig 3.

FCU condition monitoring dashboard was realised on the Rpi Zero W Node-Red graphical user interface (GUI). Node red flows were created to develop a fan-coil

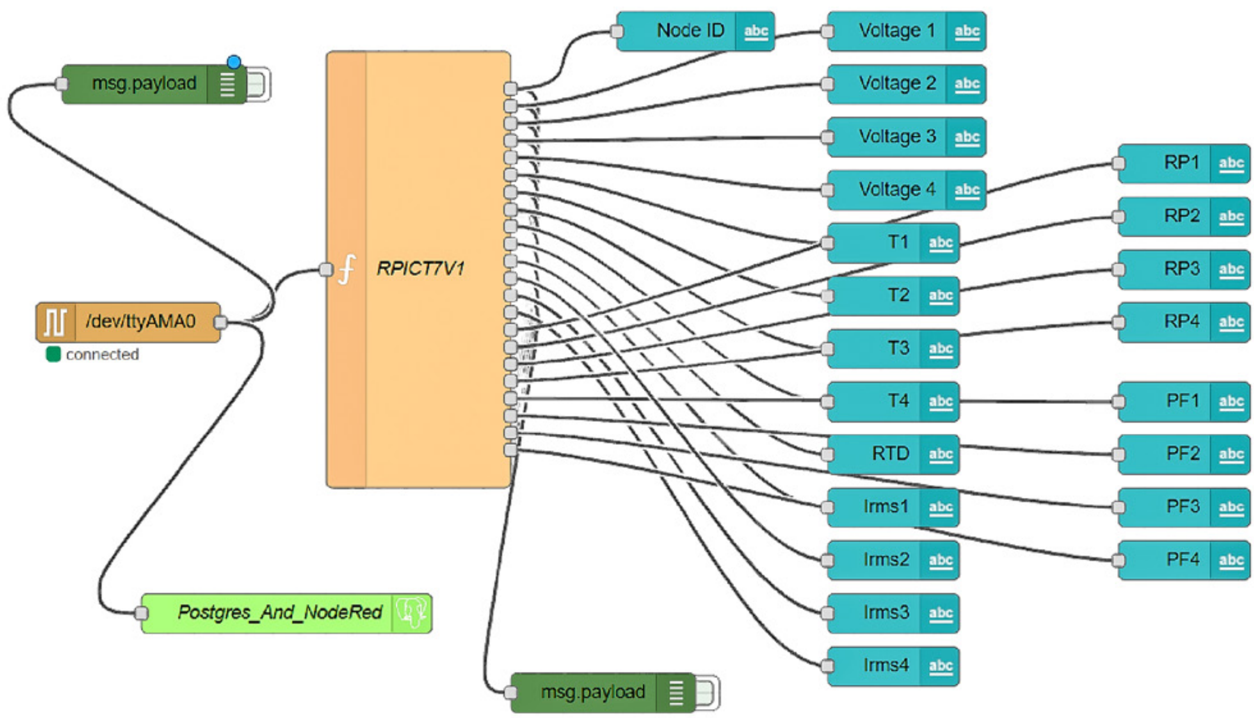

Fig. 4. *Node-red Fan coil monitoring flow [9].*

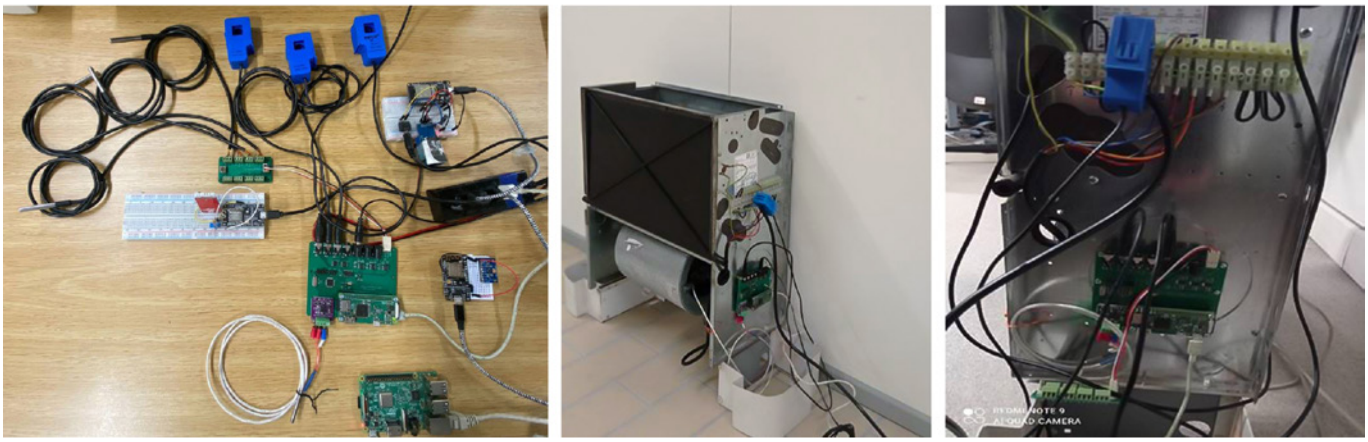

Fig. 5. *(a) sensoring system; (b) sensors equipped FCU; (c) Raspberry board and Arduino microcontroller.*

dashboard. By using the serial port node, sensors' data coming to the MCU are registered as a string. Special functions on the Node-Red flow were developed to split and convert the data from the serial port into the dashboard. Fig. 4 shows the fan coil monitoring flow on the Node-red.

3. FAULT DIAGNOSTIC THROUGH IOT

3.1. RELIABILITY IN FAULT MANAGEMENT

Failure or abnormal operation of an FC unit may be due to external causes (e.g., lack of or poor water flow, or water temperature insufficient to cover thermal loads; supply voltage anomalies, etc.) or internal causes (e.g., clogged air passages, slowed or blocked motor, etc.).

Automatic and unambiguous fault detection is a necessary condition for reliable fault management, subsequent corrective actions, and consequent statistical data collection for quality assessment. Otherwise, there would be false alarms and idle interventions that would likely turn off the system and, more importantly, run against the sustainability of the maintenance-by-repair vs. maintenance-by-replacement model.

The situation is monitored through a set of sensors. Particularly, five temperature sensors are available (T1 for supply water temperature, T2 for return water temperature, T3 for inlet air temperature, T4 for outlet air temperature, T5 for motor casing temperature), three voltage sensors are available (v1 for power supply voltage at motor speed 1, v2 for power supply voltage at motor speed 2, v3 power supply voltage at motor speed 3), and three current sensors are available (i1 for current absorbed by the motor at speed 1, i2 for current absorbed by the motor at speed 2, i3 current absorbed by the motor at speed 3). Each sensor was selected according to the accuracy class of the measurement, considering its sensitivity and accuracy, as shown in Table 1.

3.2. DIGITAL TWIN'S ID

In an ideal situation, as soon as the FCU pass the acceptance test, the sensors provide the control system with data of the original situation, that is, a kind of ID card of the digital twin under those particular operating conditions. The FM service can easily update this identity card if something has changed (components, operating conditions, facility update, etc.), e.g., similar to what happens whenever tires are changed and a tire monitoring system is involved, with the permission of the FM supervisor (and the change recorded in the database).

Once the ID card for that FCU is acquired, its values are continuously compared with those detected by the sensors in real-time and their drifts are processed to detect anomalies and faults.

3.3. WHAT'S WRONG?

An FCU that works appropriately meets the heat load on time and operates without harassing vibrations.

A temperature difference between the water inlet and outlet must be evaluated in relation to the temperature of the air entering the coil (room air). If this is in the normal range, the water-side thermal drop should also be comparable to the original one: smaller thermal gaps indicate decreased exchange capacity of the coil (low air flow or scaled coil); larger thermal gaps indicate decreased water circulation.

This excluded, a temperature difference between inlet and outlet air that is significantly greater than the original one, indicating reduced airflow, either due to filter clogging or poor fan performance. The latter case, in turn, can be verified by examining the trend of the steady-speed current and the temperature of the motor, depending on the operating speed: if the motor temperature (single-phase with the capacitor permanently on) continues to rise, the capacitor is not working and needs to be replaced; if the steady-speed current is higher than the original one, the fan encounters abnormal resistance, for example, caused by bearing wear or presence of foreign objects in the blower.

But the start-up phase can also provide interesting data: first, checking that the voltage is correct and resets to zero during stops (eddy current detection) and, most importantly, that the start-up phase does not extend beyond the appropriate time mapped in the ID card: in the latter case, this would be excessive friction or capacitor decay. With proper reading accuracy, impeller imbalances can also be detected by estimating the higher current required in the half-turn in which the heavier part of the rotating mass is moved upward and comparing it with the lower current required when the same unbalanced mass “falls” downward, dragging the impeller’s rotation with it.

So, to diagnose the faults, the procedure reported in Fig. 6 in the form of a BPMN diagram is followed [10].

4. REPRODUCING THE NETWORK OF SENSORS ON THE BIM

The sensor board memory is insufficient for Big Data storage: to avoid the overloading of the local memory, only daily maximum and minimum variables are permanently recorded and sent to the cloud and BIM server. The fault detection diagram described in the previous section is integrated into the system.

If any sensor has out-of-range values, the detecting system is designed to send real-time alarm signals or notifications to the accounted end-users, facility managers or maintenance services, depending on the kind of anomaly. Conditional data of the FCU has been transported to the BIM model of the building to support facility managers. This implementation was tested in a section of the Department of Structural, Building and Geotechnical Engineering (DISEG) at Politecnico di Torino (Italy). The local CPU and its set of sensors were installed simultaneously on one fan-coil unit to test whether their operation and calibration were replicable and reliable. Fault detection was almost always adequately sensitive, except for the current sensors used, which proved to require very accurate and specific calibrations for each motor. For this reason, the testing of the detection system is still ongoing and being improved. To visualise conditional data of the FCU on the 3D model of the building, sensors’ data are implemented to the BIM using the Forge Reference Application and two NPM modules (React UI components and Client-Server Data-Module-Components). The final custom application, IoT and BIM, developed on the JavaScript and Forge Platform, is shown in Fig. 8. The application supports a heatmap function, which changes the color of the 3D model of the fan coil according to the data coming from the sensor board. The color is “green” if the fan coil is ok, “red” if the motor is overheated, and “blue” if the fan coil is in poor working condition.

5. BIG DATA GATHERING: A PERSPECTIVE FOR LIFE CYCLE ASSESSMENT

5.1. DIGITAL TWINS’ BIG DATA & MAINTENANCE SCHEDULING

The availability of big data handled through BIM (methodological) modelling is useful for improving maintenance strategies and activities. In the building process, the management phase is in some respects replicative of the building design process (prototyping and one-to-one relationships). It exploits the continuous monitoring of the degree to which the behaviour of components matches their digital twins in order to plan maintenance services, all taking into account the data for that specific

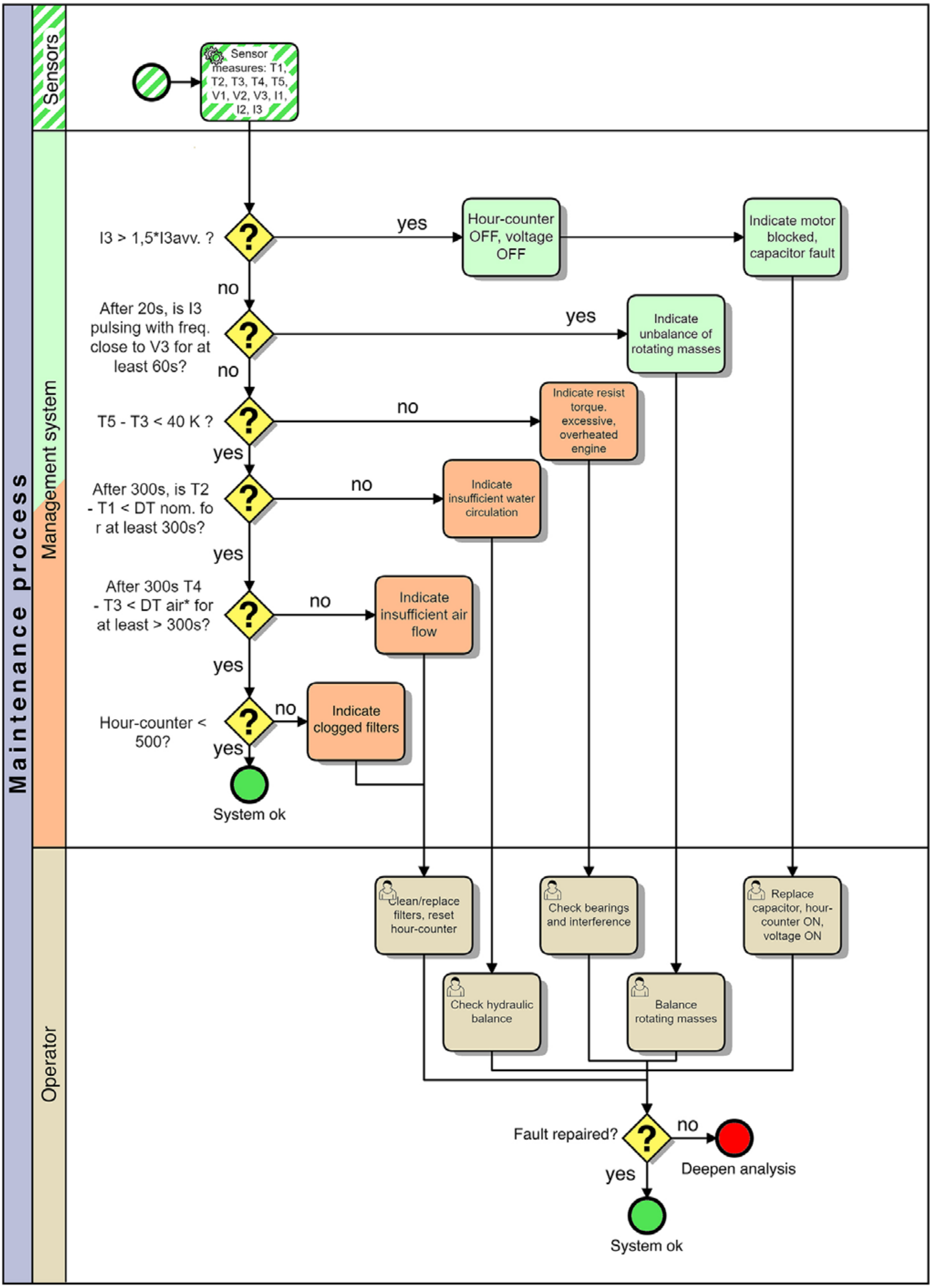

Fig. 6. *Anomalies detection & maintenance controls flow chart.*

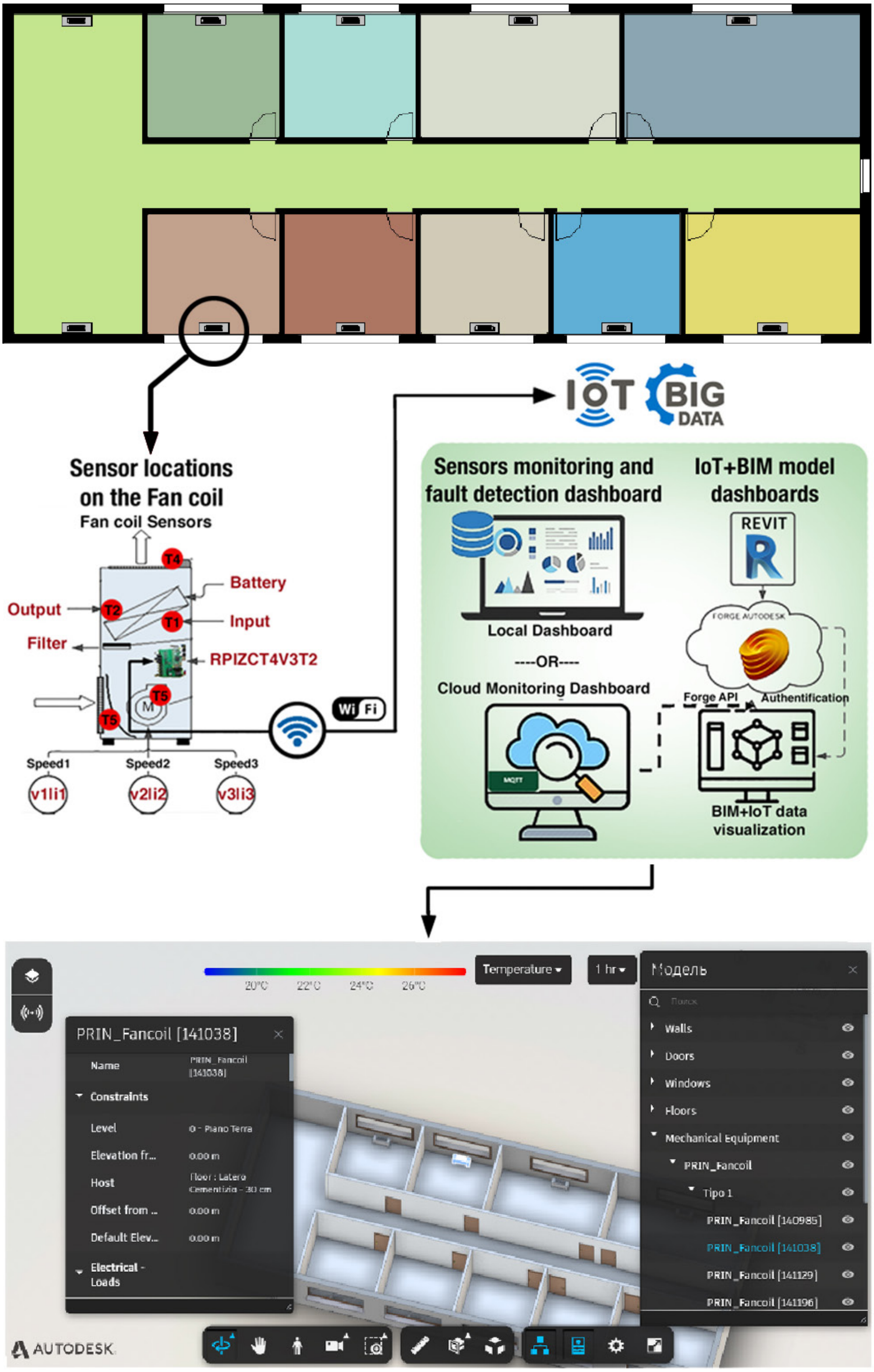

Fig. 7. *Illustrative application of the BIM model with real-time FCUs monitoring to a wing of the DISEG (Politecnico di Torino).*

situation in that particular building. That increases the sustainability of building components because it enhances their service lifespan by predictive maintenance, thus assisting both active (those who do it) and passive (those who suffer it) facility management. Better maintenance planning results in reduced wait for repair, the impact of outages, and idle visits (during periods of pandemic also associated with unwanted people-to-people contacts and quarantine restrictions).

5.2. DIGITAL BROTHERS' BIG DATA & PRODUCT PROCUREMENT

In the authors' opinion, collected data that now remain confined to the building or the appointed maintainer can instead open up to an innovative, integrated, holistic procurement slant, at least on a national market level, that will drive a shift in the building management approach.

As a matter of fact, if buildings remain for the vast majority prototypes of themselves, they integrate a significant number of components from icastic serial industrial production, e.g., HVAC elements or lighting systems. Moreover, precisely, these components have a shorter service life than the building, and their performance decay to the point of failure determines a good deal of corrective maintenance, often inclined to replacement rather than on-site repair.

In the design process, there is a great deal of need to evaluate the service life of products, as the results will depend on both material properties and the environment in which the material is working. In the procurement process, the need is even greater: a sound working strategy towards this goal could be based on a good knowledge in the field of reliability of products in real-life conditions, similarly to what the AQC's Sycodés (*Système de collecte d'informations sur les désordres de la construction*, System for collecting information on construction disorders by the Agence Qualité Construction, Building Quality Agency) did in France [11] even helping the premium management of building insurance policies.

Big data gathering can feed such a new approach in building components' Life Cycle assessment towards a favorable shift, recording not only that component's behavior but the Real Service Life of every same component in an analogous context, that is to say, nourishing the database with all of its digital 'brothers'. The statistical analysis of the digital brothers' data can lead to a sustainable holistic procurement: component selection is no longer a matter of price or performance in itself. It must be a carefully blended mix of adequate reliability (service lifespan) and serviceability. A 'never-fail' reliability will carry out of the market all the servicemen and their local knowledge and crafts, but also unserviceable components will lead to the same point because the maintenance strategy will be substitutive (the new component being probably made abroad) instead of reparative (the servicemen are necessarily local). Both lead to the same unsustainable general and permanent loss of workforce and skills.

5.3. DIGITAL GRANNIES' BIG DATA & MAINTENANCE RATING

Once the database has been populated with the data from the digital ID cards of the components in service, this data can also be used to verify and rate a service intervention. In fact, if, after the maintenance task, the data collected by the sensors are not at least as good as the original levels (i.e., the newborn 'digital twin' does not conform to his retired digital 'grandfather'), the maintenance intervention can be automatically rated as not fully effective, and if their decay is faster than the original, not fully efficient. In this way, the level of compatibility of new components with obsolete ones can also be classified with positive fallout on the quality of the procurement.

6. CONCLUSIONS

The new availability of big data in building information modelling is recognised as useful for improving maintenance strategies and activities that, possibly integrated into a digital (methodological) model, improve the environmental impact and sustainability of buildings' service life and their components. IoT sensor platform and wireless AFDD methodology to monitor and detect faults require to be designed together: in particular, sensing strategy for building management (e.g., room temperature) should not be confused with the right sensing strategy for building maintenance (e.g., temperature in the components).

The actual behavioral model of the management phase is in some respects replicative of the building design process (prototyping and one-to-one relationships) and takes advantage of the continuous monitoring of the behavior of the components: if one of the best-known courses of sustainable action is in fact 'think globally, act locally', the building maintenance ethic till now pursued sound rather as 'think locally, act locally', very different from the industrial ethic which, facilitated by the seriality and generalised diffusion of its production, is oriented in the direction of 'think globally, act globally' (e.g. the general product recalls for construction defects). Big data managed towards Life Cycle Assessment can fill up this gap.

The proposed framework's structure, which includes an IoT sensors dashboard, an IoT and BIM combined program, and a server-based preventive maintenance methodology for building facilities, demonstrates the framework's applicability and the possibility of feeding big data analytics, such as a national database on building components to have reliability rating strategy for each of them or a local maintenance assessment and surveillance system (e. g. in terms of effectiveness and efficacy).

Authors contribution

Conceptualisation, V.V., P.P.; data curation, A.V.; formal analysis, A.V. and P.P.; funding acquisition, V.V.; investigation, V.V. P.P. and A.V.; methodology, V.V. and P.P.; resources, A.V., P.P.; software, A.V. and V.V.; supervision, V.V.; validation, P.P.; visualisation, A.V.; writing-review & editing, V.V., P.P., A.V.

All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Italian government, through the PRIN2017 project of the Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR). The title of the project is "Distributed Digital Collaboration Framework for Small and Medium-Sized Engineering and Construction Enterprises".

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