Doctoral Dissertation
Doctoral Program in Management, Production, and Design (35th Cycle)

IoT for Innovation in the Building Process.

IT for Design and Life Cycle Management of the Building Envelope

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Politecnico di Torino
April 2023

Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data. Part of the work described in this thesis was previously published in the publications listed in the "List of publication" section.

Matteo Giovanardi

2023

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

Acknowledgment

It has been a long, often tortuous, journey, but full of unforgettable experiences. All this would not have been possible without the people I have met during these years and whom I would like to sincerely thank.

First, I sincerely thank my supervisor Prof. Riccardo Pollo for his constant support during the whole research. His valuable suggestions and "philosophical discussions" have been fundamental in guiding my studies and personal growth. A special thanks goes to Matteo, the hidden co-supervisor of this Thesis, for the continuous exchanges of ideas on the research (and not only). I am grateful to the whole research group and PhD student colleagues, especially I thank Edoardo, Massimiliano, and Elisa for their very precious support.

A specially thank goes to Prof. Thaleia Konstantinou. There are no words to express my gratitude for the opportunity she provided me with the visiting period in TU Delft. I would like to thank the entire Architecture and Built Environments research group for their sincere welcome. A special thanks goes to Prof. Alessandra Luna Navarro, Prof. Tilman Klein, Hamza, and Pedro for the inspiring discussions on the IoT and façades.

Thanks to everyone who participated in the final questionnaire (especially to the former FACE3 Camp participants) and interviewees (Carlo M., Carlo B., Saverio, Jacopo, Juan, Alessandro, Martijn, Fabio, Annalisa, Martino), your feedback has been essential.

Finally, the biggest thanks go to my family for their constant support during this period. Thanks to my mum, dad, brother, and Alessandra who always pushed me take the right choice.

Grazie!

Abstract

The Internet of Things (IoT) has been recognized as a key enabling technology. In the last twenty years, the mainstreaming of IoT technologies into business and organizational processes had an overwhelming impact. In many sectors, production and consumption models have been rethought thanks to large amount of data provided by "smart" asset and ubiquitous computing's opportunities. The ability to monitor and quantify different phenomena has enabled data-driven approaches able to optimize our actions and guide our decisions. Currently, information technologies are emerging in the architectural debate as potential driver for addressing the complexity of the current environmental, social, and economic crisis condition. With a view to promoting the transition to the Circular Economy (CE) and ensuring more sustainable consumption and production patterns as promoted by Sustainable Development Goal agenda (SDG 12), the IoT technologies promise new scenarios in achieving objectives in scarce resources condition enabling a continuous and cross-cutting knowledge crucial to action.

In the construction industry, the building façade sector represent a perfect incubator to explore IoT opportunities. In this context, the need to foster product and process innovation arises from several reasons. On the one hand, the linear approach of the market is stressed by the continuous economic fluctuations and heteronomous factors (e.g., rising material and energy prices), on the other, the high environmental impact in terms of resource consumption, energy, and waste production still represent outstanding issues. Therefore, the development of innovative strategies for façade sector is to be intended as a crucial to decouple economic growth and environmental impact for the entire construction industry. On the bases of these premises, the threefold interplay between IoT, building façade technology, and CE is the research starting point. This research, within the disciplinary field of Architectural Technology, investigates the potential disruptive impact of IoT technologies in supporting product and process innovation to drive the circular shift. More specifically, this thesis aims to answer the following research question:

Can (and how) the IoT enable the Circular Economy in the façade sector?

To answer the question, a theoretical framework identifies nine potential actions generated by the interlinkages between the information produced by the IoT and the CE. In this way, the benefits (and barriers) of a digital and circular transition are systematized to help façade industry stakeholders understand the enabling role of the IoT and engage in innovative product development.

The manuscript is organized as follows. *Chapter 1* introduces the background of the research, the objective, the boundaries, and the methodological approach used. The following chapters (2,3, and 4) present from a theoretical point of view the three key concepts of the research: CE, IoT, and building façade technology. More precisely, *Chapter 2* illustrates the CE topic by identifying five Circular Business Models (CBM). *Chapter 3* examines the IoT paradigm through the analysis of literature review, case studies, and lesson learnt by other sectors. *Chapter 4* presents the technological paradigm of building façades by looking at its evolution, setting new requirements imposed by the circular transition, and identifying the trajectories on the field. After the theoretical background section, *Chapter 5* reports practical experiences on the use of IoT. Assuming an integration of IoT into the façade component, three activities were carried out to test the potential (and limits) of the IoT: (i) Near Field Communication (NFC) tags for tracking and storing asset information in the building component; (ii) Radio Frequency Identification (RFId) sensors to monitor environmental parameters affecting the asset's behavior; (iii) air quality sensors to envision new functionalities to integrate into the building component. Subsequently, *Chapter 6* matches the results from the theoretical and practical experiences in a single framework (namely "Internet of Façade") to clarify the enabling role of IoT technology in promoting circular approaches in the façade sector. The framework was validated through a series of interviews and a questionnaire. This made it possible to intercept market needs and identify fields of investigation to be implemented in the future. Finally, *Chapter 7* provides conclusions and perspectives on the topic. Based on the opportunities that emerged from the IoT-CE relationship for façade systems, the idea of an integrated IoT device is proposed to increase the asset circularity. Summarizing, the main findings of this thesis are:

- clarifying the state of the art of IoT for the construction sector;
- identifying information needed to activate CBMs for façade sector;
- defining the enabling role of IoT for the CE.

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Abbreviations

AEC	Architecture, Engineering, and Construction
BIM	Building Information Model
BM	Business Model
CBM	Circular Business Model
CE	Circular Economy
C&D	Construction and Demolition
FM	Facility Management
GPS	Global Positioning System
ICT	Information and Communication Technology
IT	Information Technology
IoT	Internet of Things
NFC	Near Field Communication
PAaS	Product As a Service
RFId	Radio Frequency Identification
SCO	Smart Construction Object
UM	Urban Metabolism
WSN	Wireless Sensor Network

Chapter 1

Towards a digital and circular “City of Flows”

Chapter 1 introduces the research theoretical background, identifies problems, defines hypothesis and objective, and clarifies methodological aspect. Starting from “information society” theories, stemming from the implications of ICT development in our society, the context framing this thesis is provided. A built environment able to (re)organize its metabolic flows (energy and matter) through the support of ubiquitous information technologies such as IoT is the theoretical assumption of this thesis. The IoT was chosen as the enabling technology and the façade sector as the field of investigation.

1.1 Background

The development of connectivity and the disruptive impact of information and communication technologies (ICTs) on society are unprecedented phenomena with still (perhaps) unimaginable margins for growth (see Moore's law[1]). According to Luciano Floridi, Professor of Philosophy and Information Ethics at Oxford University, the recent development in the field of information technology has enabled a revolution in the way we interpret the phenomena that surround us, communicate, and interact (Floridi, 2014). According to the Italian philosopher, the ongoing "Revolution", the fourth after Copernicus, Darwin, and Freud ones, is grounded on the concept of a widespread, accessible, inclusive and - potentially - democratizing information. A Revolution with immaterial traits that combines dichotomies (analogue and digital), exalts oxymorons (artificial intelligence), overturns axioms (ubiquity) and creates paradoxes (sharing economy) (Scalisi, 2021). A Revolution in which the boundaries between "online" and "offline" life dissolve thanks to the hyperconnectivity and ubiquity of digital technologies (Floridi, 2014). A Revolution that will increasingly tend to become silent and a backdrop to our lives (Weiser and Brown, 1996).

In industrialized countries, the effects of information technologies on society are already tangible. Just twenty years after the birth of Wikipedia (2001), the creation of Facebook (2004), the rise of Google Maps (2005) or the release of the first iPhone (2007), it seems impossible to imagine our daily lives without their use. Work, education, health, mobility, sociality, and everything that revolves around our living is thus redefined (and sometimes filtered) according to the principles of an "informational society" (Castells, 1989) that finds new cultural and market values in access to and sharing data. Over the years, interest in digital technologies has spread rapidly across various disciplines. Architects, anthropologists, sociologists, ecologists, biologists, physical-mathematical scientists, and neuroscientists have developed theories and predictions trying to interpret the effects of this revolution.

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[1] Moore's law shows that during the development period of digital computers, "the complexity of a microcircuit, measured e.g. by the number of transistors per chip, doubles every 18 months (and then quadruples every 3 years)". Considering the evolution of technology, this implies that information processing power is inversely proportional to cost.

To clarify the cultural context behind this thesis, three main theories are quoted. The first is elaborated by Manuel Castells, Spanish sociologist and author of the trilogy entitled “The Information Age: Economy, Society and Culture” (1996; 1997; 1998). Castells developed the theory of the “space of flows” to describe a new figurative space in which the main social and economic interactions of the information society take place. The affirmation of this on the “space of places”, on which the development of industrial society was based, has had direct effects on the spatial organization of cities (Castells, 1996). From this perspective, the alienation of the distance concept generated the idea of a continuous and ubiquitous domain where the space-time relationship is strongly rethought. Some 30 years after Castells’ first theories, Vicente Guallart, architect, urban planner, and Professor at Institute for Advanced Architecture of Catalonia (IAAC), curated the exhibition “Hyperhabitat - Reprogramming the World” at the 11th International Architecture Exhibition of the Venice Biennale. The experience promoted by the Spanish architect investigates the multi-scalar dimension of a digital society. Through the concept of the urban “hyperhabitat”, in which proximity and contingency become secondary attributes with respect to multi-scalar information infrastructures, Guallart explores the potential of ICTs in “reorganizing” the world, from the scale of the single object to the global scale (Guallart Architects, 2008) (Fig. 1). With the aim of prefiguring a hybrid reality, in which the sphere of the physical world would be entirely reprogrammed according to the principles of a virtual network, the use of networks and information technologies are identified as unique opportunities to re-establish hierarchies, connections and relationships between the elements of the built environment, the natural environment, and human (Guallart Architects, 2008).

Figure 1: “Hyperhabitat - Reprogramming the World”, Venezia (2008)

Lastly, a few years later, the implications of the relationship between the digital society and the design of the urban environment takes on a broader role in the architectural debate thanks to the Carlo Ratti's theories. Architect and Professor at the Massachusetts Institute of Technology (MIT) develops the concepts of the "Wiki City" (Ratti and Claudel, 2017) and "Senseable City". Going beyond the Smart City vision, the Italian architect promotes the idea of a digitally integrated space in which the relationship between citizen and environment is constantly mediated by the digital dimension (Ratti and Claudel, 2017) (Fig. 2). A responsive space in which the hybridization of the real and virtual spheres is aimed at serving the environment. A trend, in which ICTs are embedded in the built environment, that provides us with new means of understanding to govern the functioning of urban ecosystem over time.

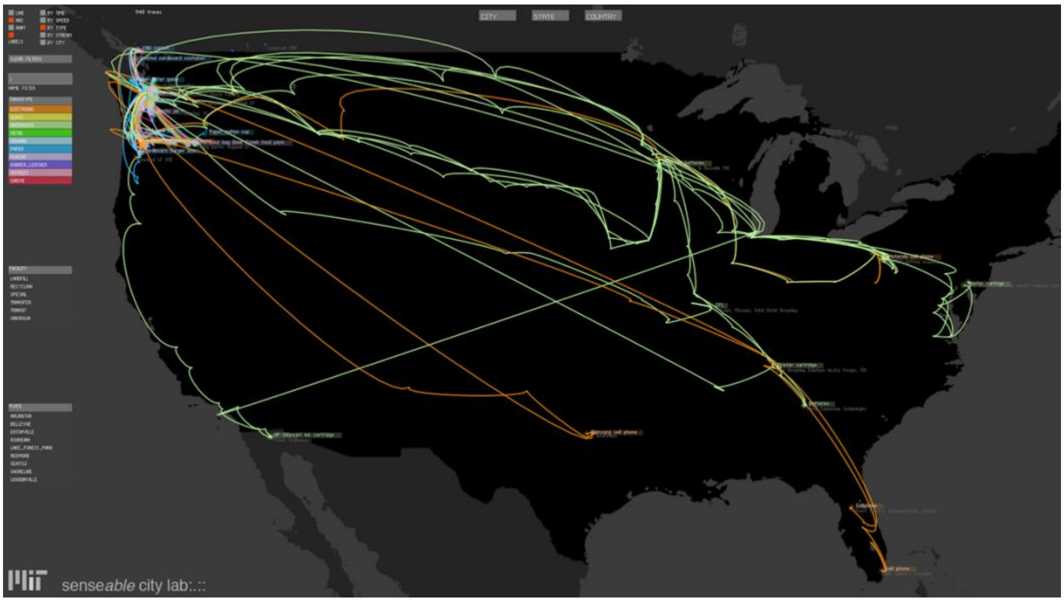

Figure 2: Senseable City, Trash Track project (Source: Senseable City Lab, MIT)

From these theoretical principles stems the idea of a ubiquitous, multi-scalar, and responsive space. A new paradigm for the built environment in which the IoT emerges as a unifying element and potential driver of shift. In this perspective, real "things" and the "network" merge into tangible artefacts capable of sharing information through the Internet. The production and analysis of large masses of data make it possible to structure our knowledge of elements, infrastructures, and places in the city itself (Losasso, 2015). Therefore, IoT applied to the built environment is understood as one of the possible technology with which to rethink interaction with our surroundings and increase the efficiency of urban processes. Currently, facing the environmental issues related to the excessive resources consumption and the massive production of waste, and climate-changing emissions, the IoT promises interesting perspectives. From this perspective, the trend to transform aspects of our lives (and the environment in which we live) into quantifiable data, identified with the term "datafication" by Cukier and Mayer-Schönberger (2013), is needed to increase knowledge and facilitate a more rational use of resources. With a view to enabling this new urban paradigm, urban infrastructure, streets, traffic lights, street furniture, buildings, building components and everything real within the city could thus be rethought thanks to the opportunities provided by the IoT. The communicative capacity provided to physical objects (Talamo et al., 2016), can be decisive in a more rational management of resources. In this thesis, the focus on the scale of building components is addressed with the aim of promoting innovative strategies that exploit the efficiency of data-driven approaches to address environmental issues. Building components, understood as potential intelligent nodes of an urban information system, thus represent the smallest element of a widespread and pervasive perceptual infrastructure. Imagining the future of intelligent building components means rethinking the nature of the components, their use and their relationships with other elements of the city.

1.2 Research context

1.1.2 Problem statements

Over the last decade, European Union guidelines paved the way setting medium- and long-term policy objectives to foster the transition to the CE. To cope with the issues of huge waste production, disposal, and unsustainable consumption of raw materials, while achieving the greenhouse gas reduction target (-55% by 2030) (EU, 2021), production and consumption patterns must be drastically redesign based on the environmental emergency (EC, 2019). This means overcoming the obsolete "take-use-dispose" model in favor of regenerative and circular systems. According to the Ellen MacArthur Foundation, a charity that has been promoting the transition to CE since 2010, the challenge of today's society is manifested in the desire to promote an economy designed to regenerate itself, in which biological material flows can be reintegrated into the biosphere, while technical material flows are designed to be revalued without entering the biosphere (Ellen MacArthur Foundation, 2013). This approach, taken up and promoted in the main guidelines and directions at global, European, and national level (cfr. 2.1.2), has direct implications on the Architecture, Engineering, and Construction (AEC) sector that is still considered among the most impactful and strategic sectors for the circular transition. This stems mainly from two reasons. On the one hand, the construction sector still exerts a worrying pressure on the environment (EC, 2020), on the other hand, it plays a central role in the European economy.

From an environmental point of view, despite the progress made over the last two decades that has led to more sustainable production processes and energy performance of buildings, the construction sector is still responsible for 36% of final energy consumption and 39% of total carbon dioxide emissions worldwide, 11% of which come from the production of construction materials such as steel, cement, and glass (UN, 2021). In this context, the sector is characterized by an internal paradox. On the one hand, there is the desire to decarbonize the built environment by updating an outdated existing building stock, on the other hand, the massive demand for energy-consuming materials (e.g., aluminum and glass) makes this a central issue. Moreover, in order to promote a complete ecological transition, further developments must be conducted to counter resource consumption and waste generation. According to ISPRA (2022), in Italy the construction sector, with 66.2 million tons (about 70 million was recorded in 2021), is confirmed as the one with the highest incidence on the total production of special waste, accounting for 45,1% of the total production. In other words, about 1 ton per capita per year, as if every citizen produced one meter cube of half-filled bricks. Despite ISPRA indicates that recycling and reuse rates exceed the 70% threshold imposed by the European Commission (Directive 2008/98/EC), current down-cycling practices limit the effects of large waste production but do not solve the problem. The transition towards CE implies first overcoming the idea of a "recycling economy" towards an economy that reduces resources demand and gives new value to the materials used.

From an economic point of view, the AEC sector is a strategic factor for national and EU economic growth (EC, 2020). The construction sector, which includes real estate, infrastructure and industry, accounts for 5.5% of the Gross Value Added[2] (GVA) and approximately 13% of the European Gross Domestic Product (GDP) (McKinsey & Company, 2020). After the recessionary phase from 2008 and 2014, Eurostat shows how the GVA trend started a growth since 2017 (Fig. 3). In Italy, after the emergence of the COVID-19 pandemic, a strong increase in investments in the construction sector, driven by a series of state incentives aimed at relaunching the economy (e.g., Article 119 of Decree-Law no. 34/2020, namely "Superbonus 110%"), led to a surge in GDP. This demonstrates a close relationship between economic growth and the construction sector. Moreover, it should be considered that in Italy the employment intensity in the AEC sector is higher than the European average, representing a key sector for sustainable development also from a social point of view. Currently, the economic sustainability of the sector, challenged by geopolitical issues such as energy dependence, raw material shortages, labor force, and global competition, forces the transition to self-sufficient and regenerative models

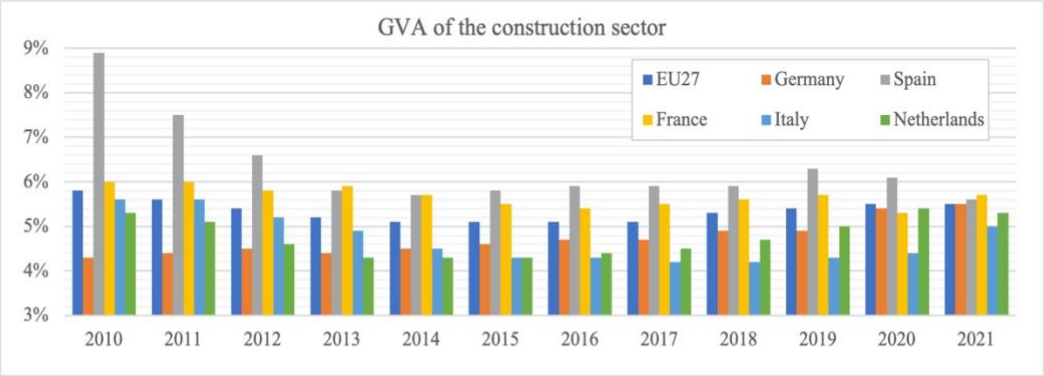

Figure 3: GVA of the construction sector, as % of the total GVA. (Source: Eurostat)

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[2] Gross Value Added2 (GVA) is an economic productivity indicator that measures the contribution of a sector to the economy. GVA provides a dollar value for the quantity of goods and

1.2.2 Boundary and disciplinary context

To investigate the potential of IoT technologies in counteracting the economic and environmental issues affecting the AEC sector, a specific and circumscribed field of application was chosen: the building façade sector. The façade, or building envelope, is defined as the (mostly) vertical element that forms the physical enclosure of the occupied areas of a building (Knaack et al., 2007). The choice of this element arises from several reasons. Firstly, façade systems play a pivotal role in determining the building's sustainability (Prieto Hoces and Oldenhave, 2021). Indeed, they are decisive in determining the operational and Embodied Energy (EE) of the building (Giordano et al., 2017) (ARUP, 2022). Secondly, as they are subject to higher renovation rates over the building service life (Brand, 1995), they generate higher material flows and waste. Thirdly, by scanning the entire city and acting as filters between inside and outside, they can be considered multi-scalar nodes of an urban infrastructure. Fourth, off-site production techniques and the industrial dimension of the manufacturing process make these components the most suitable for product and process innovation (Sangiorgio, 2021). Fifth, façade have multi-domain influence on users and therefore their performance should meet multiple criteria, making these components one of the most complex building components. For these reasons, the façade sector was chosen as the field of investigation. Furthermore, it is recognized as a perfect incubator to explore opportunities for transformative innovation in driving change in the entire construction sector (Gasparri et al., 2021). The transition to circular construction and façade management practices can thus be understood as a key action to achieve more energy- and resource-efficient buildings. Specifically in this thesis, unitized curtain wall systems was chosen as façade technology, but the theoretical approach and data collected may also be scalable to other building prefabricated components (e.g., window, roofs, etc.).

The topic is addressed in the disciplinary context of Architectural Technology. This discipline, in the field of design research, bases its practice on a systemic and processual approach (Perriccioli, 2016) overcoming a technical culture based on reductionism and specialism (Nardi, 2002). Thanks to its cultural and scientific matrices, shaped by industrial culture, systems theory, design methods, ecological and environmental dimensions, experimental operation, and the governance of complex processes (Perriccioli, 2016), the Architectural

Technology disciplinary field aims to transpose transversal knowledge into architectural design. This approach allows façade systems to be analyzed not only from a purely technological point of view, but also (and above all) from a process, management, and economic perspective over façade life cycle.

1.2.3 Hypothesis and research questions

If it is true that "data drives CE", the IoT emerges as a potential enabling technology (Alcayaga and Hansen, 2022). In a hypothetical future where data will increasingly drive our decision-making processes and allow us to predict the nature of major urban phenomena, some questions arise. What will be the new informational "performance" required of the built environment? Can buildings and components give us insights into how to manage them in a circular way? Will they be able to tell us when they are about to fail or when it is convenient to replace them and recycle them? From monitoring energy consumption to sharing information on remaining service life, we can already envision a future in which IoT-oriented façade systems can increasingly dialogue with users, producers, investors, and building managers. Nevertheless, the potential for these cyber-products to provide large amounts of data to support the manufacturing steps, buildings management, environmental quality monitoring, assets' assessment, or end-of-life management is still largely unexplored. On these hypotheses, the research question (Rq.) of this thesis is formulated:

Can (and how) the IoT enable the circular transition in the façade sector?

To answer such a broad and complex question, two additional research sub-questions (Rsq.) were identified to deconstruct the problem and make the results clearer:

Rsq.1 - *What opportunities does the IoT offer in managing life cycle information of a façade system?*

Rsq.2 - *What information is required to support Circular Business Models (CBMs) in the façade sector?*

To answer these questions, a theoretical framework is proposed based on the relationship between the three main topic (Fig. 4): IoT, building façade, and CE. In particular, the relationship between building façade and CE is presented from the perspective of investigating the environmental and economic opportunities of circular transition. The relationship between building façade and IoT refers to the perspective of product development and innovation aimed at creating intelligent cyber-physical systems. Finally, the relationship between IoT and CE is examined in the support provided by digital technologies to the spread of new business models. From the relationship of these three elements arises the “Internet of Façade”. The development of the framework is addressed to façade manufacturers, developers, and practitioners to stimulate product and process innovations.

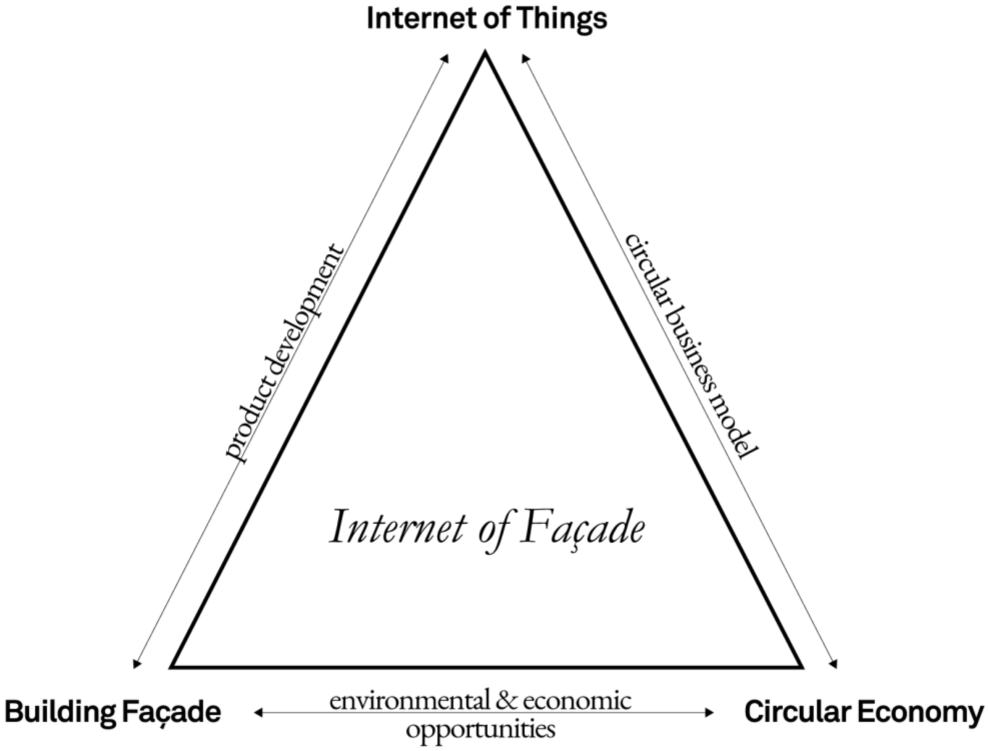

Figure 4: The thesis is structured on 3 key paradigms: IoT, building façade, and CE

1.3 Research structure

1.3.1 Methodology

The methodology used to answer the research question can be framed in the "learning by doing" approach. Theoretical and practical contributions alternate to test the benefits (and limitations) of a technology in a specific market context. The basic research required to trigger innovative processes is time-consuming but at the same time indispensable. Despite there is no one-size-fits-all methodology for the development of innovative product or process, this research takes some investigation methodologies specific to innovation management disciplines (Cantamessa and Montagna, 2016). After presenting the main CBMs imposed by the circular transition, the analysis of the literature and case studies was carried out to define a taxonomy of the IoT for the built environment and investigate the technological paradigm of building façade. Lessons learnt from other industries (e.g. automotive, textile, manufacturing, etc.) are analyzed with a view to import best-practices and innovative approach into the façade sector. Market analysis, stakeholder mapping, and innovative case studies in façade sector are presented to investigate economic, functional, and competitive requirements for an innovative façade system. After clarifying the theoretical background, some practical experiences in the use of IoT systems were carried out. Using a "what if" approach, three main hypotheses on IoT-based façade were tested to confirm the benefits (and limits) of physical-digital integration. Three low-cost IoT sensors, available on the market or developed by the Department of Automation and Informatics of the Politecnico di Torino, are examined. Despite the research is strictly related with the development of an innovative product, the main purpose of this thesis lies in the definition of a theoretical framework that highlights the potentiality of IoT technologies. Once the theoretical framework was defined, the validation process was conducted through interviews and questionnaires to professionals. In particular, the final discussion on results obtained with manufacturers, real estate developers, builders, designers made it possible to identify, among the plethora of possible applications, the priority areas to work on in the next phases of the research.

1.3.2 Relevance and expected outline

The relevance of the topic is mainly dictated by the ongoing environmental emergency. The challenge in the construction sector is to continually take the path of innovation, understood as the replacement of modes that are no longer sufficient, because they are “crystallized in a habitual vision of the built environment, with others that accentuate the rigor and agility of the design process” (translate by Vittoria, 1983). To foster the circular transition quickly, the market cannot wait for regulatory action alone. Despite necessary, these place the circular transition at the level of regulatory compliance, thus neglecting its potential in both environmental and economic terms. To favor the transition towards new models of production and consumption, it is necessary to develop innovative products and processes that are more competitive from an environmental, economic, and social point of view. Regulatory impositions, although necessary, place the circular transition as a purely matter of regulatory compliance, thus neglecting its potential in both environmental and economic terms. The real challenge, as Floridi pointed out, is to return to the intrinsic character of the economy (which has always been circular) by activating new models to make it “rich” (Floridi, 2018). Economic, technical, financial, and social aspects must be considered simultaneously. The complexity of the challenge, arising from the number and heterogeneity of the phenomena and languages that interact in a process, confirms the impossibility of adopting a closed and monodisciplinary approach to solving a problem (Marzocca, 2014). Transdisciplinarity, that means overcoming the (often) artificial boundaries separating different disciplines, is the basis of this research. A new approach, aimed at implementing design strategies capable of responding in an increasingly targeted manner to the social, environmental, and economic challenges posed by sustainable design, is needed. In this thesis, the collaborative condition of different knowledge is aimed at clarifying the potential of technology as an engine for innovative sustainable development. Basic research, in the hands of universities, can be crucial to spread knowledge on the subject that triggers highly innovative approaches. In this perspective, the synergy between the business world and universities, facilitated in the background by government action, could enable the triple helix model underlying innovation.

1.3.3 Structure of the manuscript

The manuscript is organized into 3 main *Sections* and 7 *Chapters* (Fig. 5). After clarifying in *Chapter 1* the objective, the boundaries, and the methodological approach used, the *Section I* (*Chapter 2,3,4*) reports on the theoretical background of the research. *Chapter 2* presents the main theories moving the construction industry toward CE, regulatory developments on the circular topics, and a series of district-level case studies to clarify the relationship between CE and architectural design. *Chapter 3* examines the topic of IoT for the construction industry through the results of a literature review. Here, potential benefits emerged in other sectors, case studies, and research experiences serve to map the state of the art and set a taxonomy of IoT technology for AEC sector. *Chapter 4* focus on façades technology. From a highly innovative perspective, the technological paradigm is investigated in relation to the product and process innovations that have shaped its development. Once presented the main specifics of the field, a series of case studies delineate the main perspectives on the topic.

After the theoretical background analysis, *Section II* reports on the main experiences with the use of IoT technologies. In *Chapter 5*, three main activities were conducted to test the capability of IoT technologies and technical issues related to the digital-physical integration. Tracking and storing asset information in the building component for promoting a circular and transparent supply chain, monitoring environmental parameters that affect on asset's behavior for enhancing performance and service life, and air quality monitoring to introduce new dematerialized services are the main areas of investigation. Subsequently, *Section III* brings together the results of the theoretical and practical analysis into a single framework to identify the enabling role of the IoT. *Chapter 6* presents the "Internet of Façade" framework defining potential actions to foster the circular transition of industry through IoT integration. Finally, *Chapter 7* provides conclusions and perspectives on the role of IoT in façades sector.

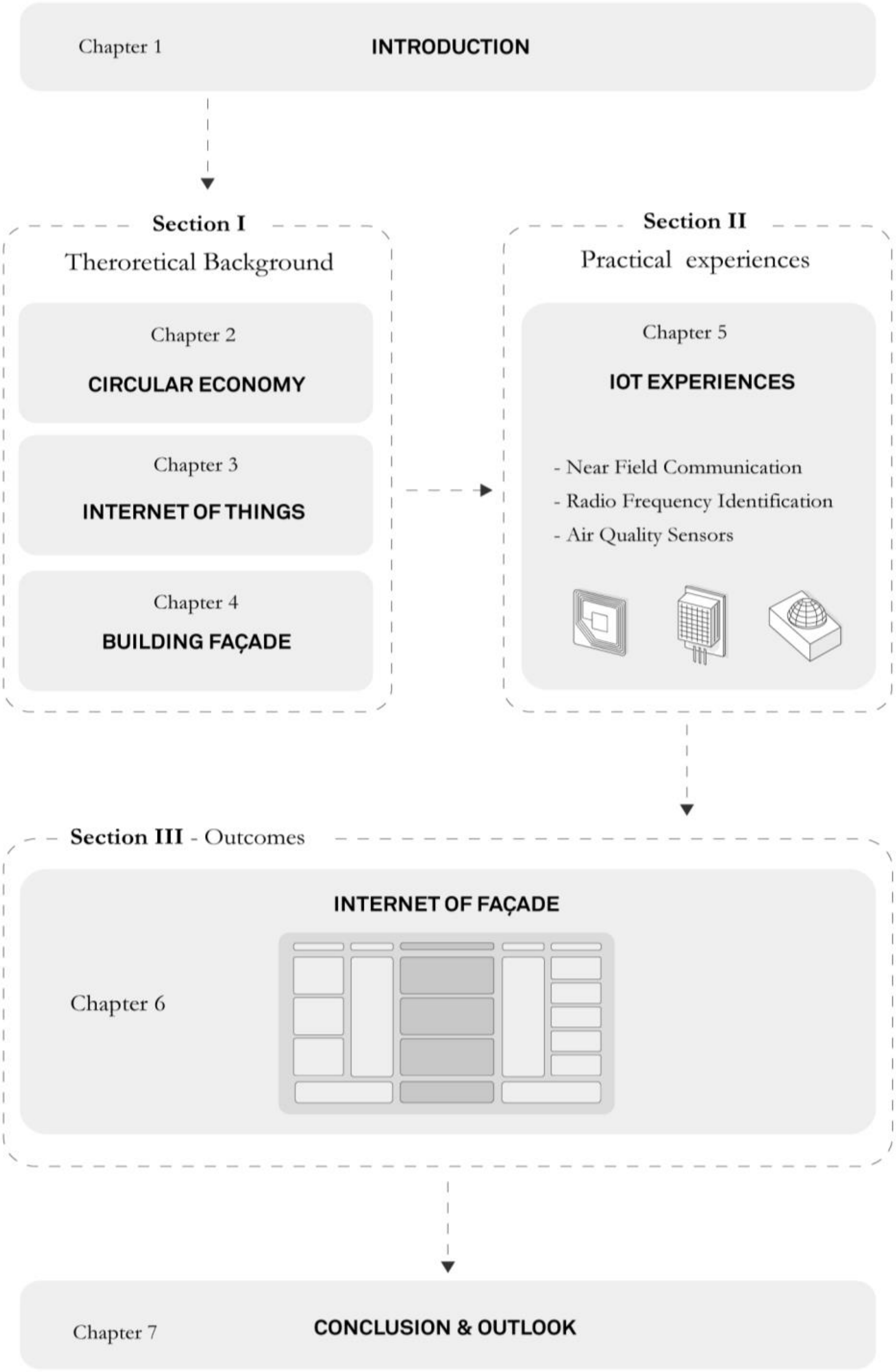

Figure 5: Structure of the manuscript

Chapter 2

Circular Economy and Built Environment

Chapter 2 introduces the first topic of theoretical background: the CE. Starting with the theoretical implications of CE in the built environment and reference to key European policies, five circular business models (CBMs) proposed by Lacy and Ruqvist (2015) are presented as circular goals for rethinking production and consumption patterns. Subsequently, a focus on five circular Smart District clarifies the relationship between CE and architectural design at the urban scale.

2.1 Circular Built Environment

2.1.1 From “The Spaceship Economy” to Urban Metabolism

With the advent of the Anthropocene (Crutzen, 2002), the impact of human activity on the natural ecosystem is becoming increasingly tangible, manifesting itself in the changing physical and biological balance of the Earth. For many years, the study of the biological cycles that regulate settlement metabolism has been a topic of great interest to scholars from various disciplines. From Kennet Boulding’s “The Spaceship Economy” (1966) to the more recent “Cradle to Cradle: Remaking the Way We Make Things” by Michael Braungart and William McDonough (2002), scientists, philosophers, economists, biologists, and architects have denounced the unsustainability of the linear growth model on which our society is based. Equating industrial processes with natural ones, they showed the limits of the “take-use-dispose” model highlighting the impact of human activities on the environment. This impact is defined by Barry Commoner as the result of the equation “I = P x A x T”, where environmental impact (I) is a function of three factors: population (P), welfare (A), and technologies (T) (Commoner, 1971).

The CE theories, “based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems” (Ellen McArthur Foundation, 2015), arises from these premises. Currently, the pressure of anthropogenic activities, which mobilize people, goods, and information at an unprecedented rate (Dijst et al., 2018), exacerbates this condition. In this context, CE concept take on a new meaning. Approximately 60 years after the first sustainability warnings, the contemporary dimension of CE extended to economic systems and industrial processes has evolved (Geissdoerfer et al., 2017) to tend towards the minimization of energy and matter flows in ecosystem metabolism (Rifkin, 1983). This implies limiting the inputs and outputs of production and consumption processes. To do this, the identification and quantification of these flows is a primary step to act. For this reason, theories, disciplines, and approaches with a strong focus on this issue are also emerging in the field of architecture. One of these is the Urban Metabolism (UM). Identified as an interdisciplinary model capable of governing the complexity and systemic character of urban phenomena (Pollo et al., 2021), UM refers to a set of complex processes of matter and energy transformation of the settlement system in its spatial-temporal dimension. The metaphorical reference to a biological process to describe social, economic, and cultural dynamics is a powerful means of conceptualizing the city as an “organism” (Kennedy et al., 2011). Through this approach, the different components have close relationships with each other and the environment, expressed in terms of growth, energy production, and waste elimination (Kennedy et al., 2007). In this perspective, the “urban organism” exerts continuous pressure on the environment (Trane, 2020), which depends on the number of its inhabitants, their consumption and lifestyles, their geographical location, and the socioeconomic and regulatory context in which it is located (Pollo et al., 2021). UM is thus an enabling concept for understanding the city as an ecosystem produced by the sum and interaction of different metabolisms (Golubiewski, 2012), which can be quantified by defining the flows of matter and energy within its boundaries (Fig. 6). The monitoring of energy and material flows and the identification of resource stocks thus makes it possible to increase knowledge of available resources, optimize their use, and plan corrective strategies.

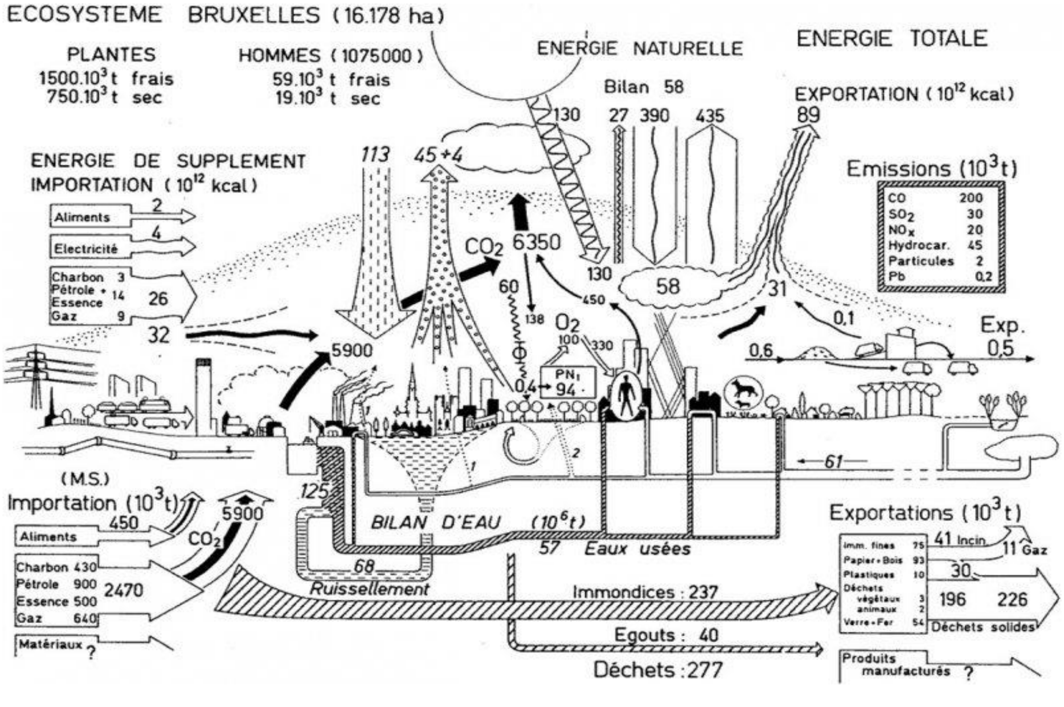

Figure 6: Urban Metabolism graphical representation (credit: metabolismofcities.org)

2.1.2 Policies and regulatory framework

The circular transition is a clear objective in global, European, and national development policies. Among the 17 Sustainable Development Goals (SDGs) developed by the UN in 2015, explicit reference is made by SDG 12 "Sustainable consumption and production" referring to the construction of circular supply chains able to reduce the consumption of energy and raw materials. Specifically, Target 12.5 points the way to a "substantially reduced waste generation through prevention, reduction, recycling, and reuse" by 2030. Since 2015, the EU has introduced a comprehensive body of legislative and non-legislative actions through the Circular Economy Action Plan to organically drive the industrial, economic, and ecological transition of member countries (EU, 2020). With the Paris Agreement's goal of achieving climate neutrality by 2050, the European Green Deal also promotes the CE to decouple economic growth and environmental impacts (EC, 2019). This translates into the revision of the Construction Product Regulation, as in the case of the recycled percentage, or the use of Level(s)3 to integrate life cycle assessment in public procurement.

In the Italian context, the application of these guidelines to the national level is transposed by the "Strategia Nazionale per l'Economia Circolare" issued by the Ministry of Ecological Transition (MITE). Related to the construction industry, since 2017, the "Criteri Ambientali Minimi" (CAM) for design introduce aspects of sustainability and circularity of resources. Obliging builders and designers to reduce their environmental impact and promote more sustainable models in public administration construction sites, they promote the use of materials composed of renewable raw materials and with a defined percentage of recycled depending on the material. Even within the most recent "Il Piano Nazionale di Ripresa e Resilienza" (PNRR) (Mission 2), the "Rivoluzione Verde e Transizione Circolare" pushes for the introduction of innovative models that reduce the impact on the environment.

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[3] Level(s) is a European reference framework to assess building sustainability performance. https://environment.ec.europa.eu/topics/circular-economy/levels_en

2.1.3 Circular Economy in the digital society

In a context closely influenced by the presence and development of digital technologies, the CE can also benefit. The enabling of large masses of data, the sharing of these among the various actors in the supply chain, and the ability to transform them into information that can guide stakeholders' decision-making are potential benefit in fostering CE (Nobre and Tavare, 2017; Argus et al., 2020). Therefore, with a view to monitoring and controlling the input and output of a system and verifying the effectiveness of the circular strategies proposed by guidelines and policies framework, data assume a central aspect in the circular transition (EPC, 2020). In this perspective, data-driven design can be considered an indispensable approach in rethinking and redesigning products and processes. Thus, information sharing can be an important driver in the circular perspective. Along value chains, access to asset data by multiple actors can be decisive. A report by Nordic Innovation highlights how data sharing is a strong enabler for CE (Nordic Innovation, 2021). The increased sharing of data and information between stakeholders has led to the development of CE maturity. Three main phases are identified in the report (Fig. 7). In the first, "maturing" phase, data sharing was internal within companies or between a few actors in the value chain. This information was mainly used for resource optimization. The most common data flows are those related to material traceability to support procurement and recycling processes, as well as product performance and other operational data needed to respond to regulatory compliance. Easier data sharing between stakeholders has brought a new level of maturity. Today, the development of shared data ecosystems and end-to-end product traceability, benefiting from aggregated data, benchmarking information, and access to quality data has led to the development of circular and collaborative markets in many supply chains (Cagno et al., 2021). New co-operations between actors are structured on the exchange of information. At the "advanced" stage already achieved in some sectors, future circular data flow will support the development of new innovative business models, where companies do not simply consider how to reduce waste in their existing operations, but rather focus on the creation of new value enabled by data and the exchange of services. Therefore, the close relationship between information tools and CE is emphasized by a more fluent sharing of information that facilitates a more rational use of resources and material value.

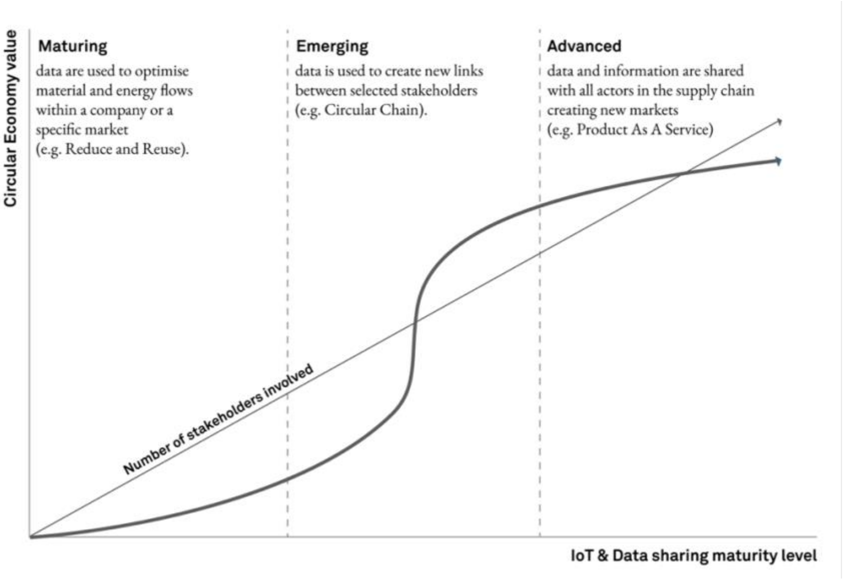

Figure 7: CE maturity evolution (reworked from Nordic Innovation, 2021)

2.2 Five Circular Business Models

Currently, the transition to CE is playing on the development of new business models that make the current traditional model obsolete from an environmental, social, and economic point of view. In this perspective, many researchers are analysing the benefits of new CBMs (Bocken et al., 2016) (Bressanelli et al., 2018) (Jabbbour at al., 2019) (Ingemarsdotter et al., 2020). Specifically, CBMs refers to “business models that aim at solutions for sustainable development by creating additional monetary and non- monetary value by the pro-active management of a multiple stakeholders” (Geissdoerfer et al., 2018).

In 2015, Peter Lacy and Jakob Rutqvist published the book “Waste to Wealth. The Circular Economy advantage” aimed at managers to inform them about the benefits that can be activated by CE. Through this text, the authors demonstrate how a new economic era could be launched without depending on limited natural and planetary resources for business success. Through a series of case studies taken from various production sectors, the authors identify five new CBMs (Tab. 1). The development of a circular supply chain, the enhancement of recovery and recycling, the extension of a good’s service life, the spread of shared platforms, and Product As a Service (PAaS) are the main circular strategies. The following examples from other industries serve to investigate the potential of the technology and investigate which approaches to integrate in the construction sector. The CBMs, not to be read independently of each other, can be described as follows.

Table 1: 5 CBMs identified by Lacy and Rutqvist (2015)

CBM	Goal	Examples
Circular Supply Chain	Using recyclable, certified and environmentally friendly resources by favoring a local and transparent supply chain	Maersk Line Product Passport, CRAiLAR nearly zero water consumption, Bhiom bio-based materials, etc.
Recovery and Recycling	Promote the reuse, recovery, and recycling of materials and components so as to preserve their value over time	Gamle Mursten recycling bricks, General Motors zero-waste programme, Interface Healthy Seas, etc.
Service Life Extension	Extend the useful life of the asset over time by ensuring the effectiveness of the design performance for as long as possible	Patagonia “Do-Your-Own”, Electrolux modular components, etc.
Shared Platforms	Sharing resources (and knowledge) through collaborative platforms that fully exploit the asset	Peerby 100, 3D Hubs sharing knowledge, Airbnb, etc.
Product As a Service	Enabling new forms of business based on the exchange of services and intangible benefits	Michelin “tires as a service”, Philips “Pay-per-lux”, etc.

2.2.1 Circular supply chain

This CBM is based on the principle that in a circular supply chain all resources composing the product are fully renewable, recyclable, or biodegradable. This implies that materials, which in a linear model would be discarded as waste, retain their value as recyclable goods or as materials with zero environmental impact. The transition from “linear” to “circular” resources may require a rethinking of product design and production processes. This CBM aims to closing, slowing, intensifying, narrowing, and dematerializing the supply chain (Geissdoerfer et al., 2018). Common examples include the use of renewable energy, the adoption of bio-based and biodegradable materials, the use of material with recycled content, or the implementation of the “Material Efficiency” concept in the design process (Marrone and Montella, 2021). For companies, moving towards circular supply chains would achieve a twofold purpose. On the one hand, they could drastically reduce their impact on the environment in terms of resource demand and waste generation, on the other hand, the benefits of a regenerative economy could turn into profits for the company. To foster a circular transition based on a circular supply chain several paths can be taken. For instance, a transparent supply chain can be initiated by improving the material traceability. More information on the characteristics of the materials can facilitate the circular management of the asset. (Santana and Ribeiro, 2022). From this perspective, several companies are investing in this approach. Maersk Line is one of the Danish companies that has started to establish a circular supply chain (GXN, 2018). A leader in sustainable shipping, Maersk Line has set a target to reduce its total greenhouse gas emissions by 60 % for every container it moves. To this, it has developed a Cradle-to-Cradle product “passport” that documents 95% of the ship’s materials to facilitate reuse and steel recycling once the ship is decommissioned. In this way, material information ensures the purity required to make steel recyclable and therefore valuable. Another example for circular supply chain is provided by the company CRAiLAR (Lacy and Rutqvist, 2015). Founded in 1998, this company produces renewable and environmentally friendly biomass resources using flax, hemp, and other bast fibers. By developing an all-natural enzymatic process, CRAiLAR production process saves considerable amounts of water. In recent years, several studies have been conducted in the construction sector in the development of bio-based materials for building components (Sandak et al., 2019). For instance, Biohm[4] is a manufacturer of mycelium/mushroom-based for buildings materials. It provides composite panels based on the vegetative filament root structure of mushrooms which provide enhanced insulation. The adoption of such CBMs, often linked to the development of sustainable materials and technologies, requires substantial capital to initiate the research. This, in addition to the tendency to retain their core business and operating modes, is still one of the main obstacles to circular development.

2.2.2 Recovering and Recycling

Recovering and recycling have long been cardinal goals of the CE. Despite recycling should not be understood as a solution to the problem of excessive waste generation, it can certainly be limiting its impact on the supply chain (Iacovidu et al., 2018). In this model, companies use existing products or resources by making a profit through their sale. As global competition intensifies and the cost of resources increases, this CBM seeks to maximize the value of the materials they already have. Through this model, a company identifies the value of its activities not only when it considers the final products, but all material flows through its business. In other words, each by-product and waste flow are optimized to maximize its earning potential. In this case, the reuse of resources that have reached the end of their lives for the purpose for which they were designed can be transformed into value through two main processes: down-cycling and up-cycling.

The first refers to the use of the material as a second or aggregated raw material, thereby losing the main characteristics of the material itself. On the other hand, up-cycling aims to convert an old product or material into something more valuable and for this reason is preferred to the former with a view to encouraging a regenerative economy (Talamo et al., 2021). By developing new technologies and creating new two-way supply chains (i.e., moving products to customers and bringing back products at the end of their lives), companies can recover almost all the resources they produce at a level at least equivalent to their initial investment.

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[4] Bhiom. https://www.biohm.co.uk/

Through reuse and recycling, in fact, the production of waste and scrap would be minimized. The real challenge, especially for companies, is to develop models that can benefit from the use of large volumes that can be recovered at a reasonable cost.

An example of this CBM is Gamle Mursten, which cleans used bricks (about 6,000/hour) so that they can be sold and reused. This company is the first in Denmark to obtain a CE mark for a recycled building material, documenting its performance. All new bricks must be CE marked, but until now this was not possible for recycled bricks, so there was no standard and methodology. In 2016, Gamle Mursten achieved a net profit ratio of 28% (GXN, 2018). Estimations by the Danish Ministry of Environment and Food indicates that the annual market potential for reclaimed bricks is 47 million bricks or 12% of the total market. General Motors launched a zero-waste program in 2011. Today the company recycles 90% of its manufacturing waste worldwide and has 120 landfill-free facilities (Lacy and Rutqvist, 2015). Interface, a nearly $1 billion company and a leading manufacturer of modular carpet, is participating in the Healthy Seas[5] initiative to reuse nylon fishing nets in carpet production. For companies, the benefits of resource recovery and recycling can be summarized as reduced waste management costs, increased revenue from the sale of unwanted products, reduced environmental impact due to reduced demand for virgin resources and energy. However, this CBM involves considering technical issues. There are two main challenges still to be address: maintaining resource quality and preserving property rights to high-quality resources. Companies must find ways to control the return flow (e.g., by launching product take-back programs) and maximize the quality of recovered resources.

2.2.3 Product Life-Extension

Extending the useful life of a product is a key strategy for slowing waste generation and rebalancing the ratio of remanufactured to consumed resources (Bocken et al., 2016). This CBM stands in antithesis to the linear model whereby

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[5] Healthy Seas. https://www.healthyseas.org/

companies maximize profits based on the volume of products sold. The goal of this model is the preservation of economic value for as long as possible. Thus, refurbishing, repairing, reconditioning, and remanufacturing items can result significant strategy to enhance the life extension of short-cycle building products (Talamo et al., 2021). Examples of this CBM typically exist for high-priced products, where services, inspections, and repairs are part of the price paid by the consumer. Therefore, moving beyond an approach aimed at quantifying profits related to the number of sales means structuring strategies that drive profits in the lasting use of an asset. Convincing consumers to repair their asset, replace defective parts, or handle the asset in the best possible way is an extremely challenging task. A case in point is provided by Amazon's Kindle. The manufacturing company itself, profiting from the paid services offered by the digital device, has an incentive to make the device last as long as possible by incentivizing its use. Patagonia, a world leader in technical apparel, provides its customers with a "Do-Your-Own" service to enable its users to repair their clothings (Lacy and Rutqvist, 2015). To facilitate this CBM, technology and product design aspect need to be considered. One example is the Fairphone[6] smartphone. In addition to the sustainable sourcing of raw materials, the smartphone design allows easy replacement of its components. In this perspective, the ability to maintain the asset efficiency over time through minor repairs or maintenance enables customers to exploit durable assets and companies to trigger customer loyalty relationships. For the design of products with an extended service life, companies need to consider several aspects in addition to contractual aspects, such as:

- *Durability*. It is crucial to create products and BMs in which durability is considered a rewarding value. The choice of materials that are durable and suitable for the way they are used are central aspects of design. Using, especially in complex, multi-component systems, materials with similar durability makes it possible to limit possible problems with obsolescence of parts.

- *Repairability*. The ability of a technology to be repaired and remanufactured is a central issue for life extension. Consideration must be

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[6] Fairphone. https://www.fairphone.com/en/

given in the design phases to the possibility of replacing and repairing parts of a system without it losing its primary functions. The reparability of individual components is an essential feature of circular products that can be partly linked to the theories of Design for Disassembly.

- *Maintainability*. Similarly to reparability, maintainability aims at facilitating the maintenance activities of the good. Design aspects of the product and the context in which it is inserted can drastically favor the maintainability of the asset by extending its useful life. Direct accessibility to the asset, the possibility of monitoring its condition, and the simplicity of maintenance activities for long-lived assets subject to continuous environmental and anthropic stress can have significant effects.

- *Upgradability*. The ability to upgrade the features and performance of a product over time allows the initial product to be exploited over time. Adding new features rather than replacing the core product limits resource consumption and waste generation. This principle, applicable to product segments where the focus is primarily on the service offered rather than the physical support, can lead to extending the asset service life.

2.2.4 Shared Platform

The concept of CE is increasingly linked to the concept of the sharing economy. This business model involves the creation of platforms to share products or services (Nordic Innovation, 2021). Through this approach, product owners can increase the "use" of them by enabling the principles of co-access and co-ownership. The disruptive impact of these models in the transportation or tourism sectors has been unprecedented. In relation to CE, more intensive use of products reduces demand of new resources. This facilitates the creation of value from previously inefficient or underutilized assets. In addition, to narrow implications on matter flows, the adoption of shared platform also has an impact on the social dimension, facilitating a range of human relationships and engagement (Viglioglia et al., 2021). The creation of such platforms is transforming the market. A 2014 study by Nielsen Global company found that 68% of online consumers are willing to offer their personal items to sharing communities for a fee (Nielsen Global, 2014). While 66% are inclined to use the resources of a sharing community. Despite it is not a given that the sharing economy is totally circular, this may have several commonalities in the intensive use of the subject matter. Such platforms are primarily based on Consumer-to-Consumer (C2C) models (they connect consumers directly) rather than as a Business-to-Business (B2B) model. Currently, the most mature markets are all C2C, including car sharing, ride sharing, room sharing, and vacation home sharing. FLOOW2[7] is a sharing platform for goods and services, from construction to healthcare, agriculture, technology, real estate, and professional services. With an offering of about 25,000 products, it aims to reduce overcapacity in terms of products we have. Another classic example is Airbnb. A home-sharing platform offers the ability for users to connect and book accommodations at generally lower costs than hotels. Uber, on the other hand connects customers looking for a ride with drivers within the city. Peerby[8], again, operates a peer-to-peer lending service for a variety of products. The Dutch startup has developed a platform where they can rent a bike, household tools, or other items for a limited time within their neighborhood. Members can send a request for items online, via cell phone or social media channels. The platform sends the request to 100 Peerby neighbors who may have the desired item. If someone nearby has the item, the requester is notified, and a connection is made. Similarly, with the growing popularity of 3D printing, 3D Hubs[9] has developed a collaborative platform for makers and owners of 3D printers. Using 3D Hubs' platform, anyone with a 3D printer can offer customized and locally produced goods to those around them. By creating a platform that connects printing capacity with users who want to print.

2.2.5 Product As a Service

This CBM completely disrupts the current linear system. The adoption of CBM related to the concept of Product As a Service (PAaS) has been underway

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[7] Floow2. https://www.floow2.com/en.html

[8] Peerby. https://www.peerby.com/en-nl

[9] 3D Hubs. https://www.hubs.com/

for several years in a many industries. Customers are foregoing the purchase of an asset in favor of buying its service. This approach, based the proliferation of short- or long-term contracts, is a source of interest to many researchers (Tukker, 2004) (Costa Fernandes et al., 2020) (Hidalgo-Carvajal et al., 2021). Cars, bicycles, smartphones, clothes, printers, solar panels, are being rented or leased instead of purchased. For companies, revising their business model based on these needs is not a given. Indeed, this CBM implies new responsibility for companies. The manufacturer, by selling a service, does not relinquish ownership of the product to the customer and takes on the task of offering a range of customized services (Hidalgo-Carvajal et al., 2021). To implement such models, new contractual forms must regulate the relationship between consumer and producer.

Some of the most common are:

- *Pay-per-Use*. Customers purchase service rather than a product. In this way, the customer pays according to usage parameters (e.g., miles driven, hours of use, pages printed, etc.).
- *Leasing*. Customers purchase the use of a product for a medium to long period of time, often with exclusive, individual access rights.
- *Rental*. Similar to leasing but for limited periods of time (usually less than 30 days). A rental configuration is generally more flexible than a lease, and customers may not have guaranteed unlimited access.
- *Performance-oriented*. Customers purchase a service with a predefined level of performance. The quality of services offered is the basis for performance contracts (e.g., cleaning, operation etc.).

In the CE perspective, by activating this CBM, the producer's ownership of the good implies that it is kept in its designed condition for as long as possible and that waste tends to zero. In fact, the companies supplying the product-service will be more interested in a more rational use of resources. Moreover, the PAaS model can enable a continuous increase in the performance offered by a product-service. Through technology maintenance and upgrade activities, companies themselves can foster better service delivery by activating performance contracts, which clear benefits from an environmental point of view as well (Costa Fernandes et al., 2020). Furthermore, this approach relieves clients of the financial risk associated with buying and selling and the possible costs of managing and disposing of the asset. The purchase of high-performance services provided by cloud-based data centers, for example, enables companies to develop their business without having to purchase the entire data center. Among the most significant experiences is the case of Michelin[10]. The world's leading tire manufacturer has developed a PAaS model that allows fleet customers to rent tires instead of buying them. The "tires as a service" BM is based on effective miles driven. Customers do not own the tires and do not have to deal with the maintenance issue. In addition, by receiving worn tires back, the company is motivated to ensure, through design and material selection, that returned tires can be reworked into a valuable input for new tires or something else entirely. Again, in the lighting sector, Philips has developed the "Pay per Lux" BM. Moving beyond the traditional model that accounted for about 40% of industrial energy consumption, Philips offers a complete lighting service that includes the manufacture, installation, maintenance, and reuse of lighting equipment based on previously established performance (GXN, 2018).

2.3 Circular implication on Smart District projects

The impact of the circular transition on the urban environment can be analyzed from several perspectives. Although the CBMs presented deal with strategies that can often be implemented by individual companies, they can sometimes also be integrated into urban regeneration projects. As mentioned in this chapter, the transition towards regenerative and circular economies implies the development of collaborative and multi-scalar ecosystems. Indeed, the ability to give new value to physical (or digital) resources takes on a broader dimension when assumed across different industries or scales of application. In this perspective, the value of each part must be considered in relation to the ecosystems it is embedded in or could enter. In this regard, each building component can be understood as a resource for the building, its neighbourhood and its city.

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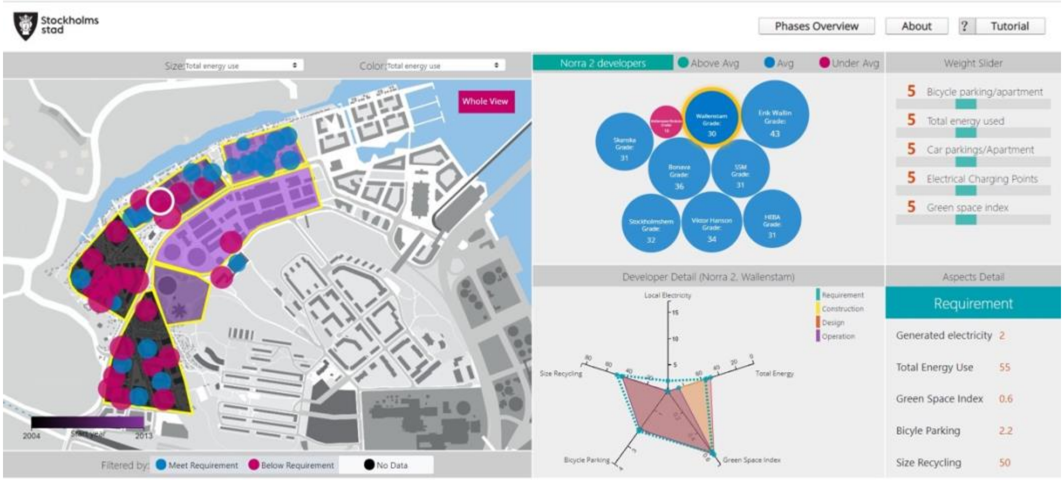
[10] Michelin. https://www.michelin.com/en/activities/related-services/

At the district scale, some of the solutions presented are tested in highly innovative projects to nurture new patterns of resource use and consumption (Viglioglia et al., 2021). The objective of involving people in initiating ecological and circular change also has repercussions on architectural design. From the choice of materials to be used to the spatial arrangement of services integrated into the built environment, architectural design can encourage the dissemination of such approaches. Often supported by the development of information technologies that offer new systems for managing spaces and resources, some highly innovative urban regeneration projects stimulate new reflections on the relationship between CE, digitization, and architectural design.

In this perspective, four main case studies of district regeneration in Europe are presented to map the state of the art and identify, from another point of view, the features of an innovative and collaborative environment in which new CBMs could settle. Especially regarding the creation of shared platforms, these experiences can be considered highly innovative. Access to shared services and resources at the district scale may be a first step in fully exploiting the value of the material and components stored in the city. In addition to these, experiences related to the creation of widespread knowledge and the monitoring of a district's sustainability indicators are key actions to control the state of functioning of a system and continuously evaluate the effectiveness of proposed actions.

Royal Seaport. The project master plan for the redevelopment of the old Stockholm Seaport started in 2009. Its completion, set for 2030, involves the redevelopment of about 236 hectares for 25 thousand people. Underlying the redevelopment project were the following goals: (i) achieving 1.5 ton/person, (ii) climate adaptation, (iii), achieving fuel-free status by 2030 (twenty years ahead of the municipality's goals for the entire city of Stockholm) (Stockholm Stadm, 2019). To do this, a close collaboration between government, universities and businesses has developed a series of highly innovative projects. These include the construction of an urban data dashboard able to show patterns of resource consumption (Fig. 8). The creation of datasets on the main material and energy flows in the urban system has resulted in searchable dashboards for continuous verification of district performance (Sharokni et al., 2015). Despite this approach is the result of experimental research projects, the prospects in quantifying heterogeneous data can on the one hand fuel feedback processes that guide user behavior, and on the other foster policy formulation by authorities to promote virtuous behavioral practices in citizens. Some limitations are presented: sharing of consumption data often finds resistance from utilities; urban data management requires significant information processing tools; and the difficulty of applying the same system to existing urban fabrics.



Size: Total energy use
Color: Total energy use

5 Bicycle parking/apartment
5 Total energy used
5 Car parkings/Apartment
5 Electrical Charging Points
5 Green space index

Generated electricity 2
Total Energy Use 55
Green Space Index 0.6
Bicyle Parking 2.2
Size Recycling 50

Figure 8: Royal Seaport rea-time dashboard (source: https://wska.github.io)

Smart Kalasatama. In 2013, the Helsinki City Council decided to use the Kalasatama port site as a development "testbed" for the future Smart Helsinki. Smart Kalastama is an "open innovation testbed of sustainable smart city services for citizens", a kind of "urban experimentation platform" where companies join with citizens and the public sector to create innovation (Forum Virium Helsinki, 2017). The district acts as a communicative enabler between the city, individuals, and companies, in a perspective of co-development of the city with future residents and key stakeholders (Kalasatama Smart District, 2021). By adopting such an approach, residents become co-creators of an improved quality of life (Virium Helsinki Forum, 2017). Despite the district is still largely under construction, some innovative infrastructure projects were already implemented in the circular perspective. Among the most interesting experiences, the project "bIoTope" project aims to create an open IoT innovation ecosystem where data from smart objects is used to increase district sustainability (Fig. 9)(Forum Virium Helsinki, 2021). Again, the creation of an IoT and MyData infrastructure allows public administrators to monitor the management, separation, and disposal of waste connecting widespread collection points directly into the collection center, located outside the district. An advanced energy smart grid supports new energy storage facilities, the use of electric vehicles, energy-efficient building automation, and on-site renewable energy production though by data produced. At the smart dwelling level, residents can monitor electricity and water consumption in real time.

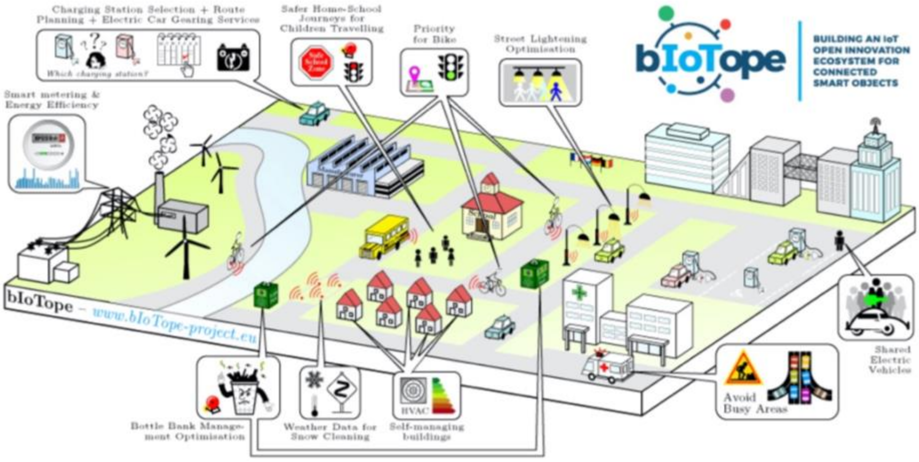


Figure 9: bIoTope project scheme (source: Forum Virium Helsinki, 2021)

Brainport Smart District. The Dutch case study, located in a suburban area of the city of Helmond, has an area of about 150 hectares and plans to accommodate 3,300 residents with the construction of mixed-use buildings (Brainport Smart District, 2022). The master plan developed by UNStudio includes a series of axes running from north to south that divide the area into several zones, each with a different building density. Shared facilities such as kitchens, gardens, reading rooms and gyms are conceived in the circular neighborhood. The project aims to realize a sustainable, circular, and socially cohesive neighborhood that enjoys self-energy generation, food production, water management, digital data management, and innovative shared transportation systems. Among the most innovative aspects, the "100 Homes" project aims to test an alternative economic model in which residents benefit from the exchange of their data (UNStudio, 2021). The economic model is based on the data on living, health, and food, that consumers and small businesses provide for free to technology companies in exchange for services (Fig. 10). The "People data platform" uses the principle of equal exchange and ensure that data ownership is controlled by the end user. Based on "user consent", residents decide which data they want to protect and which they want to share. In this way, residents have control over the services that are developed around their data. According to this vision, this will lead to new, more democratic economic models. The monitoring of people's habits can be reflected in the consequent adjustment of the offer in the provision of services and the saving of economic and material resources. The smart circular water system achieves water savings of 40 to 70 %, with framework conditions that meet health and safety standards.

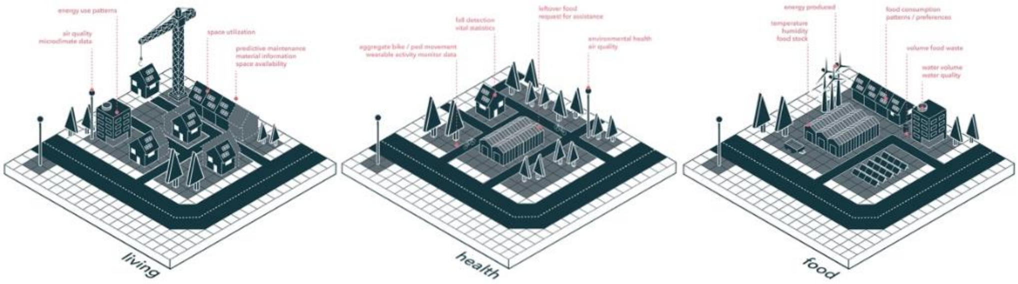


Figure 10: Smart Brainport data sharing scheme (credit: UNStudio)

Green District Cascina Merlata. The project concerns the creation of a multifunctional district in the north-overt area of Milan. Covering about 53 hectares, the Cascina Merlata masterplan integrates highly innovative aspects. Within the masterplan, IoT applications can be found at different scales. Among the most innovative aspects is a Distributed and Energy OPtimization intelligent cloud-based microgrid that is flexible and scalable (Siemens, 2021). The software platform makes it possible to monitor and optimize multi-vector grid performance (air conditioning, heating and electrical systems in apartments and common spaces) and production (as in the case of photovoltaic systems on building roofs and the centralized geothermal system). A district app allows citizens to be continuously informed about household utilities, to access information on property management, or to manage shared services (e.g. private car sharing) (Fig. 11). The innovative management of facilities services is handled by an IoT and Cloud infrastructure. This allows a greater interaction between user and building and foster resources optimization models based on predictive analysis (Cascina Merlata, 2021). The use of IoT in this context is envisaged for monitoring household consumption and sharing environmental data at the neighbourhood scale. In this way, users' awareness of aspects of neighbourhood life is constantly updated. This approach fostering a sense of community also enables, from a social point of view, a strong engagement of people to lead more sustainable lifestyles.

Come posso ridurre l'impatto ambientale ed economico legato all'utilizzo dei componenti domestici?

Perchè la mia casa è spiegata tramite 4 micro-sistemi?

Come posso evitare il distacco della corrente elettrica?

Come viene riscaldata / raffrescata l'acqua che scorre nei pavimenti radianti?

L'acqua potabile che scorre in casa è controllata?

Quante e quali tipologie di acqua scorrono nella casa?

Perchè la mia casa è spiegata tramite 4 micro-sistemi?

Uno scopo del manuale è permetterti di comprendere gli **aspetti distintivi**, a livello tecnologico e componentistico del tuo alloggio, favorendo un **utilizzo più consapevole** delle risorse utili a garantirne il funzionamento.

La suddivisione in quattro micro-sistemi permette di comprendere **l'integrazione tra le modalità di utilizzo di energia, aria e acqua e le scelte costruttive**, in modo da garantirti il massimo comfort in casa.

INDIVIDUAZIONE DEI 4 MICRO-SISTEMI

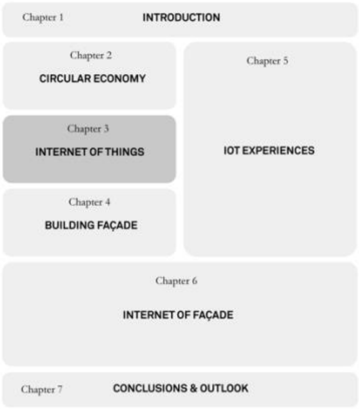
SISTEMA ENERGIA
Le nuove relazioni Energia - Dati - Componenti che alimentano la casa.

SISTEMA CLIMA

Figure 11: Cascina Merlata home handbook (source: Viglioglia et al. 2021, credit: Euromilano)

Chapter 3

IoT for the Architectural, Engineering and Construction sector



Chapter 3 analyses the topic of IoT starting from a semantic analysis of the term and definitions provided in the literature. A taxonomy of IoT technologies is proposed based on the three main aspects that emerged: (i) infrastructure, (ii) application domains and (iii) integration modes. On this basis, a literature review limited to the use of technology for the AEC sector is carried out to define the state of the art and identify perspectives on the topic. Finally, a focus on RFId technologies presents 21 case studies to clarify the potential.

3.1 Moving towards Industry 4.0 in AEC sector

The implications of ICT and IoT technologies on production processes are manifested in various ways, from process management to human-machine interaction. With reference to the former, the digitization of production processes refers to the concept of Industry 4.0. In 2011, at the Hannover Messe, the German term "Industrie 4.0" was coined to describe the digital transformation of industry, which through information technologies enables real-time decision-making, improved productivity, flexibility, agility, and design "predictability" (Lauria and Azzalin, 2019). The set of these technologies, sometimes identified as Key Enabling Technologies (KETs), are essential tools for a company to remain competitive in the market. Advanced sensing, robotics, ubiquitous connectivity, and data analytics are among the main areas in which Europe is looking to invest to start the digitization process (EC, 2021).

This approach, aimed at increasing the efficiency of processes and improving the working conditions of workers, is of great interest for the AEC sector today. As reported by Talamo and Bonanomi (2020), the construction sector has considerable room for growth, being one of the least digitized sectors in the world. Today, the AEC sector looks to the Industry 4.0 paradigm to pursue a path of hybridization with other disciplines and industries (e.g. aerospace, shipbuilding, automotive) (Barberio et al., 2021). In this perspective, the construction industry, while remaining in a state of structural backwardness (Del Nord, 2016), can look to Industry 4.0 technologies as a disruptive driver to rethink production patterns and address current environmental challenges. The evolution of the construction sector, which for years has been aiming to embrace the efficiency and organization of the industrial approach, is dictated by the articulation of the phases of the construction process. As Pierluigi Spadolini anticipated more than 30 years ago, "more than by the discovery of new technologies and new materials, and more than by the evolution of architectural design, construction today is characterized by a process of complex phases and operations, the management of which, since it can no longer be entrusted to traditional operators, requires an industrial-type organization, in terms of the method of planning and control of works" (Spadolini, 1981). In this perspective, the industrial approach on which the construction process is based must be guided by technological and organisational innovations (Dosi and Nelson, 2014). Indeed, technology and innovation constitute the essence of organisational action, which manifests itself in the achievement of goals under conditions of bounded and intentional rationality and the development of technical knowledge instrumental to action (Thompson, 1967). Information technology thus opens new perspectives for the development of the entire sector. Whereas in the past, technological development was aimed at an extension of human biological possibilities, today it focuses as an instrument for governing (and potentially also limiting) human possibilities (Salento, 2018). From this perspective, understanding natural, behavioral, and organisational phenomena is a prerequisite for the development of any innovative technology (Campioli, 2017). Currently, architectural design in its processual, constitutive, and managerial aspects can therefore look to information technologies to realize the material expression of “applied rationality” (Maldonado, 1992). Such rationality is a key approach in addressing the life-cycle oriented challenges imposed by environmental emergency. In fact, the long-term dimension of sustainability reveals an increasing need to consider the monitoring of what has been built as an integral part of the design process, with a focus on the performance of designed services (Del Nord 2016). This is evident in the recent processes of decarbonization of the building stock, where ICTs become fundamental tools to support the monitoring and control of design actions. Based on these premises, the renewal process of the construction sector cannot therefore disregard the adoption of emerging technologies aimed at building digital economies (Del Nord, 2016). In a market in which the contractual object of the project is increasingly concerned with the effectiveness of the services to be delivered and in which the demand-performance approach has overtaken formal aspects, IoT technologies can also become pivotal tools for architectural design.

3.2 The technological paradigm of IoT

3.2.1 A new concept of Internet

In 1982, researchers at Carnegie Mellon University in Pittsburgh connected a vending machine to the Internet to check the temperature of drinks before they were purchased. This is considered the first IoT device in history. Since then, tracing the evolution of the IoT means moving between academic experiments, do-it-yourself tests, and a continuous evolution of the telecommunications infrastructure that has enabled its development. In 1995, the first version of the GPS satellite program allowed the geolocalization of “objects” in space. A few years later, in 1998, the first draft of the IPv6 standard enabled an unthinkable number of devices to be connected[11]. While in 1999, Kevin Ashton, co-founder of MIT's AUTO-ID lab, coined the term "Internet of Things" giving significant impetus to the development of technology (Joshi and Gupta, 2019). Ashton introduced the concept of IoT in a presentation to Procter & Gamble executives to illustrate the potential of RFId technology in tracking consumer products. Since then, the evolution of IoT has had steady growth, finally exploding in 2015. As demonstrated by the graph (Fig. 12), over the past 7 years, the interest to the term "IoT" has experienced unprecedented growth.

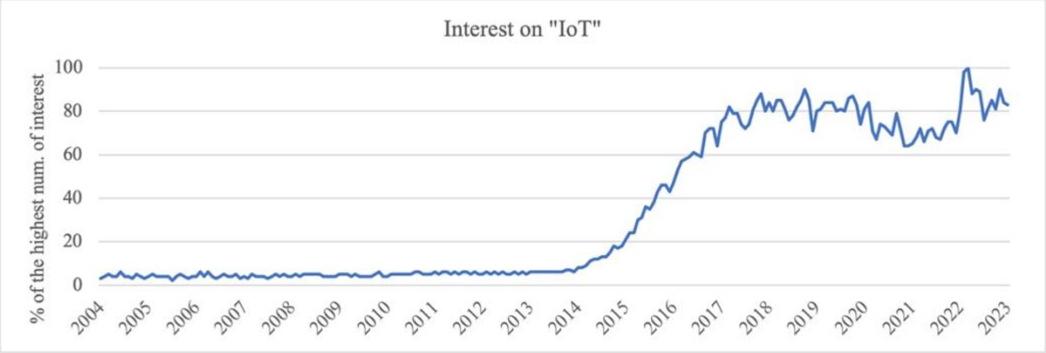


Figure 12: Global interest in the number of Google searches containing IoT. (Source: Google Trend)

This phenomenon, facilitated by exponential access to the Internet (from 1995 to today, the world population with Internet access has increased from 1% to 58%, reaching 87-89% in the most industrialized contexts) (ITU, 2020), has now become a new Internet paradigm. To understand IoT impact, since 2008 it has been included by the US National Intelligence Council in the list of six "Disruptive Civil Technologies" with potential implications for the national economy of the US (National, 2008). Over the years, the development of IoT technology has broadened the significance and potential of Internet. Atzori et al. (2010) confirmed how the introduction of the IoT would serve to exploit the full potential of the Internet, still, at the time, limited by a "host-to-host" approach. From this perspective, the IoT supports the spread of theories of ubiquitous

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[11] In December 1998, IPv6 became a Draft Standard for the IETF. IPv6 uses 128-bit and allows a total of 2^{128} address (or approximately 3.4 x 1038 addresses). The previous standard (IPv4) allowed "only" about 4.3 billion of potential connected devices.

computing, based on the principles of “everywhere”, “anywhere”, “anymedia”, “anything”, and “anytime” (ITU, 2005). The overcoming of the “one person - one computer” concept thus constitutes the theoretical background into which the IoT fits and operates.

To clarify what the neologism “Internet of Things” refers to, the meaning of the term is analyzed. The binomial “Internet” and “Things” refers to the extension of the internet to the physical world, which is identified in a new hybrid physical-virtual dimension where real-world objects can share information through the network. However, it is non-trivial to find an unambiguous definition on the subject. Despite the concept of the “Internet” as a network of computer links is a well-established concept, the term “Things” opens a greater freedom of interpretation. Therefore, depending on the objectives of the different actors, the generic term “Things” can take on different meanings and facets (Granell et al., 2020). Below are the most significant definitions in chronological order on the term IoT (Tab. 2):

Table 2: Definition list for IoT

Reference	Definition
Atzori et al., 2010	IoT refers to a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols.
Mattern and Floerkemeier, 2010	IoT is not the result of a single technology, but it is the combination of several complementary development technologies that provide capabilities, which help to bridge the gap between the virtual and the physical world.
ITU, 2012	A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.
Aggarwal and Lal Das, 2012	IoT is a global network, which allows the communication between human-to-human, human-to-things and things-to-things, which is anything in the world by providing unique identity to each and every object.
IERC, 2014	A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where

	physical and virtual “things” have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network.
CISCO, 2014	The IoT is the network of physical objects accessed through the Internet, as defined by technology analysts and visionaries. These objects contain embedded technology to interact with internal states or the external environment. In other words, when objects can sense and communicate, it changes how and where decisions are made, and who makes them.
ISO/IEC JTC, 2014	An infrastructure of interconnected objects, people, systems, and information resources together with intelligent services to allow them to process information of the physical and the virtual world and react.
Chen et al., 2014	The IoT is an intelligent network which connects all things to the Internet for the purpose of exchanging information and communicating through the information sensing devices in accordance with agreed protocols.
Borgia, 2014	IoT refers to an emerging paradigm consisting of a continuum of uniquely addressable things communicating with each other to form worldwide dynamic networks
Goldman Sachs, 2014	The IoT connects devices such as everyday consumer objects and industrial equipment onto the network, enabling information gathering and management of these devices via software to increase efficiency, enable new services, or achieve other health, safety, or environmental benefits.
Dobbs et al., 2015	Embedded sensors and actuators in machines and other physical objects that are being adopted for data collection, remote monitoring, decision making and process optimization in everything from manufacturing to infrastructure to health care.
EU, 2015	The IoT refers to a distributed network connecting physical objects that are capable of sensing or acting on their environment and able to communicate with each other, other machines, or computers. The data these devices report can be collected and analyzed to reveal insights and suggest actions that will produce cost savings, increase efficiency or improve products and services.

ICC, 2016	Simply stated, IoT is the connectivity that enables connected devices to interoperate. IoT connects the world's physical systems such as power meters, vehicles, containers, pipelines, wind-farm turbines, vending machines, personal accessories, and much more.
Sethi and Sarangi, 2016	The IoT is defined as a paradigm in which objects equipped with sensors, actuators, and processors communicate with each other to serve a meaningful purpose
Patel and Patel, 2016	The Internet of Things refers to a type of network to connect anything with the Internet based on stipulated protocols through information sensing equipment to conduct information exchange and communications to achieve smart recognitions, positioning, tracing, monitoring, and administration.
Botta, 2016	The IoT paradigm is based on intelligent and self-configuring nodes (things) interconnected in a dynamic and global network infrastructure
Muntjir et al., 2017	IoT [...] is the vast network of devices connected to the Internet, including smart phones and tablets and almost anything with a sensor on it — cars, machines in production plants, jet engines, oil drills, wearable devices, and more. These "things" collect and exchange data.
INFSO, 2018	IoT semantically means ‘‘a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols”
Matta and Pant, 2019	IoT is a paradigm with a notion of enabling the things (physical entities, e.g,: human, car, animal, mirror, bulb, plant, etc.) to communicate with each other, to transfer and receive the information (read-only data), through the use of underlying network (wired or wireless), supporting technologies (e.g., ZigBee, Bluetooth, Wi-Fi, etc.), required sensors, actuators and computing devices, and finally respond back in a way that requires least or negligible human intervention.
IIC, 2020	IoT is a concept where components are connected via a computer network and where one or more of those components interact with the physical world.
CITC, 2021	The IoT is defined as a network of devices that are autonomously able to sense, monitor, or interact with the surrounding environment, in addition to

	collect and exchange data.
IEFT, 2022	The IoT is the network of physical objects or "things" embedded with electronics, software, sensors, actuators, and connectivity to enable objects to exchange data with the manufacturer, operator, and/or other connected devices.

As pointed out by Atzori et al. (2010), three main complementary visions can be reported to highlight different interpretations on the topic: (Fig. 13): "Internet", "Things", or "Sematic"-oriented visions. The first one, "Internet"-oriented vision, refers to technology from a purely IT point of view, where the network and connection modes represent the central aspects. The second, "Things"-oriented vision, emphasizes the physical dimension (hardware and tangible goods) of new intelligent and digitally integrated objects. Finally, the "Semantic"-oriented vision, places the ways of representing, storing, interconnecting, and organizing information as the starting point for explaining technology. Recently, a fourth one has been added to these 3 visions by Jia et al. (2019). The "Human"-oriented vision is thus included to interpret the phenomenon from the user's perspective, emphasizing the implications in terms of user interaction.

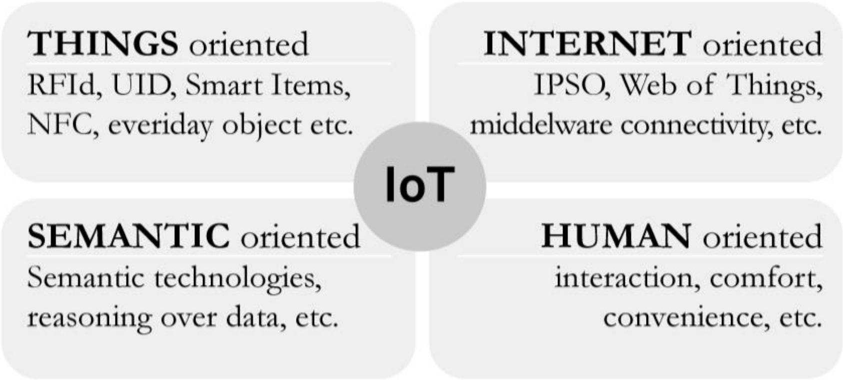


Figure 13: 4 visions on IoT: reworked from Atzori et al. (2010) and Jia et al. (2019)

3.2.2 A proposed taxonomy for IoT

From the review of definitions, some key concepts clearly emerge. As also highlighted in the literature review by Sorri et al. (2022), the keywords "network", “integrated”, and “application” are among the most recurrent terms in describing the IoT concept. Based on these three concepts, a taxonomy of the IoT is proposed to highlight the new paradigm. The tree scheme allows heterogeneous topics and aspects to be organized into a single framework, thus enabling a comprehensive overview (Fig. 14). Specifically, aspects related to the concept of “network” are identified in the type of architecture that characterize the IoT. The second concept, “integrated”, is analyzed in the ways in which digital and physical components are integrated. Finally, the term “application”, is understood as potential application domains of the technology.

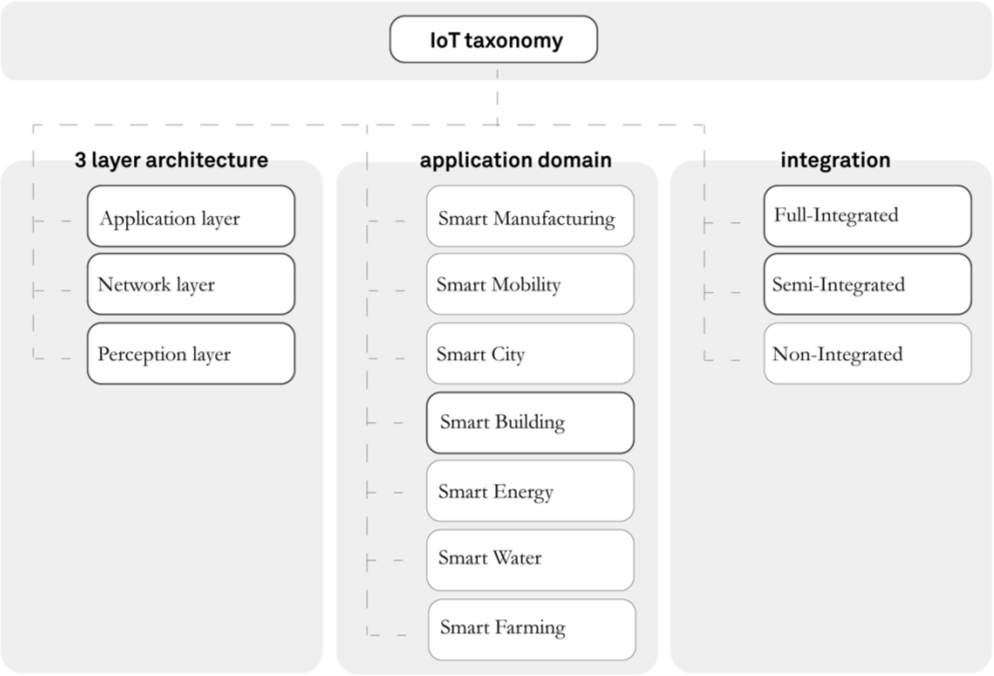


Figure 14: A proposed taxonomy for IoT

The three elements can be presented as follow.

- *3-layer architecture.* As well as for the definition of the term, there is no unambiguous classification recognized in the literature to clarify the structure of the technology. The still evolving state of the technology, coupled with a broad field of applications, has led to various interpretations of the structure. The “layer” structure, as overlapping domains assigned to different functions and closely interrelated with each other, is a particularly effective approach to explain the IoT infrastructure. Despite this structure is used by most researchers, this presents several differences. From 3 to 7 levels, the relationship between different elements of the system can be read differently. Of these, the 3-layer architecture represents the most common and widely used structure (Giovanardi et al., 2021). This thesis, to make the language uniform, adopts the 3-layer structure with the nomenclature used by Al-Fuqaha et al. (2015), Jia et al. (2019), and Daissaoui et al. (2020): Perception layer, Network, and Application layer (Fig. 15). These can be identified as follows.

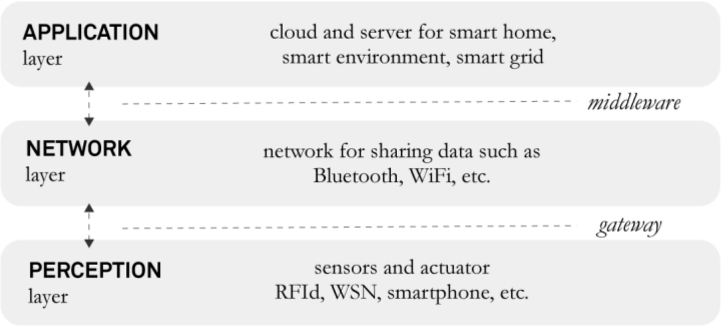


Figure 15: 3-layer architecture

The *“Perception Layer”* is the layer of the physical environment equipped with sensors to detect and collect information. The task of this layer is to detect physical parameters or identify other intelligent objects in the real environment to share the information with higher layers. Therefore, it is often identified as the layer of “everyday” sensors and smart devices. WSN or RFId are the two main families of sensors used in this level.

The *“Network Layer”* is responsible for processing and transmitting the collected raw data. The term “network” identifies the technology used to transmit the electrical signal, which is responsible for connecting intelligent objects, network devices, and servers. Communication and networking technologies are divided into wired and wireless technologies (e.g. Wi-Fi, Bluetooth, ZigBee or infrared). In this regard, issues related to signal transmission and communication protocols appear to be central themes.

The *"Application Layer"* is the highest level. It is the front-end interface with the end-user, responsible for guiding the decision-making process. According to Trappey et al. (2017), it is divided into two main level: the application level and the computational one. The former is responsible for the provision of services, embracing the entire end goal of the system, identifying the scope, methods, and protocols to be used. The second incorporates the enabling technologies that can process data, transform it into information and make it available and understandable to the end user.

- *Application domain.* It refers to the context, and consequently the purpose, for which the technology is used. The pervasiveness of technologies in this context has opened perspectives in various fields. Clarifying the application domain is therefore a central action to describe the technology. The adoption of IoT in products, domains, and processes is often identified with the prefix "smart". The introduction of sensors that enable objects to share information is thus identified as a new level of intelligence for tangible assets. According to the EC (2019), there are 6 main fields of application for IoT: Smart Building, Smart Energy, Smart Manufacturing, Smart Water Management, Smart Mobility, Smart Cities, Smart Farming, and Smart Living Environment. Specific applications can be derived from the macro domains, such as smart metering for building energy consumption, smart workplaces to increase safety, or the smart mobility platform to foster asset shareability. Among these, four are closely related to the subject of this thesis: Smart Building, Smart Manufacturing, Smart City, and Smart Living Environment. The introduction of smart approaches can be understood, from one hand, in the ways and processes in which architecture is built, managed, and preserved over time, and, on the other, in the services and performances that are provided. In this perspective, European policies in the development of projects aimed at creating an intelligent built environment confirm the centrality of the topic. From an environmental, social, and economic point of view, the introduction of IoT can be decisive in proposing inclusive, regenerative models that know how to maximize the contribution of human and social capital.

- *Integration.* It represents one of the most peculiar aspect of IoT technology. The potential application of technology to most of the everyday physical components stimulates new innovative scenarios. From urban objects (e.g., street lighting, traffic lights, sidewalks, parking lots, etc.) (Talamo et al., 2016) to personal objects (e.g., smartphones, glasses, etc.), digital integration can take place in various ways. Rethinking objects that can share information about their actions implies a redesign of them. From this perspective, several issues emerge. First, the physical integration, between hardware and the physical entity hosting the IoT, represents one of the central challenges in the deployment of smart assets. Indeed, the positioning of the IoT hardware system is a central issue for the functionality of the system and its maintainability over time. Physical-digital integration entails issues, such as system power supply or signal interactions, that need to be rethought depending on the application context. Three main integration types are identified: fully integrated, semi-integrated, and non-integrated. The discriminating factor between the three is the dependence of the sensor on the physical element to function. The former refers to those objects that are fully integrated with digital hardware. Cars, smart streetlamps, refrigerators, with built-in sensors represent the highest level of integration. Physical object and digital device form an intelligent and inseparable unicum. Semi-integrated, on the other hand, are those devices such as wearable devices such as watches, socks, t-shirts, or smart glasses, which although digitally integrated into a physical component must be adopted by a “things” into function (in the case of wearable devices, the physical “things” is the human body). Finally, there is a family of non-integrated sensors that live a life of their own and can be used in space as and when we want (e.g., environmental sensors). For example, a temperature sensor can be placed anywhere and does not need its own object to function.

3.3 Literature Review

The objective of the literature review is to establish the state of the art in the use of IoT technologies for the AEC sector. In this way, it will be possible to outline research perspectives on the topic and identify points of contact with the specific field of investigation of this research. More precisely, the literature review aims to systematize transdisciplinary knowledge in the AEC context where, to date, the few research experiences and the evolving context determine a barrier in the interesting of stakeholders in the IoT technology. This study deals with the IoT topic at the scale of the building and its components. Based on the previous taxonomy presented (architecture, application domain, and integration), the literature review fixed these three objectives:

- Goal 1 (G1): define the elements of the IoT architecture for the AEC sector;
- Goal 2 (G2): identify the main IoT application domain fields;
- Goal 3 (G3): investigate physical-digital integration ways.

3.3.1 Methodology

As highlighted in the previous paragraph, the breadth of the topic implies a clear delineation of the research domain and boundaries. With the aim of defining the state-of-the-art in the use of IoT technologies for the AEC sector, a systematic literature review is proposed. The search was conducted through two scientific online databases (Scopus and Science Direct) and a search engine (Google Scholar) to include part of the "gray" literature in the mapping. Specifically, the paper selection process consisted in 4 main steps (Fig. 16).

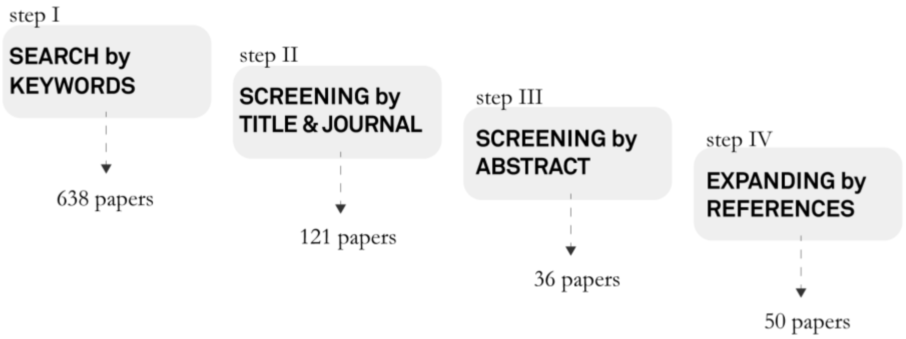


Figure 16: literature review workflow

More specifically:

- *Step 1*. The keyword search uses the string "IoT" OR "Internet of Things" AND "Smart Building*". The term "Smart Building" was identified as central to the search as result of the integration of IoT, building, and building process. Using only the word "building" expanded the search results too much, making it impossible to manage. Also, searching by using the words "AEC", "architecture", "engineering", or "construction" did not yield any useful results for research purposes. The following filters were set up to refine the keyword search: (i) publication period: 2010-2020 (June); (ii) presence of keywords in: title, keywords or abstract; (iii) publication type: open access. By combining the results from Scopus, Science Direct, and Google Scholar, 638 articles were tracked.

- *Step 2*. An initial screening of the papers was carried out by reading the titles and analyzing the journal in which they were published. This step was essential to drastically limit the number of papers to be managed and make the results coherent with the review objective. In fact, the interdisciplinary nature of the topic, widely covered in communications engineering but only marginally in architectural disciplines required a selection of journals based on disciplinary sector. This step resulted in the selection of 266 articles.

- *Step 3*. To map the phenomenon through an adequate number of articles, the abstracts were analyzed. The selection process thus saw the selection of 121 articles, which were then further reduced to 36 based on research purpose. In fact, to map the state-of-the-art, literature reviews, case studies, and more applied research experiences were preferred over theoretical contributions.

- *Step 4*. From the 36 selected articles, the number of articles was again expanded to 50 based on the references cited in these texts. Using Gephi neural network software, it was possible to include 14 frequently cited papers that had not been subject to selection by keywords (Fig. 17). This process made it possible to incorporate those texts that did not explicitly contain the keywords in the search strings but were still necessary to track the state-of-the-art (e.g., they reported the name of the technology used, without reporting the term IoT).

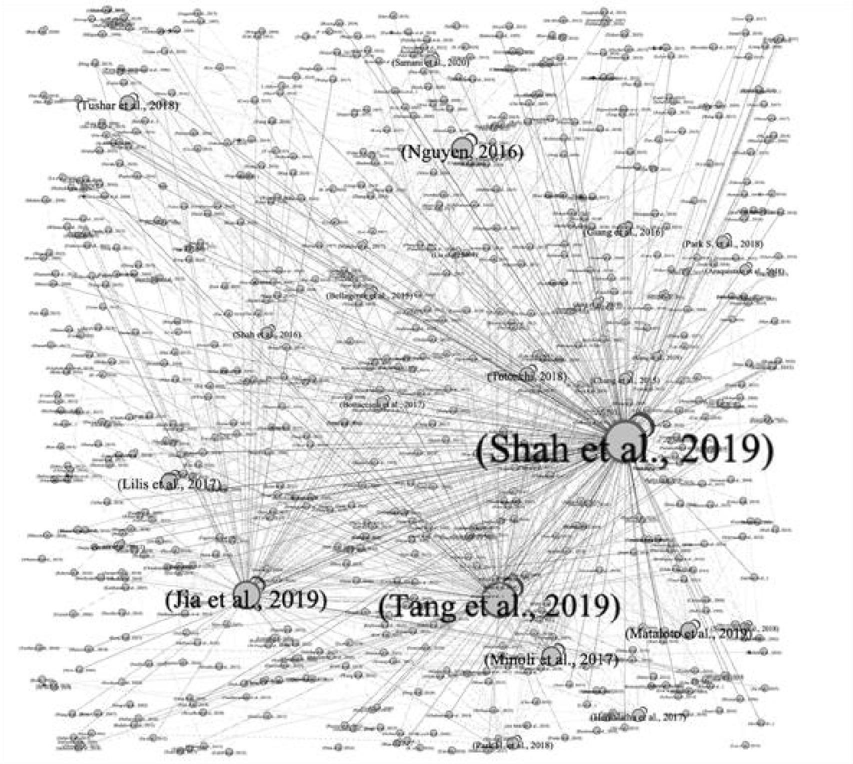


Figure 17: “IoT” and “Smart Building” publications trend. The dimension of the circle is due to the number of publications

Having defined the papers for defining the state-of-the-art, these were analyzed according to the three research Goals (Gs). Specifically, the results are reported according to: (G1) what infrastructure is being used; (G2) what application domain was investigated; (G3) how physical-digital integration is planned.

3.3.2 Metadata analysis

An initial analysis of the metadata of the selected papers offers several insights. The first concerns the trend in the number of publications integrating the topic of “IoT” and “Smart Building”. As shown in Figure 18, the production of scientific papers has intensified rapidly since 2016. Confirming the growing trends since 2015 in interest in IoT technologies, we can thus imagine how the stage of development of many IoT solutions are now mature. Moreover, the interest in IoT technology is still predominantly rooted in the disciplinary fields of computer science, information science and process management journals, while in journals related to “sustainability” this still appears to be an emerging topic. Among these, literature reviews and application case studies appear to be the main types of articles.

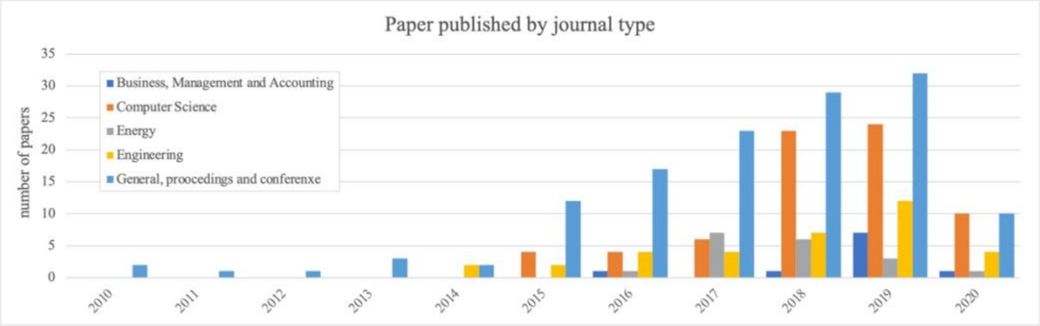


Figure 18: “IoT” and “Smart Building” publications trend. The dimension of the circle is due to the number of publications

The metadata analysis was also essential in selecting the most influential papers and clarifying key concepts. Through the analysis of the references used and keywords of the 36 papers identified from the literature screening, some considerations can be made. The references and keywords analysis were carried out with Gephi software, an open-source network analysis and visualization software written in Java on the NetBeans platform. In this way, the relationship between multiple elements (papers) is identified through nodes that are ordered in space according to the number of relationships (distance between elements) and their attractive strength. The importance of the node is thus manifested according to its position and size. Regarding citations, it is thus possible to identify which articles are most cited among the selected papers. While in terms of keywords, some pivotal concepts emerge from the relationship between IoT and Smart Building. Among them, "BIM", "Big Data", "RFId", "sensors", and "Smart City" emerge defining areas of application (Fig. 19).

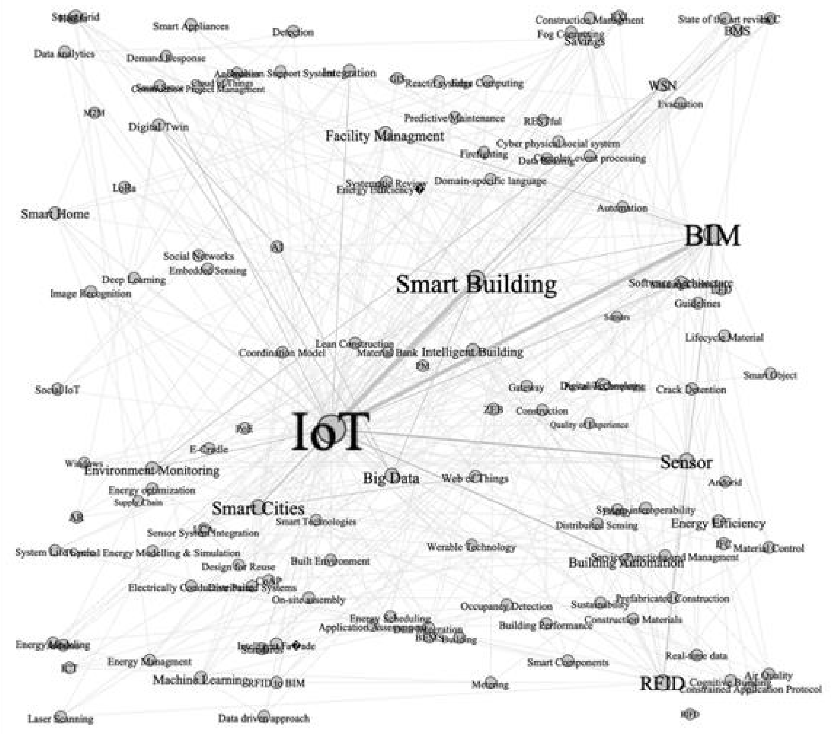


Figure 19: "IoT" and "Smart Building" publications trend. The dimension of the nodes is due to the number of publications

3.3.3 Three-layer architecture (G.1)

The reviewed papers can be classified according to the way they refer to IoT architecture. As previously mentioned, the IoT architecture is usually defined by layers, from three to seven (3, 4, 5, or 7 layers), including elements and functions (Al-Fuqaha et al., 2015). Despite conceptual and semantic differences may occur (Tab. 3), the several structures are traced back to the 3-layer architecture and, thus facilitating the comparison.

Table 3: IoT's layers architecture analysis

Layers	Layers architecture	Reference
3 layers	Data acquisition, processing, presentation	(Alves et al., 2017)
	Physical infrastructure, control, application	(Liu et al., 2015)
	Information, application, user interface	(Cheng et al., 2020)
	Field, data, processing	(Rinaldi et al., 2020)
	Sensor, communication, application	(Mataloto et al., 2019)
	Sensing, processing, reproducing	(Park and Rhee, 2018)
	Smart grid, fog, cloud	(Shah and Mishra, 2016)
	Process, communication, data	(Giang et al., 2016)
	Perception, network, application	(Al-Fuqaha et al., 2015; Jia et al.,2019; Daissaaoui et al., 2020;)
	Data-source integration, services, application	(Bottaccioli et al., 2020)
4 layers	Information, connection, service, virtual	(Park et al., 2018)
	Perception, network, data, application	(Kang et al., 2018)
	Data collection, transmission, service, interface	(Abdel-Basset et al., 2018)
	Device, gateway, cloud, App and application	(Malche and Maheshwary, 2017)
5 layers	Physical, virtualization, aggregation, servitization, application	(Floris and Atzori, 2015)

	Object, object abstraction, service management, service composition, application	(Atzori et al., 2010)
7 layers	Things, data, fog, aggregation, centralization, storage, application	(Minoli et al., 2017)

Perception Layer. A wide range of IoT sensors and smart measurement devices are available in the market. In particular, there are two main families of sensors that can be used: Wireless Sensor Network (WSN) and Radio Frequency Identification (RFId). The first one, WSNs are the most suitable solution to enable wireless monitoring of several environmental parameters. Indeed, wireless technology enables widespread use of these devices, even in environments not originally designed to host an IoT infrastructure. Air temperature, relative humidity, air pressure, lighting, presence, and acoustics are the most common parameters in the construction industry. For each physical parameter, the ways of measuring the phenomenon are different, thus creating a wide range of sensors. For example, humidity can be recorded through capacitive, resistive, or thermal sensors. Araquistain et al. (2018) developed multipurpose WSN sensors including motion, temperature, light, humidity, vibration, and UV radiation sensors to increase building energy performance. A similar approach was used by Shah and Mishra (2016) in monitoring temperature, humidity, and intensity. Again, among the most investigated parameters are those related to air quality. Kumar (2016), Xia et al. (2019) and Giovanardi et al. (2020) use sensors to monitor particulate matter (PM) 2.5 and 10. The second family is represented by RFId technology, which is mainly used in logistics and the supply and production chain. Active, passive, or semi-passive RFId sensors enable the ability to recognize an object when within an electromagnetic field activated by a reader. In fact, by sharing signals when "queried", they enable the monitoring and exchange of information between reader and tag. Significant experiences in the use of RFId tags regarding building component traceability (Lee et al., 2013), the adoption of high-frequency RFId sensors for IoT-BIM based system development (Xue et al., 2018), or the integration of low-frequency passive RFId sensors into concrete components (Niu et al., 2016; Valero et al., 2015). In addition to these two families, video camera-based systems can be counted as a sensor type. In this perspective, Dave et al.

(2017) present an IoT-oriented system in which cameras facilitate construction site operations.

Network Layer. Data transmission in the AEC sector mainly occurs via Wi-Fi, Bluetooth, or Zig-Bee protocols. These technologies are used in data transmission, for example, between meters and service providers, between building energy management sensors and indoor environmental monitoring sensors, or between building users and smart appliances (Ahmad et al., 2016). Wireless communications are preferred as they do not require an invasive physical infrastructure, although a more unstable transmission may characterize it. Wi-Fi is a communication technology that uses radio waves for local networking between devices based on the IEEE 802.11 standards. The most used frequency is the 2.4 GHz UHF and 5.8 GHz SHF ISM radio bands (Jia et al., 2019). On the other hand, the Bluetooth system can connect mobile devices over short distances, also using radio waves. Finally, ZigBee is a technology designed for short-term communication and low power consumption, exploited in connecting many WSN systems. In this context, Li-Fi (Light-Fidelty) experiences as future alternatives in data transmission are engaging (Minoli et al., 2017). The Li-Fi technology refers to the capability of LED lights to share data through light signal without this being able to be seen by the human eye. In the case of RFId tags, on the other hand, information sharing is done by means of the electromagnetic field created by the reader (Xue et al., 2018).

Application Layer. The most investigated area in this layer concerns the tools with which the end-user interfaces for managing the building system. BIM represents the most investigated tool in literature, being able to integrate in a standardized information network data from sensors placed in the environment. In this regard, Cheng et al. (2020) suggested BIM for FM activities, combining it with specific Artificial Intelligence applications to predict future building elements and subsystems state. To integrate sensor data into a BIM environment with more complex conditions, Alves et al. (2017) proposed an alternative specific language (BIMSL) to facilitate query development (Tang et al., 2019). On wider scale, GIS can represent an interesting tool for urban planning purposes, combining the information about energy and matter flows to space-temporal coordinates. GIS was also used as input data in energy simulation (Bottaccioli et al., 2020) and in managing emergency activities (Liu et al., 2014).

3.3.4 Application domain (G.2)

The analysis of application domains identified 7 main fields for IoT (Tab. 4). These can be classified as follows.

Table 4: IoT application domain for construction sector

Domain	Reference
Design	(Atzori et al., 2010; Alves et al., 2017; Bottaccioli et al., 2020; Boje et al., 2020; Kim et al., 2020)
Production	(Lee et al., 2013; Dave et al., 2015)
Construction Site Management	(Lee et al., 2013; Valero et al., 2015; Niu et al., 2016; Li et al., 2018)
Facility Management	(Liu et al., 2015; Kueng and Brunner, 2016; Hemalatha et al., 2017; Park and Rhee, 2018; Wong et al., 2018 Daissaoui et al., 2020; Cheng et al., 2020; Rinaldi et al., 2020;)
Energy Management	(Ahmad et al., 2016; Minoli et al., 2017; Araquistain et al., 2018; Tushar et al., 2018; Mataloto et al., 2019)
Comfort and User interaction	(Zanella et al., 2014; Chang et al., 2015; Sastra and Wiharta, 2017; Srinivasa et al., 2018; Park et al., 2018; Kumar et al., 2018; Dave et al., 2018; Shah et al., 2019; Giovanardi et al., 2020)
End-of-Life	(Dave et al., 2015)

- *Design*. Until now, the IoT's intrinsic characteristics have implied that its use lends itself more to process control than to be as a support tool for the project's design phase. However, generating, collecting, analyzing, and sharing information opens new scenarios. A considerable amount of research is testing the benefits in facilitating exchanges of data among the many stakeholders involved in the design process through IoT-supported interoperable platforms. For instance, Alves et al. (2017) pointed out that many experiences have attempted to link IoT sensor and BIM. Presenting the BIMSL project, Alves et al. (2017) develop a BIM that is fed by real time data trying to overcome issues related to data standards and formats. Indeed, Boje et al. (2020) highlighted how the interoperability between IoT and BIM represents one of the most barriers for a widespread diffusion of technology. Most of the experiences refers to a closed application domain, developing applications for specific areas, such as energy management, building automation, fire protection, health and safety, and augmented reality. Among these, the research presented by Dave et al. (2015) is interesting because import industrial strategies such as Lean Construction Management Systems to use data for decision-making in the design processes for construction sector. Again, the ability to reprocess large amount of data to feed and calibrate virtual simulation models allows to increase of the forecasting algorithm's reliability (Bottaccioli et al., 2020).

- *Production*. Monitoring the actions that characterize production steps is an ideal area for IoT. From this perspective, the adoption of sensors can enable a continuous monitoring of efficiency parameters. As already demonstrated in other industries such as automotive, the benefits can be identified both in economic terms (e.g., reduction of time-consuming processes) and environmental terms (e.g., greater control over process efficiency). Despite the Engineered-To-Order nature of the construction industry may limit (at least initially) the adoption of such sensors, the trend to introduce industrial approaches stimulates new scenarios, especially for some specific industries (e.g., prefabricated façade sector), where the level of off-site production is high. Lee et al. (2013) study how component traceability through RFId sensors can foster greater control in the production of materials. On the same topic, Dave et al. (2015) hypothesize the use of RFId, QR/bar codes, and GPS systems to improve traceability and geolocation of assets within the supply chain. Supported by a recent regulatory development on the topic, IoT for traceability of building elements and materials can be identified as a topic with great margins for evolution.

- *Construction Site Management*. It represents an area ideally suited for the introduction of IoT devices. Construction site logistics, cost and time control, process traceability, and worker safety are the most critical aspects that can be addressed by IoT technology (Valero et al., 2015). As well as for production stage, optimizing construction site management means reducing time and cost for companies and enhancing the quality of the product or process. Most of the activities related to the construction site management, such as the materials procurement, the notification of low stocks, material shipment, or storage can be automated through the IoT (Dave et al., 2015). In this context, the most relevant experiences concern the use of RFId tags (Lee et al., 2013; Niu et al. 2016). The adoption of IoT to automate the installation phase can generate significant benefits in terms of time and money (Liu et al., 2018). In this perspective, the research published by Niu et al. (2016) on prefabricated façade panels with integrated tags connected via Bluetooth to be recognized directly by the crane, opens interesting scenarios in the development of automated, and safety worksite.

- *Facility Management*. It has emerged as one of the most investigated areas. FM refers to the ability to monitor the performance of products or services for long lasting assets enables a greater attention to IoT technologies in building management. By analyzing 120 scientific papers on the topic of digital technologies for FM, Wong et al. (2018) highlighted how the specific scope of application in this area is varied. In particular, they report how many papers focused on the role of RFId sensors in feeding BIM models. Interoperability between different project management tools appears to be a central issue in the widespread introduction of IoT technologies. In this perspective, building maintenance represent one of the main investigated fields. Cheng et al. (2020) developed a predictive maintenance planning for mechanical, electrical, and plumbing systems based on data collected from an IoT network sensors. Temperature, humidity, pressure, and airflow sensors can generate trends and send signals to building managers if anomalies occur. Kueng and Bruner (2016) extended the monitoring to the building parts. An IoT sensor to monitor the concrete floors' static behavior has been proposed. This approach could provide a significant reduction on maintenance cost over building life-cycle (Hemalatha et al., 2017). Further significant examples include workers and users safety. Park and Rhee (2018) designed an IoT architecture to notify the safest escape route in real-time in case of fire for multi-story buildings. A similar approach is proposed by Liu and Zhu (2014), highlighting how artificial intelligence can help make more appropriate decisions in a limited time, to identify preferential escape routes.

- *Energy Management*. It represents the area where IoT has had the greatest development to date. Driven by the immediate and huge economic benefits, the monitoring of energy consumption has enabled greater insight into the real buildings' performance (Park et al., 2018). This, supported by a greater maturity on the subject, has allowed a rapid diffusion of smart metering technologies on the market (Casini, 2016). The capability to increase space's responsiveness is crucial to reduce building energy consumption. In this perspective, Araquistain et al. (2018) highlighted how redesigning the HVAC systems based on a greater knowledge of the hourly profiles of use could generate significant savings. A key issue in this area is represented by the need to connect IoT infrastructure and the Building Energy Management System (BEMS). The development of a widespread sensor network could serve to adjust HVAC systems according to the actual needs of spaces (Mataloto et al., 2019; Bellagente et al., 2015; Jang et al., 2019). In this area, the flexibility and interoperability of different monitoring systems is a central issue still to be solved.

- *Comfort and user interaction*. Efficient energy management of the building is clearly linked to users' comfort and behavior. If, on the one hand, the IoT becomes a tool to increase the comfort and healthiness of the building, it also assumes a fundamental role in informing the users and guiding them to the correct use of the building devices. IoT, by reformulating human-human, human-system, and system-system interaction modes (Dave et al., 2018), has introduced feedback and demand response approaches (Minoli et al., 2017). Regarding the comfort issue, during the last decade, researchers have proposed sensor-actuator based applications for monitoring and control of air quality, lighting, and thermal comfort (Kumar, 2018). In this perspective, the technological development has enabled greater interest in issues, such as air quality, that are closely related to user well-being (Giovanardi et al., 2020)

- *End-of-Life*. The application of IoT technologies in C&D waste management for the buildings and elements end of life is still little investigated. Although some papers mentioned the applicability of these technologies over the building’s life cycle, the experiences testifying possible advantages in this field are still scarce (Dave et al., 2015). In analogy with the installation and management of the construction site processes, we can assume that even the decommissioning phases of a building can be monitored and supported by IoT devices, widespread on the site and integrated into the components themselves. In addition, a field of investigation can be identified in the traceability of disposal materials. Indeed, the regulatory evolution, requiring growing attention to C&D waste, implies the introduction of monitoring systems to manage matter flows and processes.

3.3.5 Integration (G.3)

Physical-digital integration is a key point in defining the state of the art of technology. From the literature review, four main types of integration emerge in the AEC sector. These can be classified as follows.

- *Systems*. The ability to remotely monitor the functioning and the performance of HVAC systems involves significant benefits in terms of energy savings, costs, and comfort. This led to a rapid technological evolution in the integration of sensors in systems. Voltage, frequency, air or water flows, and electrical load sensors for mechanical, electrical, and plumbing systems can be considered mature technologies (Cheng et al., 2020). In this field, Casini (2016) highlighted how IoT can be fully integrated in energy consuming equipment, such as air conditioning systems, electrical, switches and sockets, plumbing, etc. The benefits of integrating the IoT into mechanical systems are dictated by the fact that these represent an important consumption item in the building's energy balance.

- *Building Components*. Physical integration into building components is a topic of recent interest. SCOs, such as prefabricated elements, floors, stairs, beams, and pillars, can potentially integrate useful information for the construction, use, and management of a building (Lee et al., 2013; Li et al., 2018). There are two main building components that enable the integration of IoT devices: prefabricated concreted panels and building façade. The integration in the first one opens interesting scenario in controlling construction phase (e.g., material drying) and monitoring static asset behavior once it is in use. Whereas as for building façade technology, the IoT integration allow to monitor indoor and outdoor environmental condition, thus enabling several actions. Niu et al. (2016) and Xue et al. (2018) aimed a fully integrated tag for prefabricated façade panels to collect asset's information. Again, semi-integrated strategies are developed for façade. Arnesano et al. (2019) proposed a "plug and play" device installed to improve energy efficiency of façade or Giovanardi et al. (2020) tested an indoor/outdoor air quality monitoring that could be semi-integrated into the window's frame.

- *Furniture*. The responsiveness of the digital components represents a focal point in the future development of new products for the home. In hospitals, offices, public buildings, furniture, and instruments can be traced within the spaces to facilitate locating the devices and allowing the inventory of the available items. In this perspective, product innovation has accelerated the transition to a connected and smart furniture. Lights, ovens, refrigerators, ore washing machines are just a few examples of how the IoT has already taken root in our homes (Yun et al., 2015). The IoT integration in everyday goods could provide us with large amounts of data, thus representing new information sources.

- *Personal Devices*. Finally, the proposed classification reveals a series of experiences based on the use of data produced by wearable devices mainly to be used outside the building itself. The adoption of semi-integrated or non-integrated sensor could ease the fixed IoT infrastructure in the building (Park et al., 2018). The most significant experiences in this context occur in the wearable devices for healthcare and telemedicine sectors, where these sensors help monitor patients' state of health and their rehabilitations (Srinivasa et al., 2018).

3.3.6 Discussion

The literature review shows an extremely broad and fragmented picture of technology in the AEC sector. In this field, the fragmented nomenclature, the variety of communication protocols and the proliferation of standards do not facilitate the diffusion of technology in the AEC sector. In this perspective, literature review research serves to fill a widespread information gap dictated by a still preliminary state of technology maturity. Thus, defining the state of the art can be considered a preliminary and necessary step for the development of IoT in the façade sector. The specific taxonomy proposed for AEC sector aims to offer an overview of main aspects of IoT technology (Fig. 20). Moving to the results discussion, it is evident that the growth margins for the application of IoT technologies are still high. About 10 years after the first experiences intercepted in the literature, the adoption of IoT technologies on the market has not yet been definitively achieved. From this perspective, overcoming a cultural and technical approach, still rooted in “traditional” patterns and ways of doing key challenge for technology deployment. Thus, if from an environmental and economic point of view the scientific community has already experienced its benefits, the widespread adoption of IoT is still a long way off (Santarius et al., 2020). Moreover, it is worth noting that so far the use of IoT technology has always been used to solve specific problems (energy efficiency, comfort monitoring, etc.), thus precluding the possibility of developing new digitally integrated products that can truly exploit the potential of ubiquitous technologies and host-to-host communications (Atzori et al., 2010) With reference to the three objectives of the literature review, we can summarize the following implications.

Concerning the IoT architecture (G1), the literature review confirms how 3-layer scheme (perceptions, network, application) represents the most widely used approach (Daissaoui et al., 2020). Here, WSN and RFId environmental sensors have been confirmed as being of equal importance in the field. If the former, they are mainly used for aspects purely related to the energy optimization (Mataloto et al., 2019; Minoli et al., 2017), the latter emerge to address issues of product and process traceability (Lee et al., 2013; Dave et al., 2015). There is still no preferred protocol for the types of signal sharing, it may vary depending on the purpose of the application, the frequency of the signal required, and the system architecture. Among these, Wi-Fi, Bluetooth, Zig-Bee, or LoRa are the most common used in the built environment (Ahmad et al., 2016). Finally, regarding the third layer, it emerges how the relationship between IoT and BIM represents the most investigated perspective in supporting virtual models calibrated with real-time data (Kang et al, 2018).

Regarding the application domain (G2), it is evident that there are different levels of maturity according to the field of application. While experiences in the fields of energy management (Araquistain et al., 2018; Tushar et al., 2018), facility management (Cheng et al., 2020; Rinaldi et al., 2020) and comfort (Chang et al., 2015; Park et al., 2018; Kumar et al., 2018;) have generated a spread of smart metering applications and applications already on the market, other domains are in an embryonic stage. The development of these supports the creation of datasets that enable data-driven dynamics with implications on reducing time and resource consumption (e.g. predictive maintenance). Among the sectors with the greatest room for growth, the production, site management and end-of-life phases could benefit from such applications. Process control and automation could be strongly supported by IoT.

Finally, with regard to physical-digital integration (G3), the development of SCOs introduces new scenarios in the AEC sector. On the one hand, the integration of IoT in building components would allow manufacturers to optimize processes, automate actions and provide new dematerialized services to their customers. This could lead to strong effect in reducing resource consumption. On the other hand, the introduction of devices to monitor the efficiency of a product could enable new performance-based business models. From this perspective, the development of SCOs requires rethinking technical and managerial aspects (Niu et al., 2016). In conclusion, the introduction of IoT in the building process requires a rapid rethinking of the process itself. The desire to aim for industrial approaches that aim for high efficiency in this respect can be fostered by technological developments in the field of IoT. The creation of large data sets can generate new economic and environmental values. The enormous increase in the availability of data, however, implies a shared regulatory effort on its management. In fact, although information is a primary factor in optimizing processes and resource consumption, the activities that take place in a building, which mainly determine its behavior and environmental profile, can undermine users' privacy. Finally, it should be mentioned within the limits of the literature review that an analysis of the scientific literature alone captures only a part of current IoT-oriented experiences. An analysis of patents, thus extended to market experiences, could expand the number of experiences on the topic.

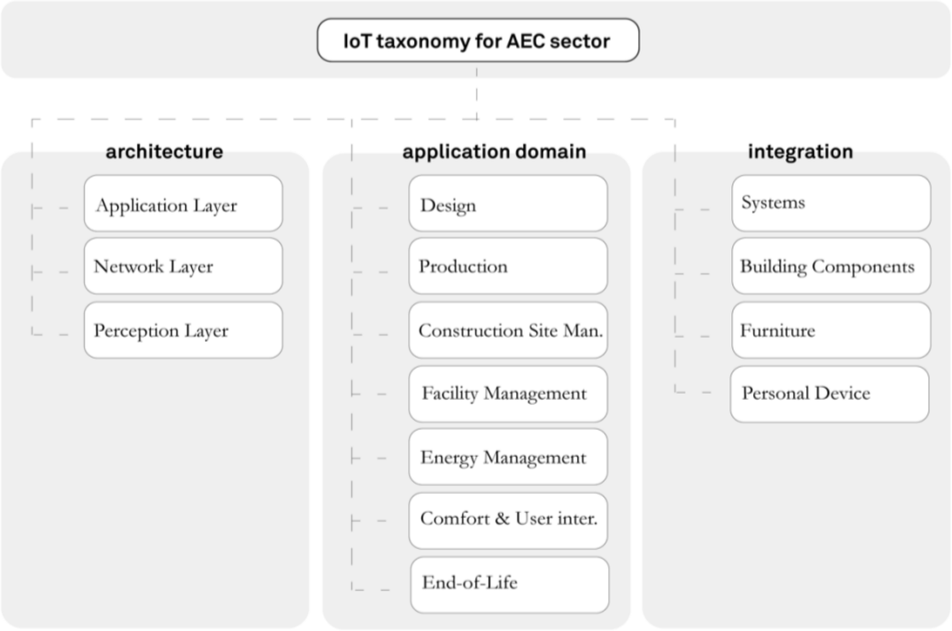


Figure 20: IoT taxonomy for AEC sector

3.4 A focus on RFId technology in AEC sector

As it emerged by the literature review, greater transparency and efficiency needed in asset management has specifically pushed RFId technology into construction industry. The ability to create, share, and transform data into information along value chains is considered a crucial action to assure product quality and reduce resource consumption. In this perspective, RFId sensors are considered the new paradigm of the IoT (Costa et al., 2021). Despite the first applications of the technology date back to World War II for "friend or foe" recognition of anti-aircraft (Erabuild, 2006), recent progress in chip miniaturization and industrial process production have allowed a drastic reduction in price making the technology extremely versatile for many applications (Lu et al., 2018). In the last twenty years, interest in this technology has been discontinuous. After a period of great interest between 2004 and 2007, the trend grew again after 2016 driven by an increased focus on IoT technologies. Used in logistics, automatic payment, access control or the identification of components or animals, RFId systems are already mature technologies that have found widespread application in many market sectors. Basically, it is a technology that allows the remote recognition of an object by using radio communication. The system architecture consists of two main elements: a reader with a data processing module and an antenna to generate the electromagnetic field, and a tag, a device placed on the object to be identified, consisting of an antenna, an integrated circuit (IC), and a substrate. Once entered in the radio signal range, the reader queries the tag, reads data, and organizes it in databases and/or shares it over the network (Fig. 21).

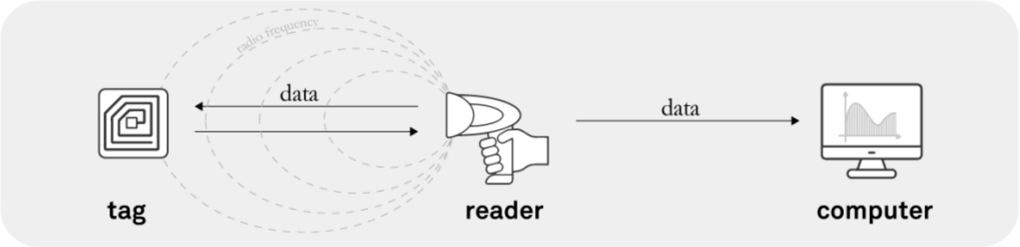


Figure 21: RFId working diagram

Several types of RFId technologies exists and different classifications can be made according to:

- *Active/passive*. RFId systems can be divided into passive, active, and semi-passive/semi-active according to the presence of a battery in the tag. Passive tags are the most popular type, they do not have a battery and receive their power from the RFId reader. Active tags have an on-tag power supply such as a battery, which emits a constant signal containing identification information (Klaus, 2010).

- *The frequency of the signal*. Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF), and Microwave (Mw) are the main types. Generally, LF systems operate in the 125 KHz to 134 KHz range and have a read range of up to 10 cm. HFs operate in the 13.56 MHz range and provide reading distances of 10 cm to 1 m. UHF systems have a frequency range between 433 MHz and 938 MHz depending on the context, offer read ranges up to 2 m, and have faster data transfer rates. Microwave frequency is less common for RFId technologies.

- *The material tags*. The chip and antenna are mounted on a substrate, which can be paper, polyethylene terephthalate (PET) or some other type of plastic. The choice of material depends mainly on the type of transponders and the types of actions to which the asset is subjected. Price and durability of the tag depend strongly on the material used (Want, 2006).

- *The memory capacity*. In current tags, identified as Gen2 RFId tags, the IC contains four types of memory: Reserved Memory, EP Memory, TID Memory, User Memory. The capacity can vary from 8 bits in the case of passive technologies up to 8kbits. Tags with memory can be of the “read only” or “read/write” type when the data can be modified dynamically (Marrocco, 2008).

In recent years, the widespread application of RFId technologies in many product sectors has been providing environmental and economic benefits. There are three main experiences that can be stimulating for the construction sector: the auto-identification of assets, geolocation and spatial monitoring of assets, and environmental parameters monitoring. 21 case studies using IoT in the building process have been identified over the last 10 years to highlight their development and perspectives (Tab. 5).

Table 5: RFId case studies

General info	Description
RFID-Based Facilities Maintenance. 2006, Frankfurt Airport (DE)	All fire shutters are equipped with RFId tags that store maintenance related information. The technicians identify themselves by scanning their badge and the tag attached to the fire shutter. After performing the checking or the maintenance, the tag is scanned a second time to record updated information. The transponders are designed to be attached to metal. The reading range is only 3 cm and frequency is 13.56 MHz. (Legner and Thiesse, 2016)
Intelligent Concrete. 2006, Tilst (DK). Dalton, Aarhus Innovation Lab	An integrated microchips for controlling production and supply chain and optimizing facilities activities for concrete panels. Concrete panel data are shared via internet and organized in specific database. By means of a personal digital assistant with a special reader mounted on the back, the men at the construction site can find all information about the panel immediately (e.g. measurements, weight, serial number, production history, mounting instruction and maintenance

	instructions). (Daly et al., 2010)
New Meadowlands Stadium. 2010. New jersey (USA). Skanska USA	In 2010, Skanska USA used RFId tag to track over 3.200 pre-cast concrete panels and visualizes it on BIM model for the New Meadowlands Stadium project. Each concrete panel, which weighed around 20 tons, was fitted with a RFId tag to allow it to monitor supply chain information in real-time. The RFId technology allowed to identify and solve problem early in the process, reducing in this way the construction period by 10 days and saving US$ 1 million. (SKANSKA, 2010)
Service-Oriented Integrated Information Framework. 2011, Seoul (KR). Sungkyunkwan Univ., Doalltech Co.	This research aims to develop a seamlessly integrated information management framework that can share logistics information to project stakeholders. To provide “just in time” delivery for construction sector, the research group have developed an integrated framework to digitalize component and building material flows. The pilot test showed that it can improve time efficiency by about 32% compared to the traditional supply chain management. The result of this research is expected to be utilized effectively as a basic framework to manage information in RFId/WSN based construction supply chain management environments. (Shin et al., 2011)
Door Control System (DCS). 2012, Bielefeld (DE). Schüco	The DCS control system provides access control using RFId technology. A passive RFId card tag for operators is the digital key to access a specific room. Integrated into the door, a RFId reader recognizes the operators and enables them to pass through. Such application is useful for security and access control to private areas such as hospital, bank, offices etc. (Schüco, 2012)
Precast Concrete. 2014, North Carolina (USA). Cherry Precast and Concrete Pipe & Precast. HUF RFId	To aid the state North Carolina Department of Transportation’s inspections, some American companies’ suppliers have integrated an RFId tag embedded in each precast concrete panel to keep track of manufacture data. The RFId led to a fast evolution of the control process. An online database (HiCAMS), accessible to all suppliers by password, allows them to view project data, orders, and delivered products. (Swedberg, 2014)

HardTrack. 2014, San Francisco (USA). Shimmick Construction Co., Wake, Inc. HUF RFId	HardTrack technology consists in active RFId (UHF) tags with integrated sensors to monitor the temperature and humidity of the concrete. In San Francisco, it was used by Shimmick Construction for the concrete foundation of building project. 16 concrete slabs integrated RFId tag and sensors. Each slab must be fully cured before the next one can be poured, to prevent it from cracking due to any stresses from the next slab. HardTrack provides real-time data on the concrete temperature and a software determines the curing date of the poured concrete. This approach has proven direct benefits on construction site timing. (Swedberg, 2017)
Redpoint. 2015, Boston (USA). Redpoint Positioning Corp., Skanska USA	The Redpoint technology helps the company to know when staff members go into an area of a construction site. The system also provides historical data so that management can identify workers who repeatedly enter an unauthorized area and provide them with additional training to prevent such mistakes from happening again. The development of such devices can find rapid application in buildings with restricted access areas. (Redpoint, 2015)
Cluster based RFId. 2015, Montreal (CA). Concordia University	In this research, they proposed a localization method based on RFId systems which does not need infrastructure. The development of an active RFID technology for the localization of movable objects is proposed. Building components, and equipment with an integrated RFId tag using handheld readers. By extending a Cluster-based Movable Tag Localization technique, a k-Nearest Neighbor algorithm is used. (Soltani et al., 2015)
Smart Construction Object. 2016, Hong Kong (CN). The University of Hong Kong	An integrated smart building component was tested and demonstrated in a real-life case in a prefabricated construction in Hong Kong. In this case, an RFId-enabled BIM system was required to track the status of prefabricated façades from off-shore manufacturing, cross-border logistics, through to on-site assembly. The tags for supply chain control included data regarding prefabrication factory, transportation routes, and a construction site. (Xue et al., 2018)
IFC-RFId. 2016, Montreal (CA). Concordia	The mechanical room of the Genomics Centre at Concordia University was chosen for the case study. The building is modeled in BIM and the mechanical elements are added to the

University	model. RFId tags are attached to a selected set of elements to host their related BIM information. Active and passive RFId tags are modeled in Revit under the electrical equipment category and added to the BIM model of the building. (Motamedi et al., 2016)
The Spot-r worker safety system. 2017, East Harlem, New York (USA). Lettire Construction, Triaxtech.	The system developed aims to ensure the safety of workers on the construction site. When workers arrive on site, building project manager can use real-time data to view the total number of workers per floor and zone and organize the work. Furthermore, such a solution allows managers to verify if potential incident occurs. For example, the RFId system can detect sudden falls. The software's algorithms can also determine if the data is indicative of a fall or if the worker may simply have dropped the device. (Triaxtec, 2017)
Elbphilarmonie façade. 2017, Hamburg (DE). Permasteelisa Group	Permasteelisa, world leader in building façade technology, used an RFId tag to optimize production and construction phase in complex project. To manage many different façade elements, each façade panel was tagged with an RFId that, thanks to a specific ID number, could remotly identify each individual element. In Elbphilarmonie project, such system facilitated and sped up the panel delivery to construction site that was particularly challenging, given its unique urban location and space constraints. This data will also be used for maintenance purposes. (Permasteelisa, 2017)
MULTIfid project. 2018-2021, Università degli Studi dell'Aquila. (DICEAA), 2bite S.r.l, Pack System S.r.l.	The main objective of the MULTIFId project is to create an innovative product consisting of an intelligent, low-cost, and low-emission panel, made from waste from the industrial processing of paper and cardboard. An RFId system is integrated into the panel to monitor the position of workers in risk areas, thermal performance, and monitoring humidity conditions. The academia project tested and verified RFId signal transmission through different campaign monitoring. (Pantoli et al., 2021)

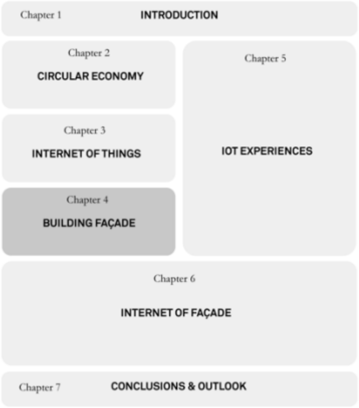
RFIBricks. 2018, National Taiwan University, Taipei. HUF RFId	RFIBricks is an academia project carried out in Taiwan University. Hsieh et al. present an interactive brick system based on ultra-high frequency RFID sensing. The researchers present a system that enables geometry resolution and geolocation of the asset in a space. Although the state of research is in prototype form, the development of a dynamic user interface opens new scenarios in the field of tracking components in a space. (Hsieh et al., 2018)
Checked OK. 2018, Cork (IE). Anderco Liftging, CoreRFId. HF RFId.	Anderco Lifting, one of Ireland's largest lift companies, is employing an HF RFId solution to improve the efficiency of inspections of the lift equipment that its customers use at construction sites. The system was developed in 2018, and the data collected is being accessed by utilities and several other customers to which Anderco provides six-month cycle inspections. (CoreRFId, 2018)
Flexible thermal monitoring. 2018, Turin, (IT). Polytechnic of Turin, DAUIN Department	Giusto et al. (2018) investigate RFId technology for indoor climate control. Benefits of a dense deployment of pervasive temperature sensors are presented. The analysis considers many features, such as technology simplicity and time of development, flexibility, wired/wireless range, battery life, reliability and cost. A case study with field test shows that the RFId network is nowadays suitable for thermal monitoring.
The SensX Extreme. 2019, Cupertino (USA). Smartrac and SensThys. HUF RFId	The SensX Extreme is primarily focused on the smart building and construction market. The aim is to develop technology for leak detection and concrete curing. RFId tags, which can be embedded in the roof section, can detect the presence of water, and the drying phase of concrete during paving, thus enabling higher quality and speed on site. The tags can be used in common building materials, such as gypsum board, insulation, roofing, flooring, and concrete. (SensThys, 2019)
IFC-RFID system. 2020, Theran (IR). Islamic Azad Univ., Shahid Beheshti Univ., East Carolina University.	This research presents a computerized system that integrates the BIM objects in IFC and radio-frequency identification to improve building maintenance performance. The computerized system is successfully applied to the building of a soccer stadium in Theran via the proposed research methodology using a qualitative and practical approach. The research indicates how a slight effort on the implementation of the proposed system could allow a significant improvement of

	overall maintenance performance. (Kameli et al., 2021)
WoodSense. 2021, Gävle (SE). Woodsense, ByggDialog Dalarna	WoodSense provides moisture measurement using passive sensors in the form of tags that can be attached to the wood building façade, wood slab panel, and or others building components. These sensors measure the moisture on the surface and must be scanned on site with an RFId reader. This solutions is particularly effective in facilities for wooden building requiring more attention to environmental phenomena. (WoodSense, 2021)
iWin 2022, SaintGobain	At Glasstec trade fair del 2022, Saintgobain, the world’s leading manufacturer of flat glass for the building industry, presents the iWin system. An RFID tag placed in the insulating glass unit incorporates all the information of the frame, allowing the maintenance technician quick access to the data (Fig. 22).

Figure 22: iWin RFId developed by SaintGobain (source: https://iwin.digital)

Chapter 4

Product and process innovation in the façade sector



Chapter 4 concludes *Section I* on the theoretical background with a focus on façade systems. Starting with an analysis of the main innovations that have shaped the evolution of façades, the current technological paradigm is presented. A study of functional, technical, and market requirements sets out the main aspects to be considered for the development of the technology. Finally, through a survey of current research project on the topic, five case studies closely related to the research objective are identified to set future trajectories.

4.1 Innovation management process

4.1.1 Innovation type

Innovation is a central aspect of our society. The introduction of new models of design, production, use, and consumption of goods is a central action for development. In today's global marketplace, innovation is conceived by companies as a necessary phenomenon to feed market competitiveness by differentiating themselves from competitors. As pointed out by Bryan Roberts (1987), innovation can be defined as the "economic exploitation of an invention". Indeed, the transition from invention to innovation occurs when the former is commercialized and purchased (Cantamessa and Montagna, 2016). This means that a manufacturer develops an innovative service or product when customers recognize its value and are willing to pay more than the cost of production. The innovation process can take a long time. In some cases, this process can require years, as it is not certain that at the time of the invention the ideal conditions are in place for it to reach the market. This period can be a major obstacle for the dissemination of the invention, as the owners of the technology will be pushed to invest in more profitable alternatives. For example, in 2013, Google launched the first Smart Glasses, glasses that through augmented reality store video, audio and data information through the display (the lens) (Google, 2013). Despite the technology was highly inventive and had no competitor on the market, it has never had a market diffusion. About 10 years later, partly fostered by the spread of home automation devices (e.g., voice assistants, smart lighting, etc.), smart glasses are re-emerging strongly produced by several companies. The innovation process is therefore not a linear process as it is influenced by economic, technical, social, and cultural factors. In the Triple Helix Model of innovation, as theorized by Henry Etzkowitz and Loet Leydesdorff in the 1990s, this process is the result of the interaction between research, government, and industry (Etzkowitz and Leydesdorff, 1995). According to this model, education and research directly contribute to the "wealth creation" of society. The interaction between these three elements thus becomes a trigger for the innovation process. In particular, the relationship between industry and government aims at job creation through the development of innovative infrastructural and fiscal systems. The relationship between industry and universities manifests itself in the development of new ideas, while the cooperation between universities and government is dictated by the development of basic research funding systems and the definition of strategic research guidelines. Invention takes place through applied research, where theoretical knowledge is tested and verified through demonstration actions. The role of industry from this point onwards becomes increasingly decisive (Fig. 23). Technology transfer from the demonstration invention to the prototype requires close cooperation with companies. To spread the technology on the market, it is necessary for it to become "competitive" on the market. The whole process has a much higher risk and failure rate at the beginning of basic research, which gradually decreases as product development and its business model are defined.

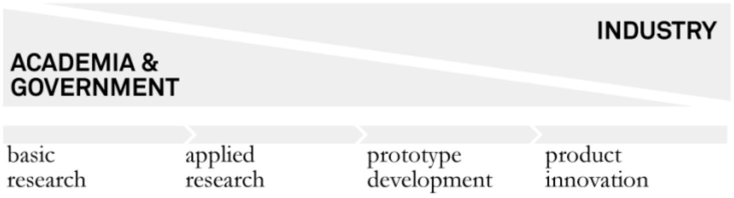


Figure 23: Typical process for the development of an innovative product (reworked form Cantamessa and Montagna, 2016)

Technological innovations can be of different types. According to Cantamessa and Montagna (2016), technological innovations can be classified according to:

- *Incremental or radical*. Identified by Dutton and Thomas (1984), the former refer to innovations that concern the improvement of the product without altering its main characteristics. Radical ones, on the other hand, significantly alter the technical trade-offs that define it. The latter will lead to products that introduce completely new functions, or a set of performance values that clearly distinguish them from their predecessors, thus introducing new values.

- *Reinforcement or destruction of competencies*. According to Anderson and Tushman (1990). The former, "competence enhancing", are dictated by the strengthening of corporate competences, while the latter, "competence destroying", aim to introduce new competences.

- *Central or peripheral*. The former relates specifically to the technological paradigm, while the latter may concern only an ancillary part of it.
- *Sustainable or disruptive*. Christensen (1997) classifies innovations according to whether they are sustainable or disruptive. In the first case, these are innovations that will never lead to significant changes, but rather to slight improvements in technology. While for the latter, these are innovations that rapidly change the market by introducing new paradigms and new players.

4.1.2 Developing innovation

To guide the development of an innovative product, several actions can be taken to assess its potential. Despite there is no one-size-fits-all path to follow as it depends on the nature of the product and the specifics of the market, two analyses can be considered essential in the field of innovation process management: the analysis of the technological requirements and the industry sector. The former (cf. 4.2) aims to define the technological paradigm. The analysis of the technology system, its constituent parts, the relationships between the different product components, the production processes, and in-use operational modes, is crucial to obtain an overview of the product technology. A list of functional and economic requirements is proposed to identify the essential characteristics for new product developments.

The functional ones concern the characteristics imposed by the essential requirements of technology and user demand. The economic ones, on the other hand, concern the aspects dictated by economic sustainability. These aspects, as argued by Ulrich (1993) in “The role of product architecture in manufacturing firms”, determine product architecture. Therefore, product architecture can be defined as a “scheme by which the function of a product is assigned to physical components”. These aspects are necessary to identify product or process competitivity.

The second (see paragraph 4.3), industry mapping, involves analyzing the market to identify a positioning of the new technology. Identifying the capacity of the market to absorb new products and technologies is essential for innovative development. Market analysis, stakeholder mapping, business models are developed to determine the competitiveness of an invention. For example, the potential number of interested customers (critical mass of the market), the return on investment, the players involved (current and new entrants), or the type of offer (e.g. B2B or B2C) are aspects to be taken into account.

4.2 Façade technology

The façade, or building envelope, is the element that forms the physical enclosure of a building. Its role is not limited to the structure of the building, but is an integral element that determines its appearance, functionality (Knaack et al., 2007) and sustainability. Indeed, it is considered a crucial technological subsystem for achieving more energy- and resource-efficient buildings. Several studies on the implications between technological system and environmental sustainability confirm its central role (Konstantinou, 2014; Gasparri et al., 2021). In addition to determining the operational consumption of the building in use, it can contribute between 10 and 20 % of total embodied carbon emissions (ARUP, 2022). This is mainly dictated by the energy-intensive materials used (e.g., aluminum and glass). Moreover, this represents a central element in the economic balance of a project. According to Klein (2013), it could cost up to 30 % of the total construction cost of the building. For these reasons, the façade system represents a strategic element for guiding the entire construction sector towards sustainable development. In this thesis, the term “façade” specifically refers to curtain wall systems. As the name suggests, curtain wall technology is an independent element from the building’s load bearing structure that protects the building’s interior from weather and climate conditions. Although the curtain wall refers to a specific façade technology, many aspects can be applied to other prefabricated façade systems. For this reason, the study carried out may open further thoughts on other types of building envelope.

4.2.1 Technological evolution

The evolution of façade systems is the result of technical and technological progress that has responded to the needs of the times. Since the late 19th century, the transition from the concept of “wall” to “façade” has revolutionized its meaning and functionality (Knaack, 2011).

Over the last century, the technological evolution of the curtain wall façade system has seen a strong development in prefabrication techniques and performance. Driven by external events such as rapid demographic growth, economic crises, and advances in materials, the technological evolution has led to a technologically advanced architectural system (Fig. 24).

Figure 24: Generali tower façade, Milan

A clear example of the influence of external factors can be seen in the energy crisis and the rising cost of oil in the 1970s. Energy consumption became a decisive factor in curtain wall design. Additional layers of glass were added to the façade structure to improve thermal insulation (Murray, 2009). And the glass material itself was further developed. Single glass panels were completely replaced by multi-layered insulating glass. Reflective coatings and so-called Low-E (low-emissivity) coatings provided the glazing part with additional functions to reflect heat coming from solar radiation. Since then, also driven by a regulatory update in terms of building energy efficiency, advances in the energy performance of the façade system have been achieved. Again, the need to optimize the production process and installation phases through industrial approach has led to rapid progress in the design of components and prefabrication.

4.2.2 System and components

To start a product (or process) innovation in a system it is necessary to identify its basic elements. Although, curtain wall technologies are considered customized products, functional elements can be listed. An analysis of such components is necessary to understand which parts can be replaced, upgraded or redesigned to fulfil new function or improve the performance of the overall system. As mentioned, nowadays curtain wall façade are completely manufactured in factory allowing a rapid installation on construction site (Fig. 25-26-27-28). In such systems, five main subsystems can be identified:

- *Frame*. The frame, generally made of aluminum, represents the grid onto which all the elements are fixed. Through point anchorages in the top of the cell, the frame is hung to the building slab. The frames, hollow profiles obtained by extrusion, can be painted or oxidised according to the aesthetic and functional requirements of the project.
- *Glass*. Defined as the "vision" panel, it represents the transparent part of the envelope system. Within this, different classifications can be made according to, for example, the way it is opened (e.g. fixed, hinged, vasistas opening, etc.), the way the surface is treated (e.g. low-e coating, screen-printed, etc.), the number of layers it is composed of (e.g., IGU, TGU), the thermal characteristics of the glass.
- *Spandrel*. Refers to the "opaque" part of the façade. Generally placed near the ceiling in vision cells to conceal architectural elements in the façade. Different materials can be used such as glazed glass, ceramics, stone, aluminium or others. Inside it, insulating materials (e.g. rock fibres) make it possible to limit heat loss and reduce thermal bridges in the vicinity of the floor slabs.
- *Gaskets and sealants*. These materials are generally used to ensure air and water tightness between the different elements. Galvanised frames, gaskets, silicones thus make it possible to increase the energy performance of the envelope by limiting infiltration and heat loss.
- *Shading system*. Internal, external, fixed, mobile shading systems are generally provided to reduce solar radiation incident on indoor environments, thus limiting the energy consumption of buildings.

Figure 25: Curtain wall factory (courtesy of Freiner & Reifer)

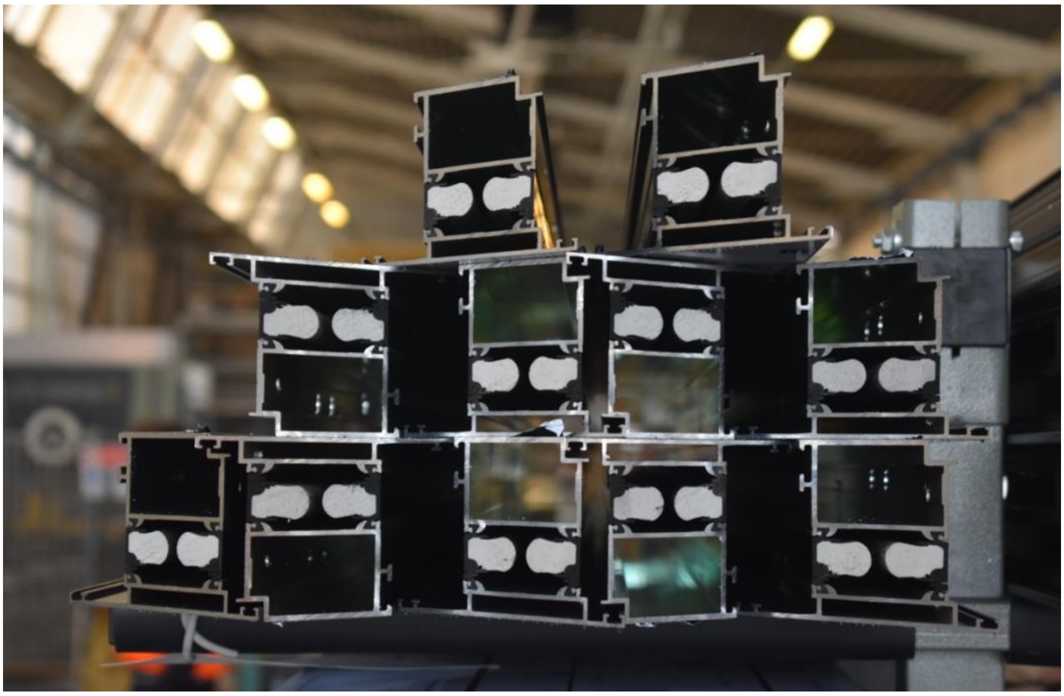


Figure 26: Aluminium bars with thermal break (courtesy of Freiner & Reifer)

Figure 27: Aluminium bars with thermal break (courtesy of Freiner & Reifer)

Figure 28: Curtain wall detail, Torre Galfa (Milan)

4.3 Market requirement

For the development of innovative products and processes, the analysis of the target market is a key action. Analyzing the specificities of the sector makes it possible to determine the market's capacity to absorb new products, processes, or services, and to develop business models consistent with the needs of the various players. The definition of a state of the art of the Italian market and the mapping of existing or new entrant stakeholders is proposed to clarify the research context.

4.3.1 Façade market

The curtain wall industry is considered a niche market. Transdisciplinary skills are required from the design phase to the management and end-of-life phase of the asset. The increasing focus on the energy and environmental performance required by the envelope system and the need to cope with projects with high complexity has led to the definition of a highly specialized specific sector. Globally, there are few leading companies that integrate all phases of development, design, production, and installation into their core business. On a national scale, the industry is populated by a myriad of small and medium-sized companies that make the market extremely fragmented. Small and medium companies compete for different projects depending on the size of the order and the complexity of the project. Façade manufacturers are medium- to large-sized companies (average revenues for more than 26 million euros) that adopt a specialized business model and make more than 50% of their revenues from curtain walls (UNICMI, 2021). Furthermore, the long supply chain of materials to be assembled aggravates this fragmentation. Considering that a prefabricated façade module can be assembled from hundreds of parts, the number of actors revolving around the production phase is significant.

Defining the status quo in such an articulated market is therefore not trivial. In the Italian context, UNICMI (National Union of Metal Building Industries of the Casing and Window and Door Frame Industry) through the reprocessing of ISTAT data monitors with biannual reports the performance of the sector. The façade sector is influenced by the trend of the construction market. The industry trend, although interrupted by the COVID-19 pandemic in 2020, has been growing since 2016. In 2021, the Italian construction market, driven by a series of government incentives, had an unprecedented growth (+13.8%) bringing the

Italian GDP to 6.5%. In 2021, of the 139 billion euros of investment in the construction sector (excluding infrastructure), about 608 million euros involved façade sectors. This figure is estimated to grow in 2022 (651 million) and 2023 (685) (Fig. 29). The shutdown period imposed by the pandemic emergency had no marginal effect on the curtain wall industry. This is dictated by multi-year orders that are less affected by short-term fluctuations (UNICMI, 2021).

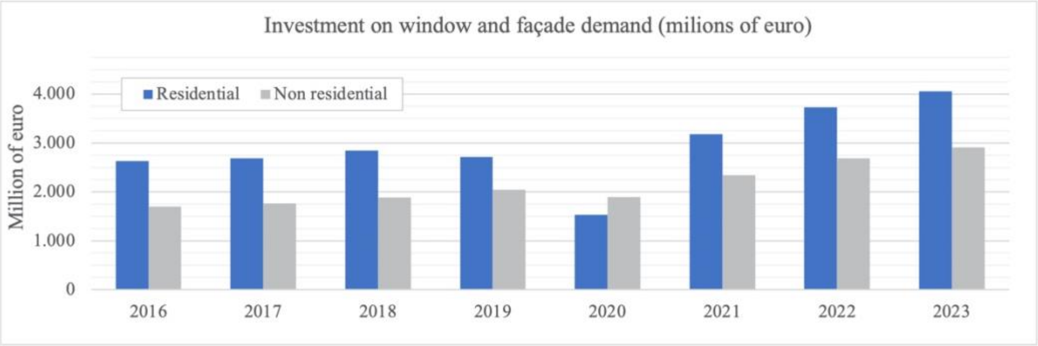


Figure 29: Investment in Italian façade sector (source: windowmarket.it and UNICMI)

For the façade sector, the “nonresidential” market segment (78,4%), and especially tertiary and commercial building, represent the main source of demand. Still in the economic analysis of the market, it is important to mention how 72% of revenue is generated by new construction work. The main reference customers are large companies (52,3%) followed by individuals (21,2%), small businesses (15,0%), and finally public administration (11,5%). Italian façade builders have an established presence in foreign markets, particularly in Europe, the United States, and the Middle East, with average exports approaching 50% of revenues in 2019, only to fall in 2020 and 2021 due to the stop of construction site operations (following the pandemic) in several countries where Italian companies operate. Indeed, it is interesting to note how the façade manufacturers’ revenues before the pandemic were about a 37% of demand (reduced to 24% in 2021). Also confirmed by the positive trend in the return on investment (ROIC) of façade companies (+3,7% for 2023 compared to 2020), data confirm positive growth for the future. With this in mind, investments in research and development are decisive actions to ensure company growth.

4.2.3 Stakeholder analysis

The market fragmentation, façade companies' size, and the "Engineer-to-Order" feature of construction projects (Montali et al., 2019) make the mapping of the players involved more challenging. Many stakeholders are part of the façade sector, especially in systems suppliers. This fragmentation increases the risks and contingencies while reducing the efficiency at every step of the design and construction process (Sangiorgio, 2022). The proposed stakeholder's map is based on three main classifications, as presented in Klein (2013), Azcarate-Aguerre et al. (2018), and Hartwell et al. (2021). Although these three classifications have a different approach, they can be used to categorize the main façade players. Clustering actors according to their role in the life-cycle of a façade, 7 main stakeholders' families can be identified according to this specific research purpose. Users, investors and developers, designers and consultants, façade providers, service providers, end-of-life providers, and community are presented in Table 4.

Each of these families includes several highly specialized actors who, although they have a limited scope of work, must rely on the work of many other actors. For instance, façade designers and consultants include various professionals depending on the project (e.g. architect, structural engineers, building physicist, lighting experts, fire and acoustic professionals, etc.). In fact, façade design activity takes place between architectural design and the analysis of systems requirements (Montali et al., 2019). Frequently, especially in larger projects, the de- signers and the façade system developers collaborate from the initial design phase through to the development of mock-ups and the construction phases. In this study, professionals involved in the material supply, processing, and assembly are included in the "façade provider" family. This latter is characterized by a larger set of players compared to other markets (Sangiorgio, 2022). Once the façade is installed and the building is ready to be used, "service providers" enter in the building process. This family includes all actors offering services related to the management of the physical asset and integrated intangible services. Often, as in the case of facility managers, maintenance providers, and building energy managers, the façade services are integrated into the building management. As reported by Hartwell et al. (2021), "end-of-life" companies must be included in a circular framework. Demolition contractors and operators in the field of material reuse and recycling are key figures in closing the circle and enabling circular strategies. Another stakeholder's family can be identified in the "investors and developers". In this category, as point out by Azcarate-Aguerre et al. (2022), the relationship between private and public investors are essential to rethink traditional business models. The recent focus on the building envelope as a key element in the energy refurbishment of existing buildings led to the spread of performance-oriented contract (e.g., project financing) on which energy service companies (ESCo), banks, and real estate companies base their revenues. As reported by Klein (2013) and Azcarate-Aguerre et al. (2022), "community" should be added to the stakeholders mapping. It mostly refers to public or private control authorities aimed at checking and certifying the regulatory compliance of the assets. Finally, as confirmed by experiences mentioned, "users" family represents one of the main set of players in façade technology as people directly involved in the asset use. To complete the stakeholders overview, information from the focus group interviews was added to enhance a more comprehensive state of the art. From these, key figures in the design (e.g., research institutes), production (e.g., project managers, contractors, transport companies), and the management of the asset are added to the list. More than forty actors identified in the façade life cycle are organized as follows (Table 6).

Table 6: Families of façade stakeholders and related specific professionals.

Stakeholders	Actors and industry professionals
Users	owner, resident tenant, worker tenant, etc.
Investors and Developers	contractors, private owners, public authorities, real-estate companies, ESCo, financial organizations, banks, etc.
Designers and Consultants	architects, façade engineers, structural engineers, building physicists, lighting designers, acoustic engineers, façade consultants, urban planners, contractors, research institute etc.
Façade Providers	material and component suppliers (glass, frame, insulation, cladding, sealant, accessories, shading

	systems, systems, automation, etc.), project managers, contractors, constructors, dealers, installers, transporters etc.
Service Providers	facility managers, maintenance providers, cleaning providers, building energy managers, building managers, building data managers, etc.
End-of-Life	demolition contractors, disposal companies, recyclers, etc.
Community	citizens, public authorities, regulatory authorities, certification organizations, etc.

4.3 Setting façade requirements

Functional and market requirements must be considered simultaneously for the development of innovative products and processes. In the early stages of the innovation process, technical knowledge is crucial for the development of alternative models that can be adopted by the market. As part of the FACE Camp project, Reifer and Demanega (2019) proposed a collaborative platform (called the Façade Wiki) that could contain and systematize technical knowledge that is still too often fragmented and entrusted to the professional experience of individuals. The innovation process starts precisely from capturing, acquiring, managing, and disseminating transdisciplinary knowledge with the aim of creating new one that supports the design of alternative products and processes. The semantic data model of the Façade Wiki, developed with manufacturers, supply chain companies and research centers, proposes customer and functional requirements. The former include compliance with the architectural layout, usability, adaptability, durability, sustainability, privacy, stability, comfort, and the outward view (perceptual comfort). These requirements are subdivided into specific requirements. Conformity to the architectural layout, for example, involves needs related to the choice of materials, transparency, or the layout of the building envelope. With regard to functional requirements, four main requirements are identified: load bearing, delimitation of the confined space, protection from external events, and utility. Again, the subdivision of the main requirements is divided into several specific needs. For instance, for protection from external events, two sub-families are proposed: protection against continuous actions (e.g., solar protection, thermal insulation, wind protection, air tightness, protection to precipitation, sound insulation) and protection against extraordinary actions (e.g., bullet protection, lightning protection, fire protection, burglary protection, smoke protection).

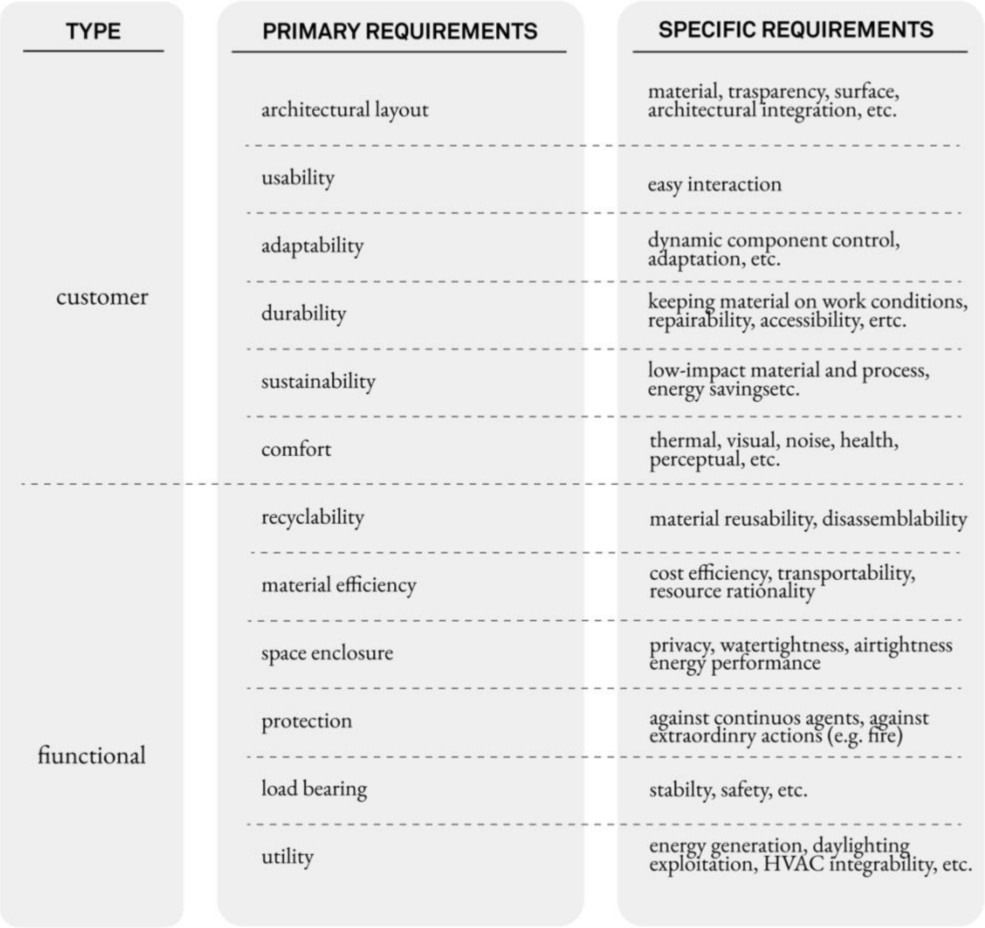
In the perspective of supporting the circular transition new requirements have to be considered (Fig. 30). These can be identified in:

- *Disassemblability*. This is a fundamental requirement for circular components. The ability to remove, disassemble and separate a part is a key action for maintenance and end-of-life activities. This is needed to increase the façade life cycle or improve reuse, recovery, and recyclability of materials and components.

- *Recyclability*. The use of materials with recycled and recyclable content drastically reduces the amount of waste to be processed. In this specific context, the use of untreated materials (e.g., float glass without Low-E coating) the transformation of materials into others of the same value.

- *Durability*. Although system durability is already a requirement, with the introduction of CE principles this becomes even more important. Designing durable goods means maintaining the asset value and the design performance over the time limiting the demand for new materials.

- *Material efficiency*. A conscious and rational use of materials is a fundamental requirement for a circular façade system. The use of materials and processes with a low environmental impact (e.g. wood) or the choice of rational design and processes can lead to a significant reduction in consumption and waste production.



TYPE	PRIMARY REQUIREMENTS	SPECIFIC REQUIREMENTS
customer	architectural layout	material, trasparency, surface, architectural integration, etc.
	usability	easy interaction
	adaptability	dynamic component control, adaptation, etc.
	durability	keeping material on work conditions, repairability, accessibility, ertc.
	sustainability	low-impact material and process, energy savingsetc.
	comfort	thermal, visual, noise, health, perceptual, etc.
fiunctional	recyclability	material reusability, disassemblability
	material efficiency	cost efficiency, transportability, resource rationality
	space enclosure	privacy, watertightness, airtightness energy performance
	protection	against continuos agents, against extraordinry actions (e.g. fire)
	load bearing	stabilty, safety, etc.
	utility	energy generation, daylighting exploitation, HVAC integrability, etc.

Figure 30: Façade system function tree (reworked from Klein, 2013)

4.4 Advanced façade

4.4.1 EU-funded project

A key action in promoting innovation in the façade sector is EU funding to support basic research. The funding set promoted by NexGeneration EU (EC, 2022) aligns with a series of investments that have been funding research and technological development for social and economic growth for years. The construction sector is a key area for EU funding. Huge investments have been provided to develop energy-efficient envelopes with a view to decarbonizing the built environment. Over the past 10 years, some 132 European projects have involved the development of materials, products, processes, and collaborative models related, more or less directly, to the building envelope[12]. For these projects, the total EU funding is around 500 million euros. Analyzing the trend of the funded projects, 87 projects started between 2012 and 2017 while only 45 started between 2018 and 2023 (first three months). The average amount of the projects is 3,7 million euros and about one third of these are fully financed by the EU (Fig. 31). Approximately 30% of the projects have an EU-funded amount of more than 5 million euros. This analysis provides an identification of the main future directions for the building envelope technology.

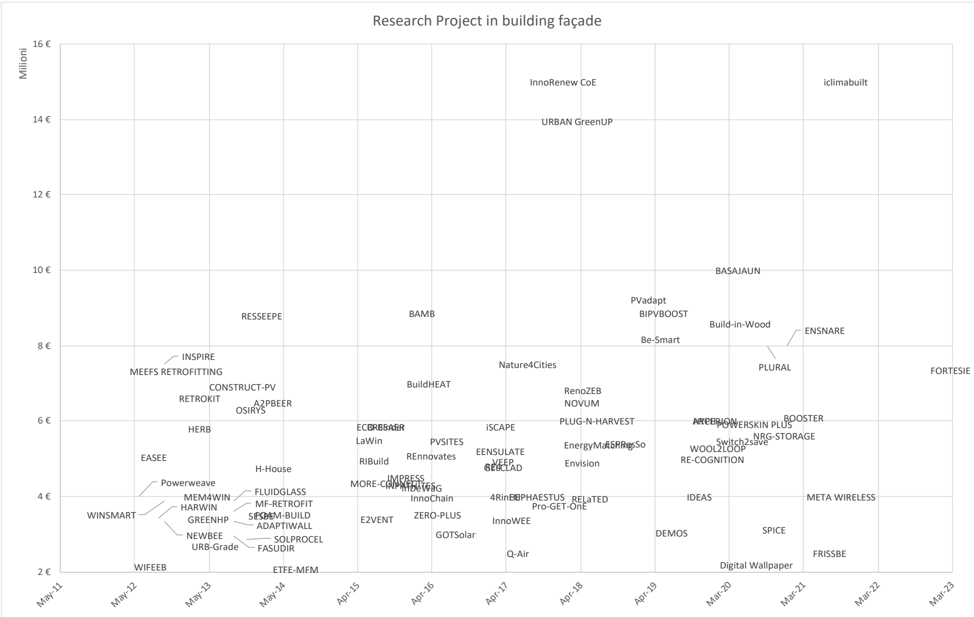


Figure 31: EU-founded research project related to building façade technology since 2012. The size of the circle indicates whether the EU financed a part of the project (smaller orange circle) or the whole project (bigger orange circle)

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[12] Search using keywords in the CORDIS database (https://cordis.europa.eu)

From the analysis of European projects, 7 macro research strands can be identified. These can be identified as follows.

- *Circular and ecological materials and process*. The development of biocompatible, recyclable materials with a low carbon footprint is a clear objective in the decarbonization process of the construction sector. This research refers to the development of materials and techniques for recycling materials (e.g. WOOL2LOOP for mineral wool used as insulation), the development of low-carbon systems, or the introduction of dry assembly practices that facilitate the disassembly of components.

- *High-energy performance*. A topic that has been central to improving envelope system performance for many years, the focus today is on the development of new materials and plant regulation systems. From the use of phase change materials to the development of dynamic systems for regulating heat input, the development of innovative solutions allows for better performance during the use phase.

- *Multifunctional and integrated façade*. The topic of integrating new functionalities is a key area with a large number of research experiences (e.g. PLUG-N-HARVEST, RENOZEb, ENSNARE, etc.). From the integration of energy production systems (e.g. photovoltaics and solar energy) to the introduction of ventilation and plant systems, the topic is extremely central. Especially for retrofit activities, advanced multifunctional integrated panels allow to address technological and mechanical system aspects through a single element (Pracucci et al., 2021).

- *Indoor Comfort*. Attention to user comfort is an emerging topic, also from a regulatory point of view and measurement methods perspective (Brembilla et al., 2022). Strictly related to other experiences such as energy-efficient or multifunctional façades, these exploit digital technologies to make the indoor environment more responsive to user needs. Investigations into the adjustment of dynamic components based on user satisfaction represent the most advanced research steps.

- *Additive manufacturing*. In terms of process, the application of additive manufacturing to the construction sector stimulates extremely innovative scenarios. Although experiences in the field are still at the prototype stage (Naboni and Jakica, 2022), the development of additive manufacturing technologies for metals and polymer-based materials opens scenarios in the development of complex components rethinking production and management processes (e.g. maintenance).

- *Automating processes and site construction*. A further field enabled by the evolution of digital technologies is process automation. Particularly for the installation phases, the automation of site phases can generate important savings in terms of time, costs, and workplace safety. An interesting research by Iturralde et al. (2022) tests the benefits of a cable-driven parallel robot for curtain wall module installation.

- *Facing Climate Change*. In the face of new demands imposed by the climate crisis, the envelope system is considered a central element in defining outdoor microclimate conditions (Naboni et al., 2020). The development of façade systems that limit the phenomenon of urban heat islands or water flow management problems. In this perspective, innovations in the façade system may have implications at the scale of the building and its micro-environment

4.4.2 Case studies

Given the EU-supported perspectives for the development of advanced façade systems, 5 case studies are presented with the aim of stimulating reflection on future scenarios. Although the case studies often have different characteristics and purposes, they may prove useful for the purposes of the thesis. Powered by industrial development or academic research, the case studies provide an overview of the maturity state of technologies and potential large-scale applications.

Cellia Façade[13]. The project aims to develop a multifunctional integrated façade that can be used for new buildings or retrofits. Resulting from the collaboration between Focchi S.p.a. and Progetto CMR, an heating and cooling system is integrated into the façade component (Fig. 32). Integrated below the glazed panel, the thickness of the system remains within the façade mullion thickness, thus ensuring maximum architectural integration. The façade module can be design with a wide range of additional functions, such as photovoltaic panels, solar shading systems with brise-soleil and motorized blinds, and interior and exterior lighting. This ensures a greater customization according to user needs and building features. In addition to the advantages in terms of energy savings due to the decentralized heating and cooling system and the possibility of generating income thanks to photovoltaic systems, considerable benefits are ensured by the installation phases. Indeed, high prefabrication maximizes the quality of the process and allows users to remain in the building during installation operations. These, in terms of construction site speed and tenant displacement issues, are innovative aspects. In addition, the use of mini cranes instead of tower cranes and scaffolding drastically reduces costs. In this perspective, the innovative façade prototype introduces the topic of real-time monitoring by IoT. The heating and cooling systems and the dynamic components installed (e.g. solar shading) imply the need to monitor operational parameters, electrical productivities, and environmental data (internal and external) to fully exploit the potential of such system.

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[13] Cellia Façade. https://www.cellia.it/cellia_interactive-cell.php

Figure 32: Cellia façade prototype developed by Focchi and Progetto CMR.

Façade Leasing. Following the "Façade As a Service" concept, several projects in recent years have concentrated on testing alternative business models (Coalition Circular Accounting, 2020; Andaloro et al., 2022). The purchase of the façade through a leasing contract is being studied by the Façade Leasing project[14]. In particular, the experience conducted by the University of Delft within the CLIC project is aimed at developing a technological and economic system that can rethink the traditional model (Azcarate-Aguerre et al., 2018) (Fig. 33). By leasing the façade service to building owners, the project tests new long-term service contracts for the façade market. In this perspective, the manufacturer remains the owner of the asset over time and sells customized services through it to the customer. Thus, on the one hand, energy savings are promoted through the provision of a service, on the other hand, the rehabilitation of energy inefficient buildings is made more attractive. The redevelopment costs and payback time for energy upgrades are still barriers for building owners. The environmental implications of façade leasing are different. As the asset becomes the producer's profit vehicle over time, more attention to maintaining the design conditions over time will be provided. The extension of the useful life of the system, which can be achieved for example through proper design and constant maintenance, will be a common goal for all players in the system. The façade as a service thus stimulates new markets in which both parties (producers and consumers) benefit from a durable, high-performance good. Furthermore, the extension of the manufacturer's environmental responsibility with respect to the good supplied can trigger greater interest in the reuse and recycling of the materials used. Desptite, from an economic (long payback times for companies) and legal (the extent of the façade is part of the ownership of the real estate) point of view, some issues still need to be resolved, this model represents an interesting alternative. In this perspective, the IoT emerges as a potential tool for monitoring the performance of the asset. The possibility of monitoring the effectiveness of the service offered would allow the development of performance-oriented contractual relationships between product-service provider and user.

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[14] Façade Leasing Project. https://www.climate-kic.org/projects/facade-leasing/

Figure 33: Façade Leasing prototype at TU Delft campus university

Building Impulse Toolkit (BIT). Capturing occupants' satisfaction with their environment in buildings is the goal of the Building Impulse Toolkit (BIT) project (Luna Navarro et al., 2021) (Fig. 34). The project, developed as part of Luna Navarro's doctoral thesis (2021), produced an IoT prototype consisting of a set of sensors that capture the holistic and transient influence of façades on IEQ and occupants. Specifically, the kit consists of three main parts: a set of sensors placed on the façade glass, two devices placed on the workplace (one for monitoring glare and the other for shading devices), and a device with which users can vote. The main parameters monitored are air temperature, noise level, humidity, CO2 levels, horizontal illuminance, incident solar radiation and globe temperature. The glare monitoring station also detects the quality of ambient illuminance from the workstation. BIT is based on a Rasberry Pi single board computer and allows the data collected to be shared via a Wi-Fi network. Thus, each time the occupants press an uncomfortable button, the BIT station records a measurement of the relevant environmental variable and sends a measurement mandate to BIT Glare via MQTT. This experience has demonstrated the potential of IoT in the development of innovative systems that increase the quality and healthiness of indoor spaces. The relationship with home automation or HVAC regulation systems may allow for more efficient adaptive and responsive systems in the future.

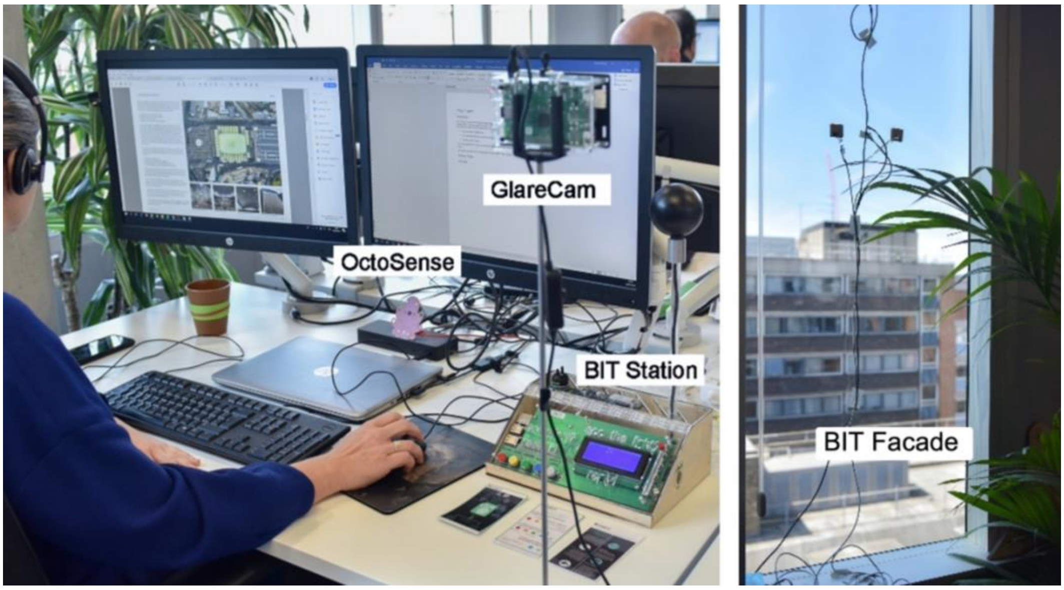


Figure 34: BIT during testing in a real office (credit: ARUP).

Thinking Skin. Thinking Skin is the result of a doctoral thesis conducted by Böke at TU Delft (2022). A smart façade prototype was developed to demonstrate the benefits of integrated and distributed intelligence (Fig. 35). Through the integration of sensors, processors, and actuators, the façade can adjust the actuation of parts depending on the monitored data and logical instructions set to it. Thus, when the incident solar radiation exceeds a defined threshold, the shading will be activated, limiting the solar input. Again, potentially a ventilation system will be activated when the percentage of CO2 in the room is not adequate to perform certain functions. Various functions can thus be developed and regulated through networked decentralized system components. In the Thinking Skin project, a router provides the independent WLAN. The different modules of the façade, which are used to test different functionalities, communicate in this network using the MQTT protocol. The broker, an open source Mosquitto server installed on a Raspberry Pi 3b+, forwards all messages sent by the system. The functions are set using Firefly tool, a visual programming in the Grasshopper environment.

Figure 35: Thinking skin prototype developed by Böke (credit: Böke, 2022).

Physee Smart Window. Physee is a start-up company based in Delft (Netherlands) that focuses on intelligent technologies for buildings, using advanced sensors, software, and data analysis (Physee, 2021). The company's main product is a smart window called SENSE (Fig. 36). Through the integration of sensors in the spacer of the double-glazing, the smart window enables hyperlocal monitoring that can regulate shading devices and HVAC systems. A multi-sensor (temperature, humidity, and solar radiation) monitors the main environmental parameters, and dn antenna allows information to be shared. A small photovoltaic panel allows the sensor to be self-powered so that it does not have to request power from the grid. To make full use of the collected data, the Dutch stat-up developed SENSE Connect. The data platform allows all IoT sensors and actuators in the building to be connected to a digital twin of the building. From environmental parameters to usage patterns, the platform offers a complete overview of everything that happens in the building. The prototyping of the system made it possible to quantify the benefits in economic terms. By making full use of solar inputs in the balance between indoor temperature and light intensity, the reduction in energy consumption can be as much as 30%.

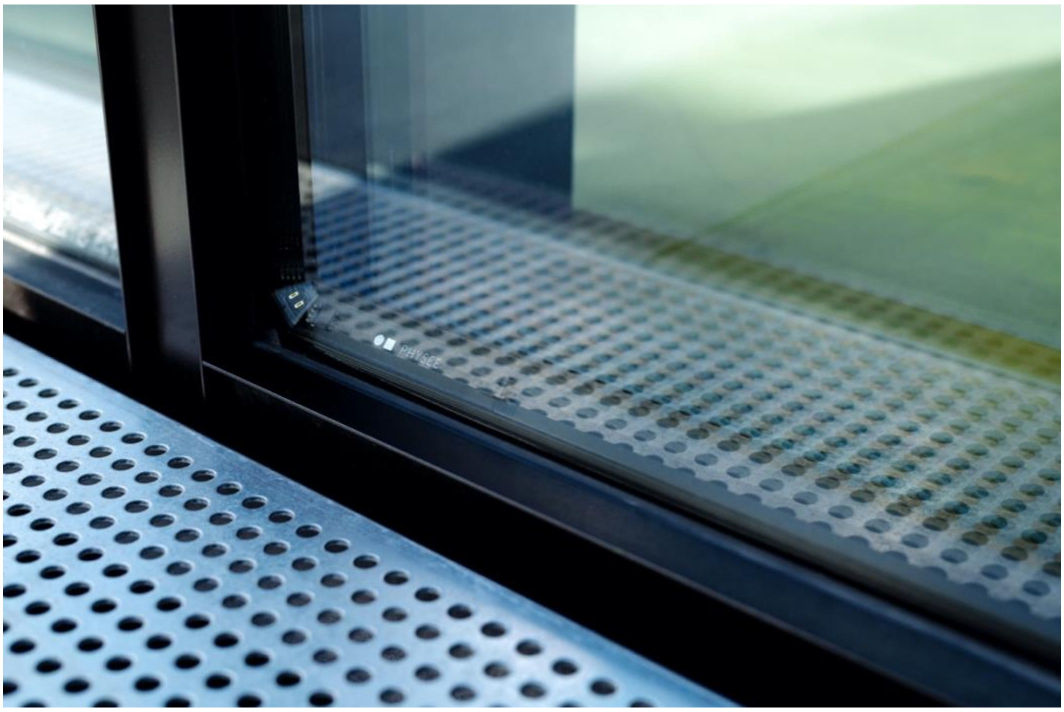
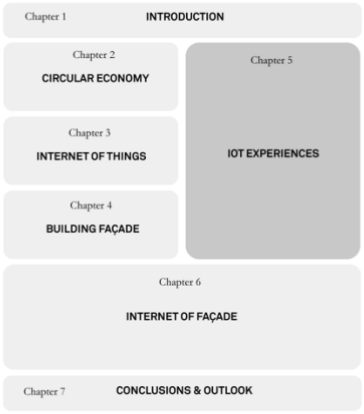


Figure 36: Physee SENSE - Smart Window (credit: Timbuiting).

Chapter 5

IoT Experiences



Grounding on the lesson learnt so far from literature and best-practices from case studies, *Chapter 5* reports on some tests exploiting the benefits of IoT technologies. Three practical experiments were carried out to address the implications of physical-digital integration, assess the reliability of diffuse monitoring, and analyze potential innovative developments. More specifically, (i) NFC tags for tracking asset life cycle information, (ii) active RFId sensors for monitoring indoor and outdoor environmental conditions, and (iii) Particulate Matter (PM) sensors to envision the development of innovative integrated systems were used in monitoring campaigns and application tests.

5.1 Introduction to practical experience

Having defined the new CBMs (cf. 2.2), the IoT technologies and sensors that can be used in the construction sector (cf. 3.3), and the technical specifications of the façade component (cf. 4.2), three practical experiences using IoT technologies are carried out. Specifically, the three experiments relate the opportunities offered by the IoT to the needs arising from the circular transition: (i) increased demand for traceability data to facilitate the collaborative supply chain and reuse of materials, (ii) monitoring of environmental parameters affecting system performance and lifetime, and (iii) the introduction of new dematerialized services to enhance asset value.

For each experience, monitoring campaigns or data transmission tests highlight the technical and managerial implications of physical-digital integration. The experiments carried out with low-cost IoT technologies are to be understood as actions aimed at defining their innovative potential rather than the definition of a ready-to-use system. Indeed, data monitored and presented in the following chapters have an acceptable degree of reliability for the purpose of the research. At this stage, it is most significant to test the IoT infrastructure, discover the technical implications, and verify phenomena described in the literature.

Colleagues from the Department of Control and Computer Engineering (DAUIN) of the Politecnico di Torino collaborated on the IoT experiments.

Before showing the results obtained from the 3 Experiences, it is necessary to point out how the absence of a systematic and lasting data collection does not allow for statistical investigations. The qualitative assumptions made in the discussion of the results are the result of a theoretical knowledge of the main phenomena affecting the façade system. Further analyses should be carried out to verify the integration methods and the coordinated management of data flows.

5.1.1 Goal

The aim of the practical experiences is to analyze the advantages and barriers in the integration of IoT technologies. Through the analysis of data and implications gathered from monitoring campaigns, three different hypotheses are presented.

NFC, RFId, and PM sensors are tested in three different experiments to clarify the benefits on production and management of the information. In fact, rather than the development of an integrated sensor, this step of the research aims to identify the benefits generated by a widespread and real-time information. These experiences, on the one hand, make it possible to verify the main technical issues concerning monitoring and data transmission and, on the other hand, to identify potential relationship with CBMs. Although the reported experiences can be considered transversal to several CBMs, some a priori associations were made. More specifically, the first experience concerns the use of NFC tags to identify new smart labelling systems that favor the creation of a circular supply chain and the enabling of re-use and recycling practices. The second experience test active RFId tags to monitor environmental parameters during the use phase. The ability to monitor agents affecting asset performance could (theoretically) drive actions to extend the asset service life. Finally, the third experience focus on air quality monitoring to increase the asset functionality. Imagining new functions for the envelope would increase asset economic value and feed data sharing on shared platforms and support new PAaS models.

5.1.2 Methodology and assumption

All three research experiences were conducted in Turin (Italy), between February 2020 and October 2022. The IoT experiences are designed on theoretical hypotheses emerged from the literature. Through a “learning by doing” approach these hypotheses are tested and validated with low-cost and self-assembled sensors. In particular, the process used for each experience is similar. The problem is identified from a theoretical point of view (e.g., loss of or difficulty in accessing asset data is a barrier to reuse of building components), an analysis of how the problem has been solved in similar contexts is taken from the theoretical background (e.g. in the food sector, the introduction of smart labels), a possible technology that could solve the problem is selected (e.g. NFC smart tags), the IoT technology is tested, and, finally, various considerations are proposed. Even from the point of view of physical-digital integration, the assumptions made will have to be validated in the next stages of research. The semi-integration of the sensors with the façade component can be considered an acceptable assumption of the analysis for this stage of the research. Experiments were carried out on opening windows and doors as they allowed more freedom of action in interior and exterior tests, however, these considerations can also be scaled to curtain wall systems.

The paragraphs’ structure relating to the experiments follows the scheme: (a) the identification of the theoretical frame, the identification of main problem statements, and the definitions of the research hypotheses; (b) the focus of the IoT technology used; (c) the discussion of the results gathered and, finally (d) theoretical, technical, and managerial implications.

5.2 Exp. I. Tracking and storing life-cycle information

5.2.1 Theoretical framework and hypothesis

The ability to keep track of an asset's information over time is a key aspect in fostering circular and sustainable approaches. The experience of the Japanese pavilion ("Co-ownership of Action: Trajectories of Elements"[15]) at the Venice Biennale 2021 curated by Kozo Kadowaki is particularly significant. After completely "disassembling" a typical Japanese house, each individual building piece were tagged with QR-codes containing its material data and its positioning in the house so that it can be reassembled elsewhere. Despite in the Venice exhibition the house was never rebuilt and the individual elements were used to create new various objects (e.g. benches, tables, etc.), the traceability of building components proved to be a strong enabler of the practice of reuse. Therefore, access to product life-cycle information is to be considered a prerequisite for the circular management of the asset. Indeed, as several researchers have shown, traceability is considered a key action to increase knowledge with which guide the decision-making choices of the various players (Katenbayeva et al., 2016; Giovanardi et al., 2023). In this perspective, several researchers recognize that it is precisely the absence of data on building products and components that can be an obstacle to the spread of circular strategies (Hartwell et al., 2021; Giorgi et al., 2022). Furthermore, it is well known that the search for information about the good is still a time-consuming action for many players (Snyder et al., 2018). In addition, traceability information (e.g., production, installation, etc.) are emerging in the AEC sector as key data for environmental certification (e.g., EPD). Recently, the proliferation of standards and product labelling have required important updates in the ways the information is recorded, stored, and shared. Thus, new labels that make it easier to access asset information have been developed in several industries, such as food, textiles, or delivery. For example, the increased focus on food quality led to the development of smart labels that could guarantee product quality. Therefore, smart labels can ensure the freshness and quality of food (Smits et al., 2012)

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[15] Co-ownership of Action: Trajectories of Elements. https://www.vba2020.jp

In the construction industry, QR-codes, RFId, and NFC technologies could be identified as innovative tools to replace paper-based barcode labels (Fig. 37). For the five CBMs presented (cf. 2.2), the topic of traceability can be understood as a common strategy for all models. In this case, the focus of the experience is on the creation of a circular supply chain and the reuse and recycling of materials.

Figure 37: Current paper-based labelling of a façade system (courtesy of Focchi)

Towards greater building components traceability, different technologies can be used (e.g. barcode, QR-code-PDF417, RFId, NFC, etc.). In this research, NFC tags are tested. The advantages of quick access to information, the possibility of accessing information directly from personal smartphone, and the capability of recording information though the smartphone on the tag make the NFC technology potentially interesting. In the field of product management and logistics, it is well known that paper labels not only deteriorate more easily when subjected to the action of external environmental agents (e.g. solar radiation, water, etc.) but also require a field of view to be “read”, making the materials stock more complex. Theoretically, the switch to NFC or RFId technologies would automate several processes, making the recognition of an asset much faster. These aspects could promise new scenarios in the façade industry in the production and installation phases where component recognition is often required in the succession of different steps.

The hypothesis of Experience I is therefore:

If the circular transition requires greater traceability on asset life cycle information, the development of a smart labelling for façade components could facilitate the shift. Rethinking the way information is managed by favoring the updating of data over time and accessibility by all actors, is the objective of Experience I.

5.2.2 Technology: Near Field Communication

For Experience I, passive NFC technologies have been tested. Like RFId, NFC technologies are wireless devices that enable signal transmission through radio frequencies (Fig. 38). This set of contactless communication protocols was jointly developed by Philips, LG, Sony, Samsung, and Nokia in 2004. The wireless technology operates via radio using a basic frequency of 13.56 MHz with a short range (up to 10 cm) and a data transmission rate of 424 Kbit/s (Birch Pedersen, 2018). The short reading range (typically 2 cm) is considered an advantage in terms of security. The proximity between the devices reduces the likelihood of signal interception. For this reason, it is increasingly common to use NFC tags for contactless payment systems, for opening doors, labelling clothing, and other consumer products (Birch Pedersen, 2018). Different types exist on the market, classifiable by range, speed, energy requirements and security features. Similarly to RFId technologies, NFC are composed by two main elements: a device used as a reader (e.g. smartphone) and a tag characterized by an alphanumeric sequence (e.g.: ##:##:x#:#x:##:#x:##) that ensures uniqueness. The tag can be "active" if it is able to initiate communication with another NFC device, or "passive" whether it needs the presence of the reader to function.

There are three modes of operation for NFC technology:

- *Read/Write Mode*. The reader communicates with an NFC tag, reads, and writes data into it.

- *Peer-to-peer Mode*. When communication is bi-directional between two NFC devices.
- *Card Emulation Mode*. When an NFC tag "emulates" a contactless smart card, and acts in the same way.

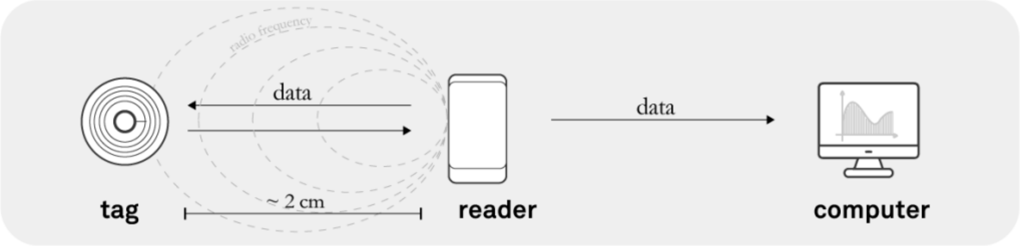

Figure 38: NFC technology read-write operation mode

Two commercially available tags are chosen for this experiment (Fig. 39):

- *NTAG 213*. Develop by NXP is from Typo 2 is a 25 mm diameter adhesive tag that can be read at up to 10 cm. It has a memory of 144 B with approximately 36 pages of available read/write space. The data sheet indicates a data retention time of 10 years with write endurance of 100K cycles. Cost 0.83/tag.
- *Mifare Classic*. Developed by NXP is fully ISO/IEC 14443 Type A 1-3 compliant, has 1 kB memory. Write endurance 100K cycles, security Crypto 1. Cost 0.75/tag.

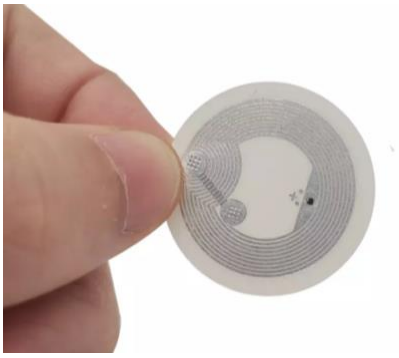

Figure 39: Adhesive NTAG tag used for experience

These models were selected because they are already available on the market and can be accessed through the free "NFC Tools"[16] app, which is available for both Apple and Android devices (Fig. 40). This app, which acts as a reader, allows you to read, write and schedule tasks on NFC tags directly from your smartphone. The app is organized into four major function areas: read, write, other (settings), and saved tag. By bringing the reader close to the NFC tag and pressing the "read" button, it is possible to display data such as the manufacturer and type of tag (e.g.: Mifare Classic, NTAG213, etc.), the serial number of the tag, which technologies are available and the standard of the tag (e.g.: NFC A, Type 2, etc.), information on the size and availability of the memory, whether the tag is writable or locked, and finally, all the data contained in the tag. The "write" tab allows you to record data such as a simple text, a link to a website, a phone number, a predefined text message, a geolocation or other. To increase the security of the device and ensure the reliability of the data it contains, an alphanumeric access code can be set for the "write" and "read" functions.

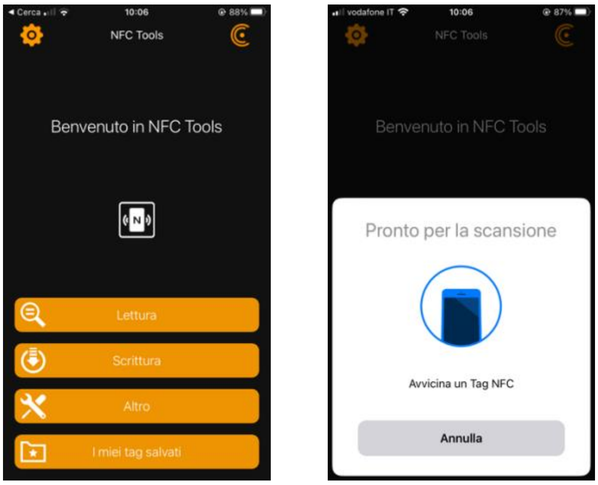

Figure 40: "NFC Tools" app

The tests were carried out on a sample of window. Once the adhesive label had been placed in the window frame, a data writing and reading simulation was performed. Several tests on the read proximity, the speed of writing information, and the ability to manage that data in the network identified the benefits. The

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[16] "NFC Tools" app. https://apps.apple.com/us/app/nfc-tools/id1252962749

comparison, albeit theoretical, with other types of tracking and labelling was then conducted on several parameters: cost, reading distance, ability to record information, and service life. Through these parameters, the effectiveness of the proposed technology for smart product labelling is assessed.

5.2.3 Results

The experience confirms a simple and user-friendly mode of interaction. The tags and the use of the app do not require any specific computer knowledge to manage the exchange of information. A demonstration test was carried out in which information on a hypothetical maintenance operation was recorded to be read later by another user (Fig. 41). This made it possible to compare the NFC tags with other labelling systems such as a passive RFId sensor, QR-codes, or barcodes. For RFId sensors, key-shaped tags compatible with the RC522 (13.56MHz) reader were used.

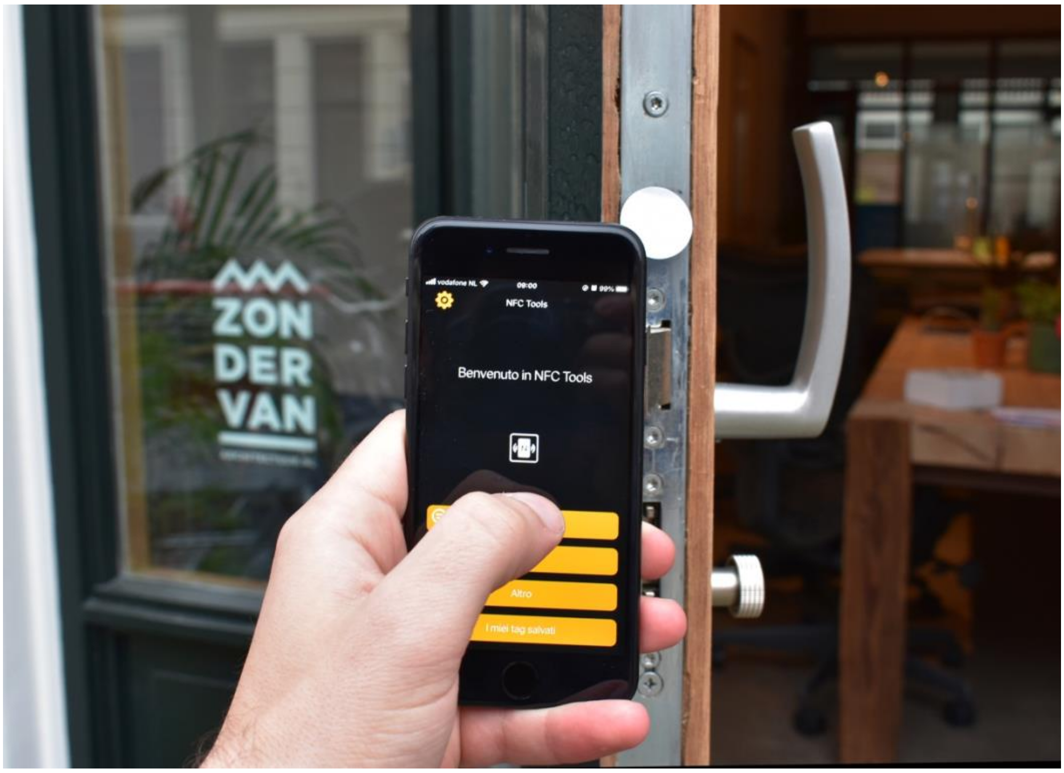

Figure 41: Scanning an NFC tag placed on the door-window frame

As anticipated, the comparison between the different smart labeling technologies was made according to reading distance, the ability to record information, durability, and cost (Tab. 7).

Table 7: Tracking and memory sensor tag comparison

Sensor	Distance	Memory	Writable	Durability	Cost*
NFC NTAG 213	~2 cm	144B	Yes	10 years	T: < 1€, R: up to 300€
NFC Mifare Cl.	~2 cm	1kB	Yes	10 years	T: < 1€, R: up to 300€
RFId passive	~5 cm	1kB	Yes	10 years	T: < 1€, R: up to 1000€
QR-code	~50 cm	3kB	No	10 years	T: < 1€, R: up to 300€
Barcode	~50 cm	100B	No	10 years	T: < 1€, R: up to 2000€

*T: tag cost, R: reader cost

Distance. Concerning the reading distance between reader and tag, both NFC tags used enabled the reading and recording of information at close range or by contact. For both tags, reading may take a few seconds. The ability to detect the tag strongly depends on the reader used, different detection rates were found using different smartphones. For accessing the information of a hypothetical façade system, the very close distance can be a limitation as it restricts the placement of the tag in visible and easily accessible places. Regarding RFId tags, the sensor used allowed the exchange of information up to 5 cm, but other devices could be tested to increase the reading distance (and without field of view). Again, the reader, programmed through an Arduino board, allowed rapid access to data. Finally, QR codes and barcodes can scan the object from greater distances (up to approximately 50-70 cm). However, an open and unobstructed field of view is required for these systems, which could be a limitation for application in a façade system.

Memory. The ability to store information is a key point for tracking technologies. Comparing the two NFC tags, the Mifare Classic offers a larger memory capacity (1kB versus 144B). For the passive RFId system analyzed, the capacity is also similar, while we have a higher availability for QR-codes. However, it must be pointed out that even in the case of a smaller capacity, information concerning the type of good, materials, seller, etc. can be stored seamlessly. Furthermore, the possibility of access to online databases via web links makes the asset storage capacity practically infinite.

Writable. Whether a tag is writable can be crucial in its application in the construction context where long lasting assets may need to have their information updated during their useful life. Depending on the application of the technology, it is possible to choose between writable and non-writable tags. Thus, NFC, as well as RFId technologies, allow information to be written directly on the tags. Through the implementation of cryptographic security techniques (e.g., blockchain), this data can be considered certified and authentic. For barcodes, on the other hand, writing is not possible representing a limitation for its application.

Durability. Tag durability is a difficult issue to investigate a priori. The sensor service life is highly dependent on how the tag is installed. NFC tag technical datasheets indicate an average of 10 years for sensor service life. Their general application on assets with a very short useful life implies that there is no information on the real durability of the tag. For NFC and RFId systems, the question can be considered the same. As far as barcodes and QR-codes are concerned, these have a hypothetically infinite lifetime. If the tag is stored properly (e.g., covered from sunlight and protected from water) these retain the information for years. Therefore, a central aspect to be taken into consideration for improving durability is the material of the tag. Paper-based systems will certainly be more susceptible to deterioration over time.

Cost. Finally, cost can be a significant parameter for the sensor technology choice. Indeed, hypothesizing tagging the façade components of large building stocks, the sensor cost would be a discriminating factor. Regarding tags, the cost of smart labelling (NFC and RFId) is extremely limited and comparable to more traditional labelling (QR-code and barcode). Affecting the overall cost could be the reader and the data management infrastructure. While a simple smartphone can be used for NFC tags and QR-code systems, RFId and barcode systems require a specific reader. For the latter two cases, the price range can vary greatly. From RFId and barcode readers costing a few tens of euros, it can be as much as

2,000 €. In this case, the ability to read the tag at great distances generally affects the price of the reader.

5.2.4 Discussion

The objective of Experiment I was to evaluate the benefits of a possible smart label that could facilitate the traceability of asset information and ensure quick access to different players. The experience gained has led to several insights. From a theoretical point of view, the implementation of smart labels through IoT would enhance communication and information sharing among stakeholders. This would allow players in the façade industry to efficiently record and retrieve data directly on the assets, thus improving asset management activities. Thus, a smart labeling could rapidly provide information on material composition, access to environmental certification, retrieve information on manufacturing process, or allow to record information on maintenance activities. In this perspective, tracking building components with smart tag could support the widespread adoption of material passport experiences. Experience I served to clarify theoretical, technical, and managerial aspects. These can be summarized as follows.

Theoretical Implications. The introduction of NFC tags for tracking and labelling of façade components introduces the issue of the reliability of collected data. While the availability of data can be a benefit, the reliability of that information is a key issue. In this respect, the uniqueness of NFC tags compared to more traditional and easily replicable systems increases transparency and limits, at least potentially, possible counterfeiting. In this regard, the continued development of the technology, together with blockchain systems and information encryption, can lead to a key breakthrough in the deployment of the technology. Data transparency is therefore crucial to reduce that information gap between producer and customer and to foster self-monitoring processes in the supply chain. Denouncing through a smart label, the consumer's and company's commitment to sustainability and circularity issues can be understood as driving interest in new technologies.

Technical implications. There are three main technical implications. The first concerns the unit of the component. If for consumer goods the uniqueness of the product is clear, for façade systems it may not be. Especially for non-modular systems, identifying the unity of the component for complex, continuous systems is a central challenge (e.g. stick system façade). The second is related to physical integration. The need to read the tag at small distances can be considered a limitation for production, operation, and maintenance activities. Although this is a central feature of the technology, especially for payments, this implies that the tag must be organically integrated into the frame and be easily accessible. The development of ad-hoc solutions with longer distance reading possibilities could facilitate their application in the construction sector. Finally, the third consideration concerns the tag service life. Several datasheets assure a useful life of the smart tag of 10 years, which is still much shorter than the useful life of the façade component. Maintainability and the possibility of replacing the tag itself over time must thus be planned from the design phase. Although this may seem like a limitation, it should not be forgotten that technological evolution is extremely rapid and that storing data in the cloud can easily solve the problem of technological obsolescence.

Managerial implications. Finally, there are managerial implications associated with the use of smart labelling. The interest of companies in maintaining the information of an asset over time is strictly constrained to their responsibility. In a still highly linear market, the interest in maintaining data and sharing it is limited. Given the linearity of the market, so far companies had a low interest in collecting, maintaining, and sharing data on processed and products. Thus, the interest on these kinds of applications was limited, too. It is worth noting that consumers are becoming more conscious of a company's environmental efforts, and such adherence will likely be reflected in their demand for the product. Moreover, the benefits of such applications are still unclear to companies. Quantifying the benefits in economic terms is indeed a limitation for companies when evaluating life-cycle-oriented strategies.

5.3 Exp. II. Monitoring and optimizing operational stage

5.3.1 Theoretical framework and hypothesis

Maintaining and exploiting the asset as long as possible is a key purpose of the circular transition. Moving away from the traditional "take-use-dispose" approach by embracing long-lasting asset involves reducing the need for new raw materials and energy and limiting waste production. Despite for long-lasting assets such as façade systems this may seem a secondary issue, there is still room for improvement. In this regard, Dunham et al. (2018) present a study in which they point out how the trend in the longevity of building façade systems in USA has decreased over the last 50 years. A comparative analysis of 140 buildings showed that the first failures in a façade system occur after about 12 years. The authors identify the increasingly complex systems as the main cause of this phenomenon. This condition may be (partly) aggravated by phenomena related to global warming. More intense phenomena and the presence of chemicals in the air could have a greater effect on the deterioration of building façade components (Lacasse et al., 2020). On this basis, the façade durability, a central aspect for circularity, may depend heavily on aspects related to:

- *Design*. A proper design is crucial for building long-lasting systems. Aspects related to the choice of materials (e.g., non-corrosive materials), their protection against weathering (e.g. flashings for rainwater run-off), or accessibility for maintenance activities are crucial. Additionally, designing systems that are easy to disassemble, replace, and repair is key to prolonging their service life.

- *Maintenance*. Maintenance considerations are closely tied to the design of an asset. Regular and proper maintenance, such as adjusting frames, lubricating joints, and cleaning, can greatly impact the longevity of a façade system. To optimize cost management for large real estate assets, proactive and predictive maintenance strategies are becoming increasingly popular. Although for building envelopes, corrective maintenance is still the most common practice, new scenarios are emerging.

- *Use*. The impact of how a building's envelope is used by its occupants is a challenging aspect to predict but is extremely significant. The interaction between the users and the building envelope, especially for moving components such as shading devices, can play a crucial role in the asset longevity. For example, mechanical parts that are becoming more prevalent in façade systems, frequently and improper use can lead to an increased likelihood of failure and a shortened service life of the entire system.

The lack of one or more of these aspects can result in a decline of performance or the complete failure of the system. The focus on CBM for extending the life cycle means prioritizing maintaining the design performance of the building envelope for as long as possible. The ability to monitor phenomena related to system performance or specific environmental parameters can be crucial in anticipating the failure of the entire system. Thus, as with applications on HVAC systems (Rota et al., 2020), performance monitoring has a twofold meaning. On the one hand, it can identify isolated problems (e.g., lack of proper sealing of components) that affect the durability of the component (e.g., water or air infiltration can lead to system failure), on the other hand, it is essential in assessing the performance provided by the system. For façade systems in particular, environmental stresses are central aspects for system durability. The influence of solar radiation, temperature trends to which the system is subjected, and the presence of point phenomena can become key information for defining the stress level of the system and anticipating possible failures. For example, for one and the same building where the façades are subjected to different phenomena depending on exposure can be decisive in directing maintenance and investigation activities. Thus, in the perspective of supporting new service-based CBMs, the ability to monitor the effectiveness of a component could enable new performance-oriented forms of contracting.

For Experience II, two main monitoring campaigns of air temperature and humidity were carried out. Since the environmental parameters that could affect the façade component (e.g. solar radiation, humidity, vibrations, etc.) vary according to the type of building envelope, temperature and humidity were chosen as common parameters. The purpose of this experiment was primarily to collect and share environmental data rather than focusing on specific parameters. Additional considerations for selecting parameters will be discussed in *Chapter 6* (cfr. 6.2.1). The approach tested in this experiment can be theoretically replicated with different environmental sensors.

It should be mentioned that the monitored data refers to the temperature of the air close to the component. Despite the frame or glass panel surface temperature is different compared to the air temperature, for the purpose of the current research this data can be considered reliable.

The hypothesis of Experiment II is therefore:

If the functioning of a façade system is closely dependent on the environmental boundary conditions and the way in which it is used, by monitoring environmental and operational parameters we could identify, evaluate, and predict its operational performance. This would allow the development of innovative management scenarios for extending the useful life of an asset.

5.3.2 Technology: Radio Frequency Identification

In Experiment II, active RFId sensors were utilized to monitor air temperature and humidity. The PUCK RhT sensor (Fig. 42), produced by ELA Innovation[17], measures both Relative Humidity (Rh) and Temperature (T) and is primarily used in industrial indoor settings. The device, which is compact in size at 57x18 mm and weighs around 36 grams, allows data to be transmitted wirelessly in an open field up to 150 meters due to its internal battery and 433 MHz signal frequency. The minimum interval between data readings is 200 ms, and the maximum is 10 hours. According to the product specifications, the sensor has a battery life of 10 years when used at the lowest interrogation frequency, confirming a lower power consumption for sensor. For the purpose of this experiment, the encoder tag was used to configure sensors to transmit data every 10 seconds. The sensors transmit signals that can be read in real-time. An application developed by the DAUIN Department enables the monitoring of the sensors’ operation by receiving real-time data. The sensors have the following features.

Relative humidity sensor:

- Range: 0 to 100% Rh;

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[17] ELA Innovation. https://elainnovation.com

- Resolution: 0.04% Rh;
- Accuracy: ±2% Rh max from 20% to 80%, ±5% RH max from 0 to 100%;
- Hysteresis: ±1% RH;

Temperature sensor:

- Range: -40◦C to +125°C;
- Resolution: 0.0625°C;
- Accuracy: ±.4◦C max from 0°C to 60°C; ±1.2◦C for the remaining range.

Figure 42: PUCK RhT sensors by ELA Innovation used for Experience II. From left to right: the antenna, a tag encoder, 10 RHT sensors, and 2 lux sensors

Both experiments were conducted at the Department of Architecture and Design of the Politecnico di Torino, located in the Castello del Valentino (Fig. 43) on July 18th (Test A) and July 19th (Test B) 2022. The rectangular-shaped building, measuring over 80 meters in length, is oriented in an approximate west-east direction. The structure houses a double-height library, and two floors of offices. The building's long façades (the northern one facing the offices, the southern one facing the corridor distribution system) feature continuous glazing interspersed with a regular overhanging reinforced concrete structure clad with exposed brickwork. The building's vertical circulation - the stairwells and elevators - are located at the end of the building. These rooms feature a continuous glazed mullion and transom façade that encloses the interior space.

The data collected with the RFId ELA sensors serve to draw initial qualitative indications on the subject and stimulate reflection on the prospects. Further analyses on the quality of the collected data should be carried out to understand the correct position of the sensors, the accuracy of the collected data.

Figure 43: Department of Architecture and Design of the Politecnico di Torino, From left to right: external view of the building, the corridor to the offices, and the stairwell

As anticipated, two monitoring campaigns were carried out using 10 PUCK RhT sensors.

Test A. The first test lasted approximately 24 hours. RFId sensors were placed inside the building to monitor temperature and humidity differences close to the façade at different locations. Specifically, three sensors were placed close to the façade (east, north, and west) (Fig. 44), one sensor was placed outside (north front) to monitor the temperature difference, and the other six were placed in interior areas away from the façade to assess the differences. This arrangement was designed to make as many comparisons as possible once the data had been obtained. A RFId reader, positioned barycentrically to the position of the sensors, allows to collect data for an entire day. Approximately 40 meters separate the sensor from the reader. Preliminary tests verified that the building structure did not interfere with the signal transmission. In some places, in fact, the internal concrete parts did not allow the sensors' signal to be read.

Test A aims to assess the potential of widespread monitoring of environmental parameters. This experience stimulates reflection on new monitoring methods and perspectives in the field of asset management. Approximately 40,000 data were collected throughout the day by the sensors used. Regarding the monitored data, it should be noted that during the day of the monitoring campaign, the cooling system was not in operation and the daily average temperature on 18 July was 29.4°C (max. 35.1°C).

Figure 44: RFId sensor installed on the internal façade during the first campaign monitoring

Test B. The second test was aimed at mapping the external temperature (and humidity) differences of a curtain wall. Real-time monitoring of the environmental conditions affecting the façade system is carried out for the creation of historical data and (hypothetically) for more precise regulation of indoor comfort. Monitoring the different conditions occurring on a façade (e.g., solar radiation, temperature, water, wind, etc.) can be crucial in assessing the durability of a system. In this case, 10 sensors have been positioned to form a grid that scans the planarity of the façade in height and width (Fig. 45-46). All the sensors face north and have no solar radiation incident on the sensor. As in Test A, the temperatures monitored refer to the air temperature near to the façade, the temperature of the frames and the glass panel could be drastically different. The reader in this case was placed in the building opposite (Room 1V), at approximately 50 meters from the analyzed façade. This also made it possible to estimate the maximum distance between reader and tag within which data can be sent. The monitoring lasted approximately 5 hours (from 2pm to 7pm) and around 8.000 data was collected for research purposes. Even if one cannot speak of a curtain wall, the conformation of the building determines a good assumption of the calculation.

Figure 45: RFId sensor grid installed. In the building on the right was placed the antenna

Figure 46: RFId sensor installed on the external façade during the Test B

5.3.3 Results

Test A. The monitoring campaign of indoor environmental parameters collected a significant amount of data to enable initial insights. The arrangement of the sensors in the building under study is shown in Fig. 47. The results provide a temperature and humidity comparison for the sensors placed near the interior façades (tag_ID8 for east exposure, tag_ID5 for north, and tag_ID10 for west) in Fig. 48, while the comparison with other sensors placed in the building is presented in Fig. 49. The orange graph identifies the outdoor temperature trend recorded near the north façade.

Comparing the temperature data close to different façades, (naturally) different trends were recorded throughout the day. In the summer period, with the air-conditioning system switched off, differences of up to 5°C were recorded between the sensor located on the east (tag_ID.8) and the west façade (tag_ID.10). A greater difference (up to 14°C) can be recorded when comparing the data from the stairwells with the north-facing office façade (tag_ID.5). Although this could easily be predicted from the orientation of the building and its spatial conformation (stairwells are triple-height room where the phenomenon of air stratification occurs most), real-time monitoring offers more accurate parameters on which to make observations. Regarding the comparison between temperature and relative humidity, in the office façade both parameters follow the same trend during the day, while in the two stairwells the maximum temperature values occur when the humidity is lowest. As far as the humidity values in the stairwells are concerned, the sensor on the inner façade to the west records values of up to 55 % during the early hours of daylight. On the other hand, a constant humidity value is present in the office located to the north (around 50%) where the influence of environmental parameters and the conformation of the building limits the daily offset. In the office, between 10am and 6pm, the more irregulate trend is more is (probably) due to the presence of people. The comparison with the other sensors used shows how the different temperature trends occur within the same floor depending on the façade proximity. This, exacerbated by the lack of an air-conditioning system, confirms how the conformation of the building and the façade technologies are decisive in controlling the internal comfort.

During the monitoring campaign, the data flow was constant, some brief interruptions of the signal were signal around 14.00 and 21.00.

Figure 47: Key-plan of sensor positioning

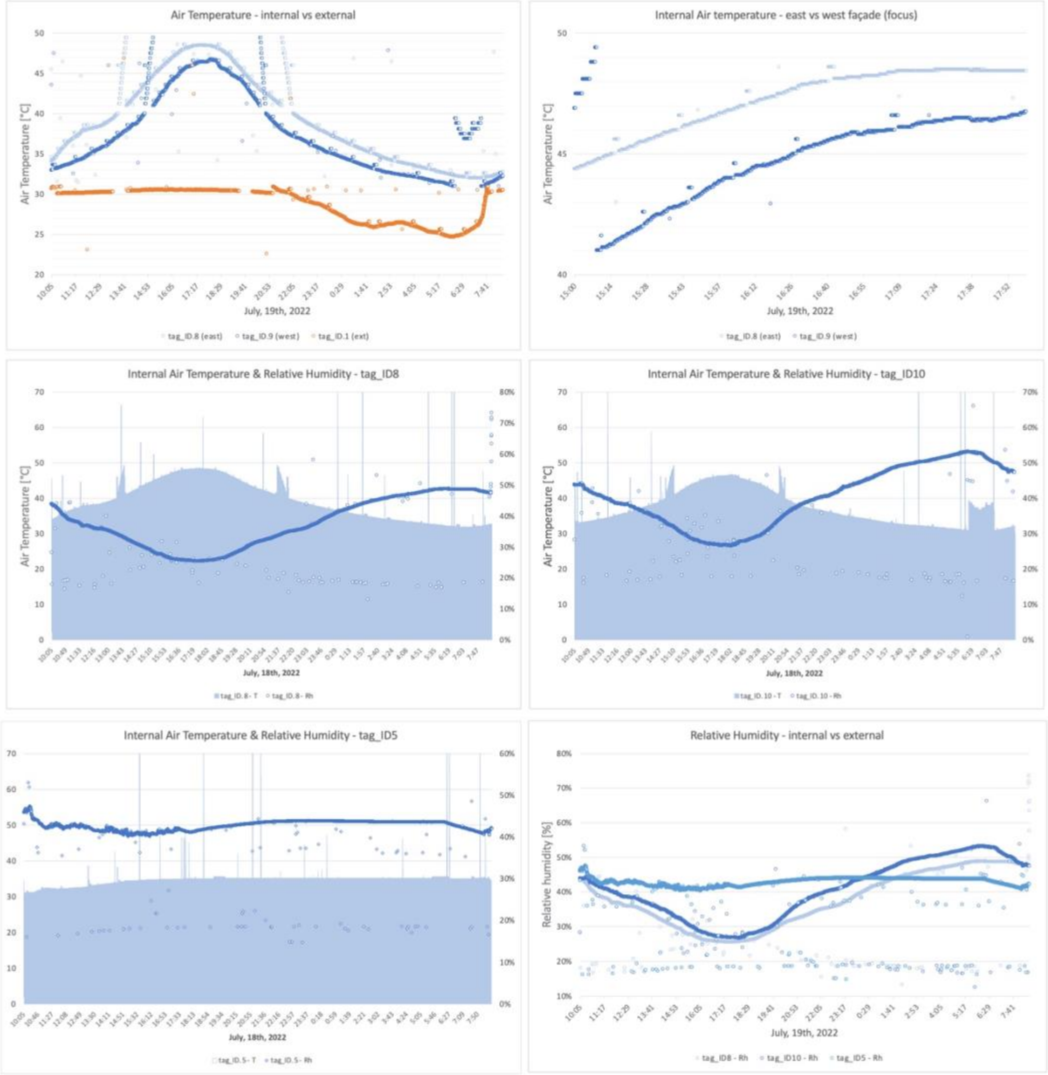
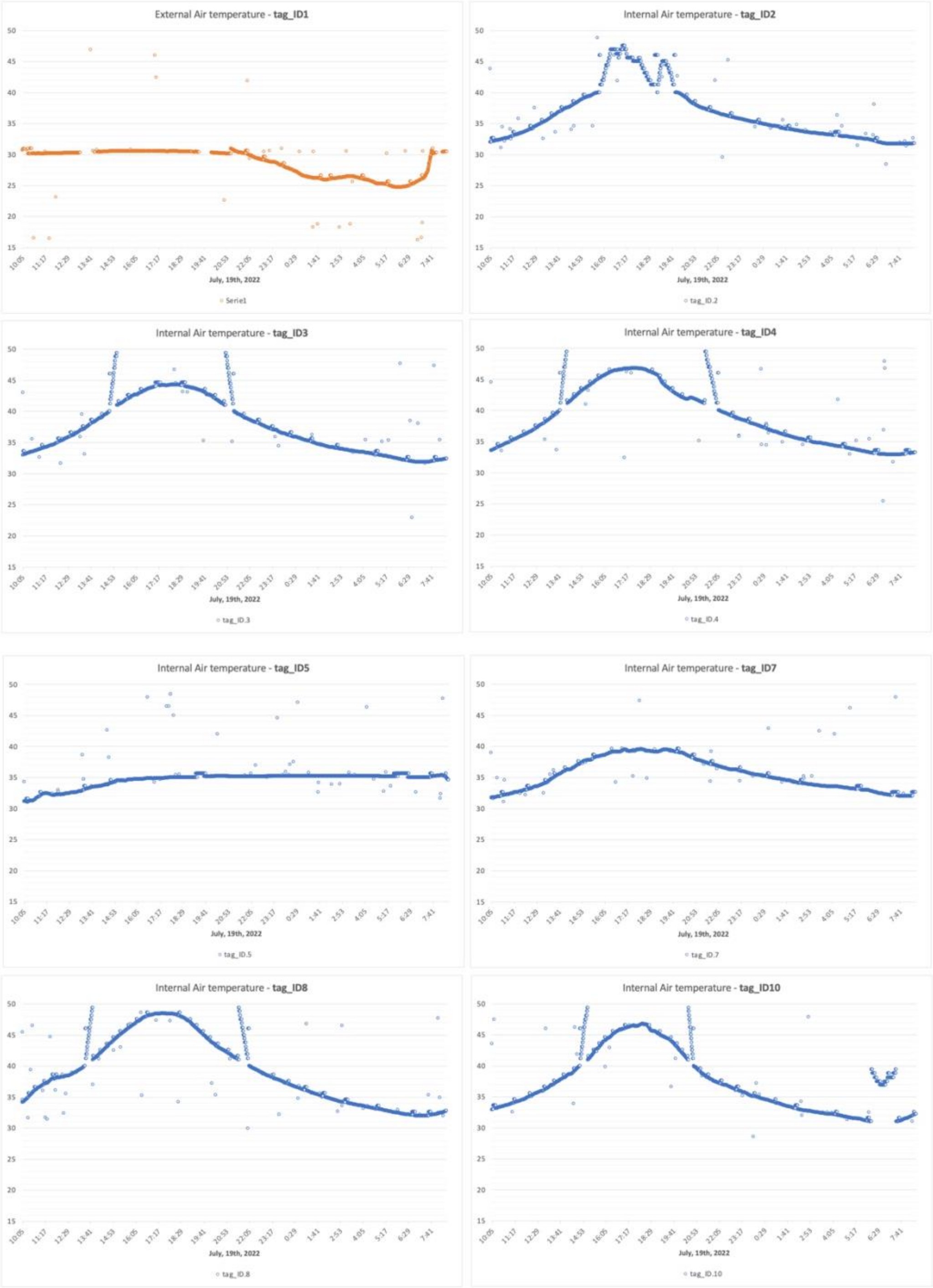


Figure 48: Air temperature and relative humidity comparison in office and stairwell



External Air temperature - **tag_ID1**

Internal Air temperature - **tag_ID2**

Internal Air temperature - **tag_ID3**

Internal Air temperature - **tag_ID4**

Internal Air temperature - **tag_ID5**

Internal Air temperature - **tag_ID7**

Internal Air temperature - **tag_ID8**

Internal Air temperature - **tag_ID10**

Figure 49: Test A. Temperature data monitored by RFId sensors. In orange the external temperature.

Test B. Test B aims to map the distribution of outdoor temperatures and humidity and to identify the range of the technology for medium and long-distance reading. Fig. 50 shows a schematic of the positioning of the sensors on the façade. The monitoring of the north façade was chosen to reduce the effect of incident solar radiation on temperature data. The recorded data, compared with the official data provided by ARPA, proved to be reliable and accurate for the purpose of the research. Indeed, as shown in the first graph in Fig. 51, the trend of external temperatures monitored at the Castello del Valentino is similar to that monitored by ARPA at three different points in the city of Turin. Between 2pm and 7pm on 19 July 2022 (the monitoring campaign period), the data record outdoor temperatures between 32°C and 36°C.

The active RFId sensors indicate on average about 0.5°C higher values than the ARPA data (Station "Giardini Reali"). The comparison of the temperature data shows a temperature difference of up to 4 °C between the sensors placed on the same façade (Fig. 51). It is interesting to see how the temperature is directly influenced by the height of the sensor. In the library (orange trend line), at a height of zero relative to the ground floor, significantly lower temperatures are recorded than in the other sensors. For all sensors located in the offices (green, blue and yellow trend line), the temperatures can be considered similar. A further difference can be seen in the sensors in the stairwell (grey and dark blue), where the greater exposure to the west front has (probably) influenced the temperature increase. The height comparison shows temperature differences of up to 4°C, whereas the comparison of sensors on the same level is about 2.5°C. The two focuses presented show how the daily trend of environmental parameters can be approached with greater spatial and temporal accuracy than current monitoring systems. This condition can be exacerbated in the case of multi-storey buildings or in denser urban settings, where shadows brought by adjacent buildings obstruct solar radiation, thus leading to very different microclimatic conditions.

In Fig. 52, the signal frequency was monitored. Although the signal pattern is more irregular than in Test A, we can state that at a distance approximately up to 70 meters, the signal is transmitted without any problems. In this case, signal transmission is easier in the open field as there are no obstructions present that could limit signal sharing. Only in one case, the "tag.ID10" (dark red trend line), the signal was lost a few minutes before the start of the test.

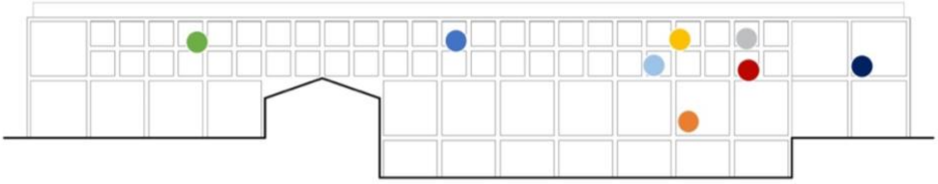
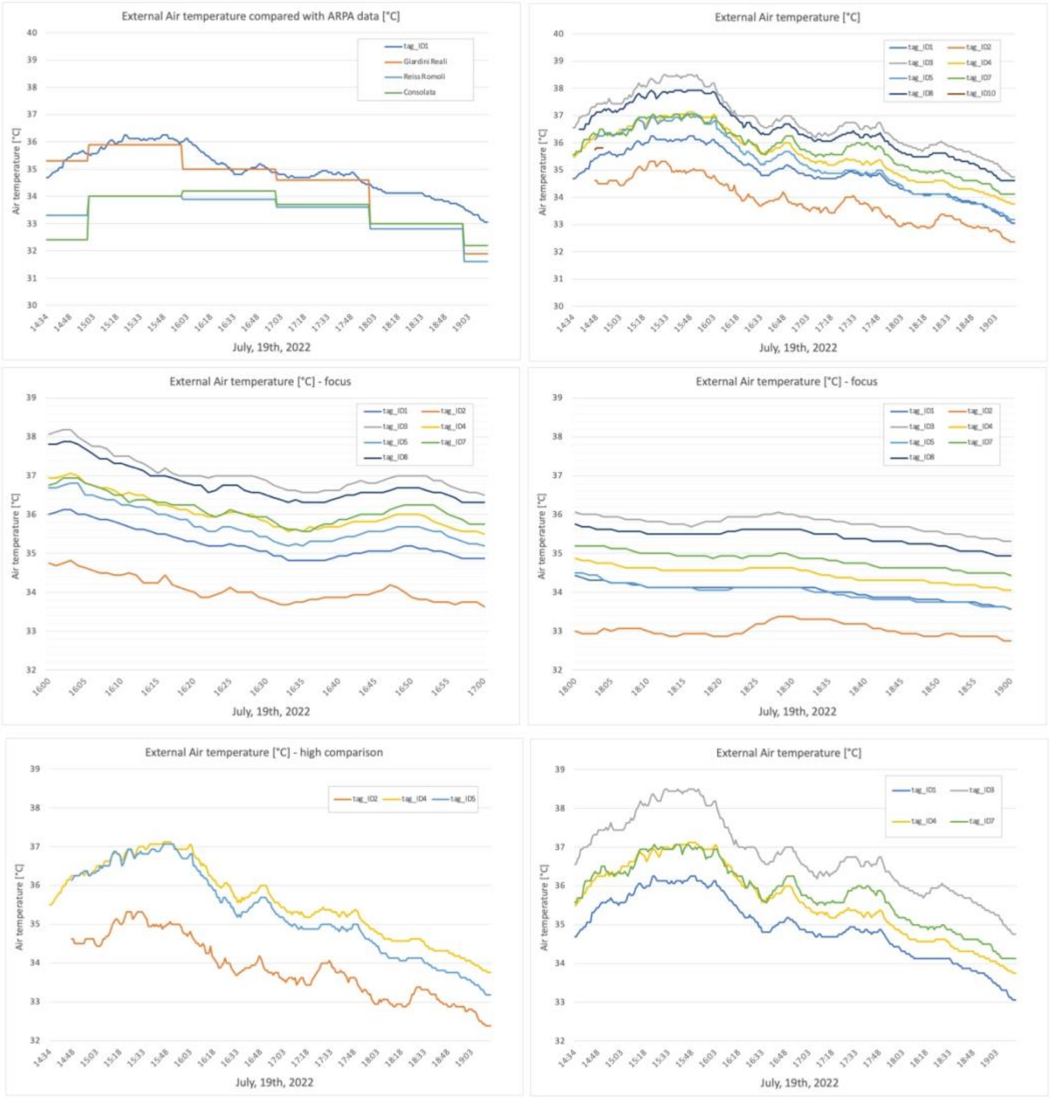


Figure 50: North elevation of the façade monitored. The colored dots represent the RFId tag position.



External Air temperature compared with ARPA data [°C]

External Air temperature [°C]

External Air temperature [°C] - focus

External Air temperature [°C] - focus

External Air temperature [°C] - high comparison

External Air temperature [°C]

Figure 51: External air temperature comparison

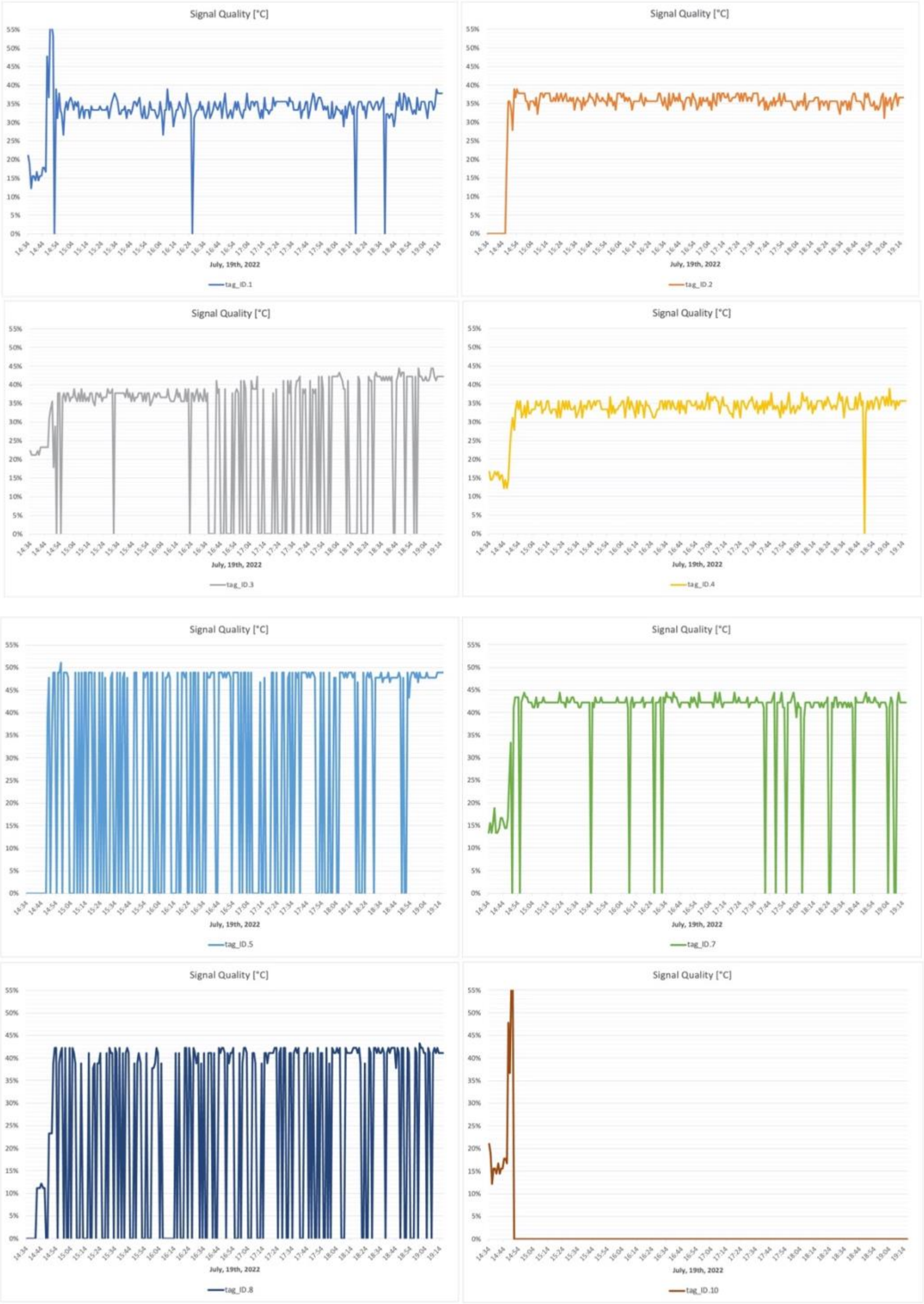


Figure 52: Sensor signal transmission level for Test B

5.3.3 Discussion

Experience II aimed to investigate the benefits of widespread monitoring of environmental parameters to enable more rational and circular management scenarios. As already mentioned, Experiment II should not only be understood in reference to temperature and humidity but to the continuous monitoring of various parameters. These, in addition to comfort regulation and optimization of HVAC systems, can also be decisive in the management of a façade system. It is well known that environmental factors are the main stress of a façade component that is designed to last for years. The acidification of the air and the increased intensity of storm phenomena induced by global warming exacerbates this condition. Incident solar radiation, water, and temperature (hot-cold cycles) are factors affecting the tightness of materials and their ageing. Thus, monitoring these phenomena could facilitate maintenance activities for huge building stock. For example, the façade modules most subjected to UV radiation can be serviced more frequently to avoid vulcanizing sealants. At the same way, monitoring air pressure in the glazing chambers (an element that affects the transmittance of the window frame) or interstitial humidity in the joints could point out any air or water leakage. Based on façade features, different kind of monitoring can be designed to reveal trends and possible anomalies at the most fragile points.

Theoretical implications. Among the theoretical implications of the research, it is worth emphasizing that such experiments should be followed by failure model analyses for specific façade systems. Although from a theoretical point of view, the relationship between phenomenon and failure is evident, there is a total lack of literature on the subject. This makes it more difficult to identify the relationship between, for instance, temperature, solar radiation, and the service life of external seals. In this perspective, the creation of large datasets would facilitate the construction of thresholds and limit values on which operators could organize their activities. Despite today diagnostic actions for corrective maintenance are the result of the experience of specialized technicians, in the future these could be influenced by large datasets. In this case, the advantages provided by such an application would have to be evaluated from an economic point of view. In complex and dynamic envelope systems, where there is widespread environmental monitoring for comfort issues, the use of such for additional purposes could ensure greater interest on the part of the various actors.

Technical implications. The main technical implications include signal transmission. The RFId technology can be extremely functional in open environments where physical interference is extremely limited. In Test A, the indoor test, the data collection was possible because the internal shape of the building provides a long corridor with no particular obstructions for sharing signal. Furthermore, using a single RFId reader it was impossible to receive the signal from sensors located on the lower floor or where concrete wall were present. This implies that for office buildings, the number of readers may be high, making the system, also from an economic point of view, not sustainable. In this regard, since the environmental sensor can be integrated with a regular mesh that is not too dense, wiring through cables could be the ideal solution for new façade components.

Management implications. Finally, the management of data and sensors is an issue to be addressed. Today, the maintenance of building envelope of a certain importance outsourced to third parties limits the collaboration between manufacturers and operators. In current market, the manufacturer’s interest is limited to a few years after the sale of the asset due to insurance issues. The management of the asset, which is essential for the maintenance of the design conditions over time, is often entrusted to facility companies. The lack of collaboration between asset manufacturers and service providers implies little interest in the subject. Furthermore, it should be noted that service providers use already often advanced procurement management systems. Therefore, such an approach could emerge in CBM where the façade manufacturer is responsible for a longer period of the asset in use. In this case, the producer’s interest in maintaining the performance of the asset would be central to generating direct profits.

5.4 Exp. III. Integrating new customized services

5.4.1 Theoretical framework and hypothesis

Experience III focuses on integrating new services rather than just managing and reducing material flows. One of the main objectives of CE is to shift to a dematerialized market where services are exchanged and shared instead of physical goods (Bocken et al., 2016). This approach allows customers to gain economic benefits without consuming large amounts of resources and creating waste. In this perspective, a key task is exploring the potential uses and new functionality of a "smart envelope".

One of the most fascinating functionalities of the façade is its potential to monitor the quality and healthiness of indoor and outdoor environments. As a filter, it can play a central role in monitoring environmental parameters that impact human health and subsequently act to regulate these conditions. A case in point is air quality. As reported by the WHO, approximately 4.2 million premature deaths in Europe are caused by fine particle pollution (WHO, 2021) and lives are reduced by approximately 8 months in the most polluted areas (EEA, 2020). With increasing awareness of the air quality problem, the development of air monitoring technologies is gaining unprecedented popularity. The façade system, generally regulating the exchange of air between inside and outside, could include such functions. The monitoring of indoor and outdoor conditions offers a twofold advantage. Firstly, it ensures continuously monitored air quality levels for building occupants. Secondly, if integrated into a larger infrastructure for measuring environmental parameters at the district or city level, it can aid in detailed mapping of air pollution pattern. Diffuse monitoring at the urban scale, as reported in the literature (Atzori et al., 2019) (Mora et al., 2019) (Montrucchio et al., 2020), allows specific critical phenomena to be identified in densely urban areas. In fact, the spread of pollutants is not only influenced by primary sources such as heating and cars, but also by ventilation. The latter, which is favored or hindered by the conformation of the urban fabric (e.g. height of buildings, distance from buildings, surface temperatures, etc.), can determine a concentration of dust that is very different from the average data recorded on an urban scale. These assumptions are closely related to the CBMs of the sharing platforms and the PAaS. For the former, it is possible to imagine how the creation of continuously recorded data from a façade system can feed shared databases where access to information became a commodity. For instance, the sale of data for the development of shared platforms on meteorological and urban pollutant data. As far as the PAaS model is concerned, this experience should be understood as one of the possible functionalities that can be customized according to customer requirements. For the development of projects where comfort (e.g., offices) and healthy environments (e.g. hospitals, nursing homes) are a fundamental requirement of the envelope, such applications can find new meanings. The following experiences, besides triggering a debate on the future of the façade functionalities, attempt to clarify aspects such as the spatial resolution and temporal granularity of data.

The hypothesis of Experience II is therefore:

If the circular transition requires the creation of service-based markets and shared platforms, the introduction of new intangible functionalities in the façade system could foster new ways of use.

5.4.2 Technology: Air Quality sensors

For Experiment II, fine dust sensors for monitoring Particulate Matter 10 and 2.5 (PM10 – PM2.5) were used. Specifically, some station boards were developed including temperature, humidity, pressure sensors, and PM sensors. The monitoring of several parameters at the same time can be essential in studying the relationships between them. Before the monitoring campaign, the station boards were tested and calibrated at ARPA's official monitoring station in Via Rubino (Turin). It must be emphasized that the data presented below, although they have no normative value because they were measured with instruments that were not officially calibrated, allow us to make qualitative considerations on the potentiality of IoT technologies. The calibrated data demonstrated a sufficient degree of reliability for the purposes of this research. The board assembled at the Politecnico di Torino and inserted into a 3D printed case includes the following elements (Giusto, 2021) (Fig. 53):

- *PM 10 and 2.5 sensor.* The sensor used is the Honeywell HPMA115S0-XXX, which is commercially available at a price of approximately 25-30 US dollars. This sensor detects PM2.5 and PM10 particle concentrations in the air for values between 0 and 1000 μg/m^3 with a sensor accuracy is

15%. The sensors, measuring 4.3x3.6x2.3 cm (WxDxH), provide 20k hours of autonomy in continuous use (approximately 28 months). The sensor uses the Light Scattering technique. This means that a rotating fan draws air into a chamber, this is then hit by a laser beam, and a proprietary algorithm within the device estimates the concentration of particles using a photodiode. The sensor communicates with the board via UART communication and writes new data every second. At this stage of the research, four boards were used in series to have such redundancy of the results.

- *Temperature and humidity*. The DHT22 is a low-cost but very accurate digital temperature and relative humidity sensor. Humidity readings range from 0% to 100% with an accuracy of 2-5%; temperature readings range from 40 to 80 degrees Celsius with an accuracy of 0.5°C and the sampling rate is approximately 0.5 Hz. Dedicated APIs are used to interact with the sensor.

- *Pressure*. The Bosch BME280 is an accurate barometric pressure and temperature sensor. Barometric pressure sensing range: 300-1100 hPa; resolution: 0.03 hPa/0.25 m; operating range: 40-85°C, with an accuracy of 2°C; values are conveniently retrieved via I^{2}C interface using dedicated APIs.

- *Time*. A Unix Time Clock is used for time synchronization of data.

- *Monitoring board*. A Raspberry Pi Zero Wireless was chosen as the single-board computer. The operating system chosen for this project is Arch Linux for ARM, which ensures that only the essential components of the operating system run and does not waste resources. All sensors are queried via Python scripts executed as system units.

For Experience II, two different tests were carried out (*Test A* and *Test B*).

For both Tests, a comparison is proposed with official temperature and PM data recorded by ARPA at the Turin Rebaudengo, Turin Reiss Romoli, and Turin Consolata stations. More than a comparison of data, this evaluation should be read as a possible advantage in widespread monitoring and as a benchmark for comparing official and low-cost monitored data.

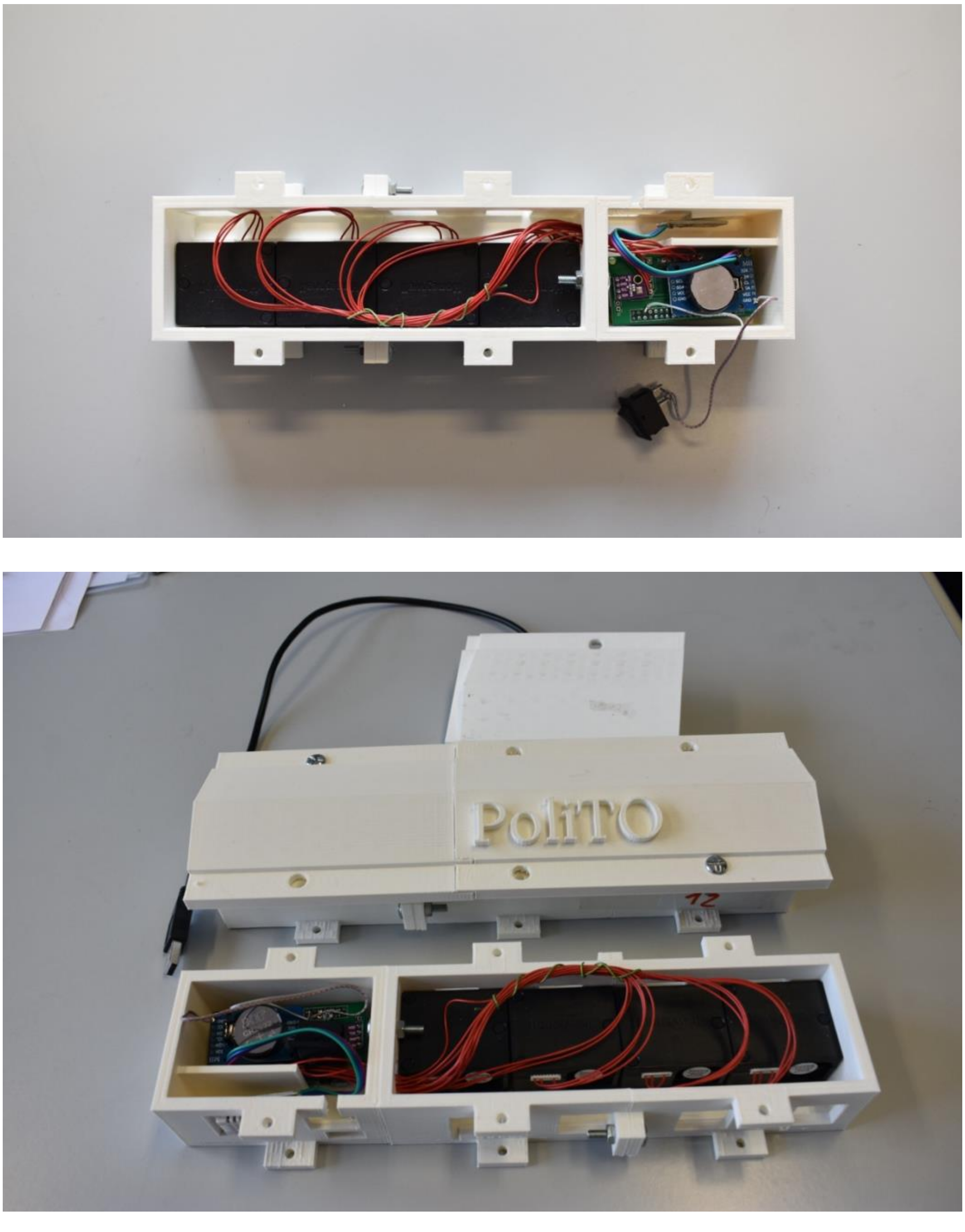


Figure 53: Views of the of the monitoring board station used for Experience II

Test A. The goal of Test A is to monitor internal and external values of PM10, PM2.5, temperature, humidity, and pressure. The case study chosen was an office located on the second floor of the DAD offices at the Castello del Valentino (Torino) with a glass façade facing north. The test aimed to assess the difference in values between indoors and outdoors, to check whether opening the window caused an interaction between indoor and outdoor PM levels, and to qualitatively compare the low-cost data with those officially monitored by ARPA. The monitoring campaign was conducted from Tuesday 11th February 2020 to Monday 17th February. The first 3 days of the campaign were characterized by the presence of office people, while during the last 4 days the office was closed. The two monitoring stations were placed near the façade (Fig. 54). The external one was fixed to the window and electrically powered via a cable passing through the window frame, the inner one was positioned close to the façade to simulate a potential integrated monitoring. Approximately 3 million data were collected on the memory card on the board and processed with Excel.

Figure 54: Two monitoring stations were placed inside and outside the façade

Test B. The goal of this test was compared the effect of façade exposure to external anthropogenic factors. To this, two flats were identified as case studies (namely “via Ghedini” and “via Gallina”). Both located in the Regio Parco area in northern Turin, they are part of a complex of courtyard buildings (Fig. 55). The double exposure of both apartments (street front and courtyard interior) made the comparison possible. The sensor boards were placed on the balcony for both exposures facing the street and anchored to the window frame to ones facing the court (Fig. 56). In this way, the sensors were connected to the electric power. Although the road bordering the building is not a high-traffic road, the different exposures of the façades are evaluated. The monitoring campaign was carried out in 3 different seasons between 2021 and 2022 (April, July, and February) to assess the effect of background dust and the seasonality of the phenomena. For each campaign, approximately 13 days of monitoring made it possible to assess monthly trends without the data being influenced by the meteorological specificity of the day. A total of 38 days were monitored.

Figure 55: Test B case study view

Figure 56: Via Gallina (images on the left column) and Via Ghedini (right column) case studies

5.4.3 Results

Test A. The first test shows a comparison between interior and exterior by monitoring PMs close to the façade (Fig. 57). The days before monitoring campaign were characterized by significant wind intensity in Turin (around 25km/h). For this reason, the initial external PM values (lower than 10 μg/m^3) are much lower than the seasonal averages (around 50 μg/m^3). The PM10 values monitored by the official ARPA station - Turin Rebaudengo (approximately 5km away) confirm the trend detected by the low-cost sensors (official values report daily average levels above 80 μg/m^3 on 16th,17th February). The first two graphs above show the PM10 values for indoor (blue graph) and outdoor (orange graph). The average of the four sensors on the board makes it possible to limit possible anomalies and sub-optimal calibrations. The data recorded outdoors show a rapidly increasing trend, from an average of less than 20 μg/m^3 on the first two days to over 100 μg/m^3. Please note that the monitored data is data recorded every second while ARPA's data are daily averages. Regarding internal board, data shows for the first three days (Wednesday, Thursday, and Friday), when the office is used during the day, a more discontinuous daily trends. Specifically, during daily hours there is a substantial increase in values probably due to the switching on of the air fan coil unit (close to the façade). Indeed, during the weekend while the office is closed and the air fan coil unit was switched off the daily values are more constant. However, there is a slightly increasing trend in PM10 during the weekend (office closed) that seems to follow the external trend (an increase of about 10/15 μg/m^3). A longer monitoring campaign would be needed to investigate these relationships. Regarding temperature and humidity, The daily outside temperature fluctuation was around 10°C, with minimums around 6/8°C and maximums (except for the first day) of 16/18°C, while for humidity the values changed throughout the day with a delta of around 20%. Internally, the temperature values were always between 22°C and 28°C with the office in operation, dropping at the weekend to 18°C (heating system switched off). From the temperature and humidity graphs it can be seen that the influence of the people in the office makes the values fluctuate more (first three days). To qualitatively analyse the exchange of PM between inside and outside, a relationship between PM10 and indoor temperature was reported. The sudden drop in temperature (from 27°C to 21°C) represents the time when the window was open. Subsequently, there is a drastic increase in indoor PM. This can probably be dictated by the use of the fan coil with maximum air flow to reheat the office. Further analysis on the exchange between indoor and outdoor should be conducted.

Finally, comparisons between PM10 trends and temperature are reported. Although there are not enough data to make statistical assessments of the mutual influence of the parameters, we can deduce that the temporal granularity of the data produced would allow for more detailed analyses of the relationship between the environment and the built environment.

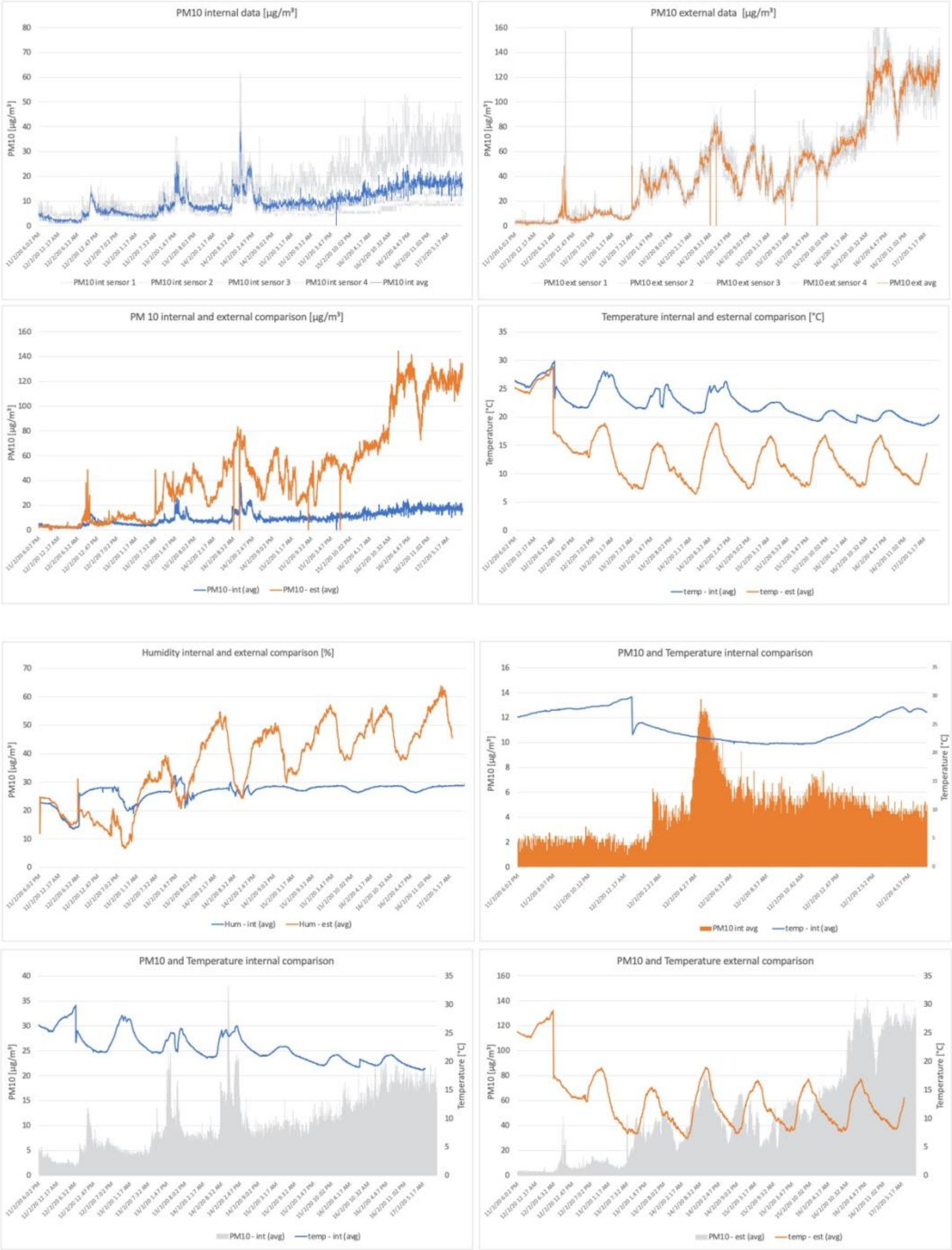


Figure 57: Test A. Data collected in one-week monitoring campaign of the office (internal blue, external orange)

Test B. The second test aimed to identify the benefits of diffuse monitoring as a function of façade exposure based on different seasons (Fig. 58). Three main aspects were to be verified: (i) the comparison of façade exposure, (ii) the comparison of two façades at approximately 100 meters to give initial indications of the spatial resolution of the monitoring mesh, (iii) the reliability of the data in comparison with the official data monitored by ARPA. For the first goal, it must be anticipated that the roads bordering the building are low-traffic roads. Different values could be found in busier urban contexts. Further investigations should be conducted in buildings close to busy streets. Probably influenced by this reason, the first two graphs of PM2.5 show no particular difference between the trends in indoor courtyard and street front in the April campaign. For all three monitoring campaigns, similar values were recorded. Slightly higher values were recorded by the sensors exposed towards the inner court (with peaks of even PM2.5 20 $\mu g/m^3$). The data collected show higher peak values for the courtyard façade, possibly due to turbulent and non-linear air currents that hinder dust ventilation. The comparison between the courtyard interior and the façade of the same building did not therefore generate significant differences.

The second comparison involves the analysis of the two points that proved to have more significant values at different times of the year (April, July, February). The creation of a multi-season dataset allows initial reflections to be made. The two monitored façades, approximately 100 metres apart as the crow flies, showed no significant differences over the 38 days of monitoring. The slight differences in the three periods of analysis are probably dictated by the same conformation of the urban fabric, the same orientation of the two buildings, and similar influence of external factors (e.g. car presence and domestic pollution). Further analysis could prove useful to define a minimum mesh size to identify possible trends. Finally, on the basis of the data collected, it is possible to conduct an analysis of the reliability of the data. After the three monitoring campaigns, it was possible to analyze the mean square deviation of the data provided by ARPA. From this point of view, a value of 6.5 µg/m3 can be considered extremely good for research purposes. The data analysis also showed how the level of approximation decreases in the autumn and winter seasons, where dust levels are higher. A greater deviation of the low-cost sensors from the officially monitored data may occur in the summer period. However, it remains evident that an hourly trend can provide much more detailed information than the daily averages provided by ARPA.

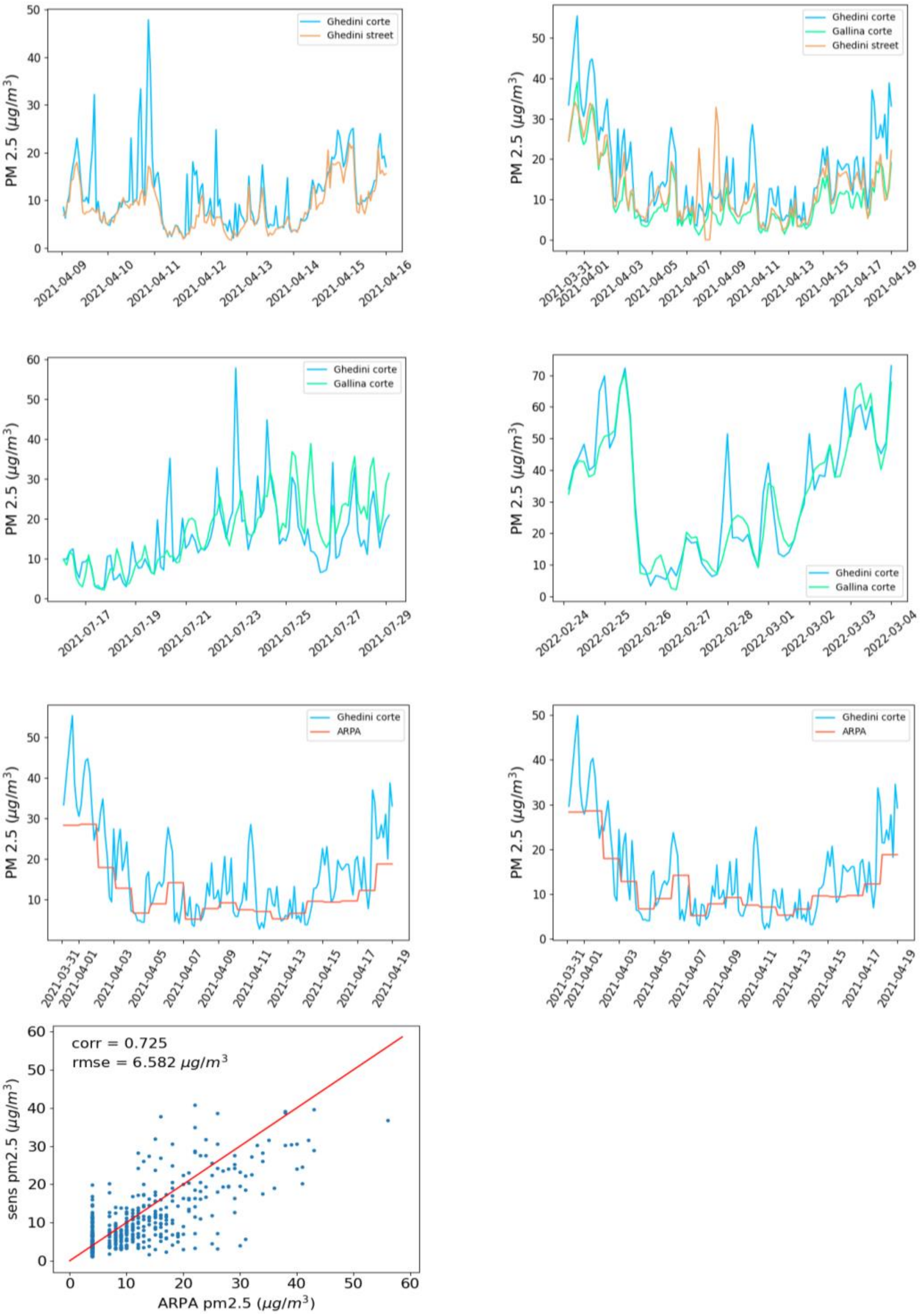


Figure 58: Test B. PM2.5 data collected from different monitoring campaigns

5.4.4 Discussion

Experience II aimed to investigate new functionalities to be integrated into the façade system in order to support the provision of new services and (potentially) enable shared platforms. The focus on air quality should be understood as one of the opportunities offered by the IoT. In this perspective, the increasing focus on indoor environmental quality and the proliferation of urban monitoring platforms on the real-time distribution of pollutants represent key points for technology choice. Although the development of systems offering new technologies requires updating business models, this experience opens new scenarios on the topic.

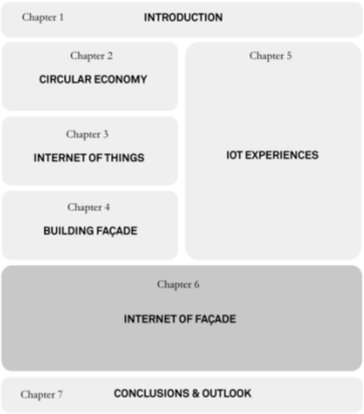
Theoretical implications. First of all, awareness of the determinants of occupant comfort and health must be consolidated. Although the WHO, sustainability protocols and other organizations have been warning for years that the quality of indoor environments can have serious effects on human health, the subject is still not widely discussed. Data sets and experiences of this kind are needed to create greater awareness of the problem. When the topic is of interest to the majority of users, the demand for sensors and smart enclosures will (perhaps) grow proportionally.

Technical implications. In the specific case of air quality monitoring, several aspects need to be considered. First, it is necessary to understand, depending on the case study, the number of sensors required to map the indoor and outdoor built environment. Particularly for envelope systems with opening components this may be particularly significant. In contrast, for curtain wall systems and forced ventilation systems this necessity is lessened. In fact, in the latter case it would be more correct to measure the air quality in the center of the room (or near the workstations or most frequented) to obtain useful data. As in the previous experience, the wiring of sensors would guarantee greater security in the transmission of data. However, advances in short-range transmission protocols (e.g. LoRa) allow for greater versatility.

Managerial implications. From a managerial point of view, the most important issue is to estimate the value of the data produced. The development of CBM based on data exchange and guaranteed performance is a complex and interdisciplinary issue. The biggest obstacle to date is the fact that the potential revenues produced by an enclosure system would (still) be limited compared to the cost of the façade. Thus, the manufacturer’s interest in developing specific components is extremely limited. In addition, the need to integrate new know-how of a purely digital nature implies the introduction of new professionals into the workforce. This can represent an unsustainable cost item for a company, especially in the embryonic phase of the technology.

Chapter 6

Internet of Façade



To clarify the enabling role of IoT (Rq, cfr. 1.2.3), the “Internet of Façade” framework is presented. Lessons learnt from literature and field experiences are used to identify the innovative potential of technology in the circular perspective. Before detailing the nine enabling circular actions, sections 6.2 and 6.3 identify the opportunities offered by IoT technology (Rsq.1) and the interlinkages with CBM requirements (Rsq.2). Once the theoretical framework has been defined, research implications and barriers are presented. Finally, *Chapter 6* ends with the validation process, performed with interviews and a questionnaire, aimed at prioritizing the enabling actions with a view to develop an IoT-based façade.

6.1 Framework development

The "Internet of Façade" framework address the main Rq of this study:

Can (and how) the IoT enable the Circular Economy in the façade sector?

This framework offers a broad overview of the perspectives of IoT in the façade sector with a view to promote circular innovations. The knowledge gained from the theoretical background and field experiences are combined to clarify the potential enabling role of information technology. This theoretical framework is primarily addressed at investors, developers, and façade manufacturers who want to invest in the development of CE-oriented innovations.

Before presenting the results, it is necessary point out some limitations of the research. The exploratory research was conducted primarily on the basis of qualitative data and considerations. Further market and technical investigations would be necessary to assess the reliability of the proposed results. However, for the purpose of this research, the data obtained are necessary to feed a debate on the topic. However, for the purpose of this research, the data obtained are necessary to feed a debate on the topic.

This *Chapter* is organized as follows. First, the structure of the framework and how to read it is explained (6.1.1). In section 6.1.2, the Internet of Façade is presented by providing a general overview on the subject. Subsequently, the focus on the opportunities offered by the IoT (6.2) and the information requirements imposed by the circular transition (6.3) are clarified. Section 6.4 reports the results of the exploratory research clarifying the potential enabling role of the IoT and the implications of the research. Finally, section 6.5 presents the validation process used to confirm the collected data and define the future of this research.

6.1.1 Framework's structure

The "Internet of Façades" is organized into four main parts (Fig. 59). The first part (the left-hand box) identifies and summarizes the opportunities offered by IoT technologies in producing, sharing, and storing information addressing the Rsq.1:

What opportunities does the IoT offer in managing life cycle information of a façade system?

To this, two types of analysis are carried out. The first concerns the setting of parameters that can be monitored by sensor integrated into façade systems. While the second focuses on information management tools to identify the opportunity in creating new information flows among stakeholders. On the other part of the framework (right-hand box), the information requirements imposed by the circular transition are defined to address the Rsq.2:

What information is required to support CE in the façade sector?

Again, two actions were carried out in response. First, the relationship between parameters that can be monitored with the IoT and CBMs was identified. After that, 12 types of information concerning the useful life of a façade were defined by analyzing the literature and the main experiences in the field of material passports (MPs).

The opportunities offered by the IoT (Rsq.1) and the information requirements imposed by the circular transition (Rsq.2) find a point of intersection in the middle box. Thus, three application domains were identified as key "Strategies" in which IoT technology could be adopted to enable CE. Within this, nine potential "Actions" are presented with a view to stimulating reflection on the future of digital technologies and smart building components and answer the main Rq. Having defined these aspects, a fourth part (the box below in the framework) clarifies the technical implications (coming from IoT opportunities), management implications (coming from CBMs), and the main barriers in the development of digitally integrated systems.

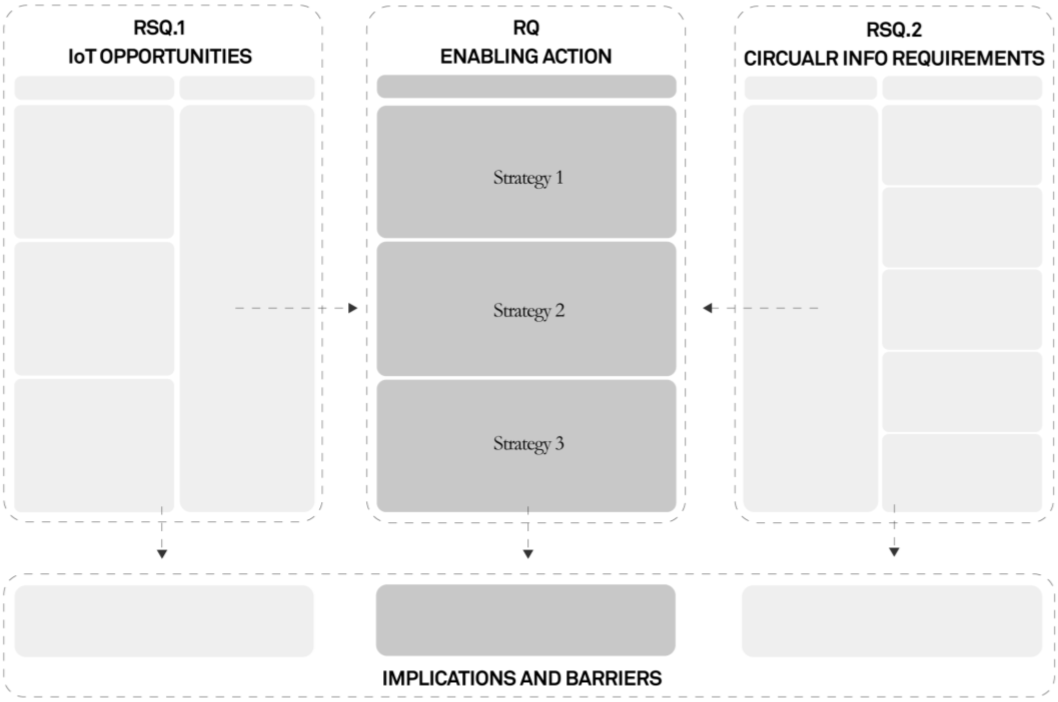


Figure 59: Structure of the “Internet of Façade” framework

6.1.2 The “Internet of Façade” framework

The framework represents an organic and synthetic re-elaboration of the theoretical and technical aspects identified during the research (Fig. 60). This offers an exploratory insight into the potential of IoT technologies in the façade sector. It can be read from left to right or right to left, depending on whether the problem is approached from the perspective of the opportunities offered by the IoT or the requirements of the circular transition. The use of icons and numbering of the different factors is designed to make reading more intuitive. In the middle, the nine potentially enabling “Actions” are divided into three “Strategies” according to the purpose of application. For each of them, the types of information required, and the type of actors involved are highlighted by means of circle icons. Whereas, for each action, the type of sensors to be used (S.) and the CBMs that can be activated (CBM#) are highlighted through an abbreviation below the Action’s description. In the lower part, technical implications (bottom left), managerial implications (bottom right) and barriers (bottom center) are given.

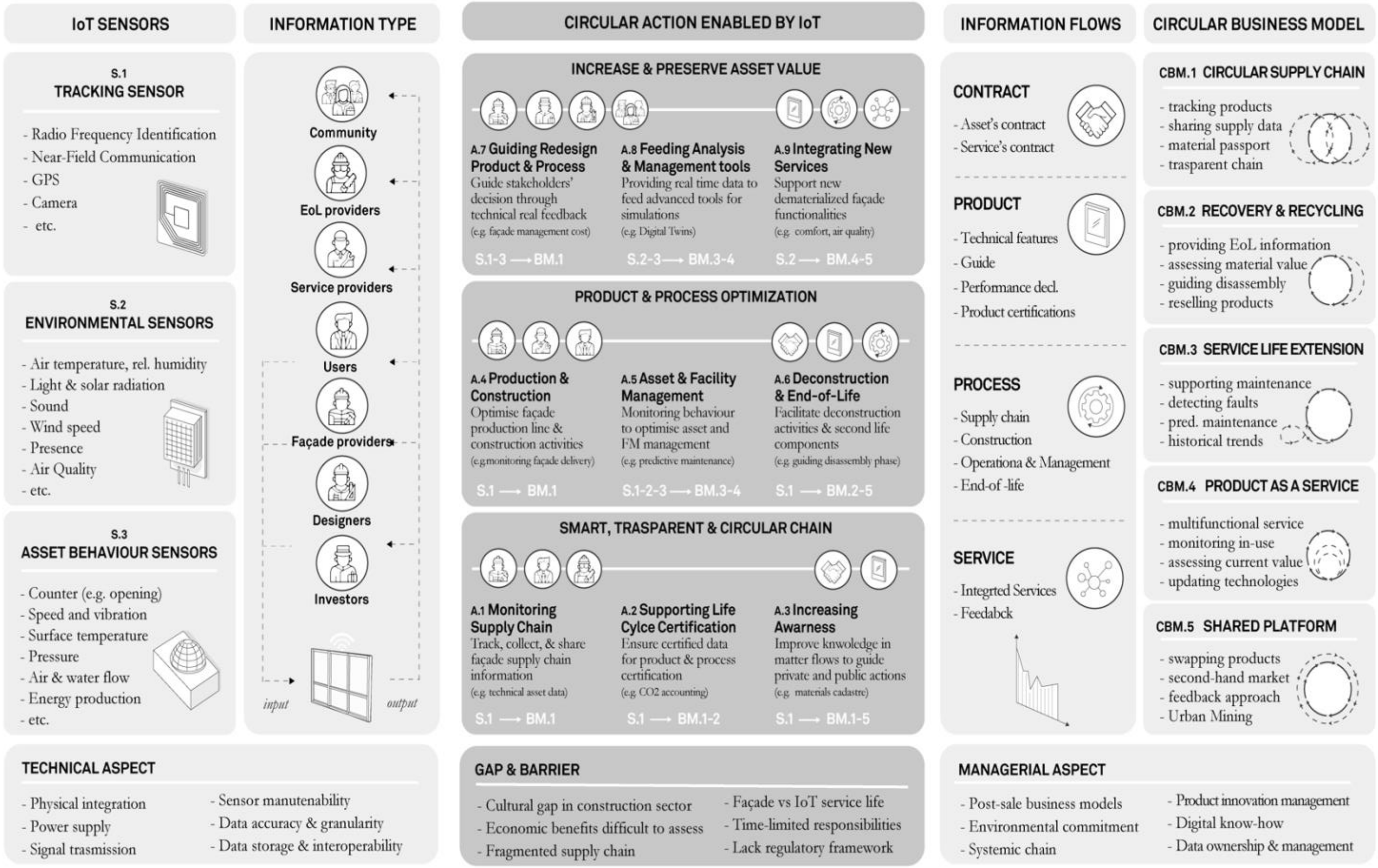


Figure 60: The "Internet of Façade" framework

Although the framework is to be used as a working tool, it can be regarded as a starting point for the development of further research. Further aspects related to the opportunities offered by the IoT but not strictly related to the circular transition have not been highlighted in the text. The explanation of each parts will be made in the following paragraphs. The discussion proposed in section 6.4 will explain the results obtained.

6.2 IoT opportunity

The IoT offers a wide panorama of opportunity. New information flows enabled by IoT technologies can trigger the exchange of value between different stakeholders by promoting (hypothetically) a more rational use of resources. Several researchers are investigating the opportunity of IoT in driving ecological and circular transition (Demestichas, and Daskalakis, 2020; Cagno et al., 2021; Dantas et al., 2021). In this perspective, quantitative and qualitative data on products and processes thus become a commodity and a new form of commercial profitability among stakeholders (Argus et al., 2020). For instance, as already demonstrated in others sector, traceability data can increase asset quality and guide consumer choice.

To identify IoT opportunities (Rsq.1), two main aspects were considered: the ability to produce data and to share it. Regarding “producing”, a list of primary parameters was proposed to identify which types of sensors could be integrated into the façade. As far as “sharing” is concerned, an analysis of the main information management tools and the role of the different stakeholders makes it possible to identify the potential of the IoT.

6.2.1 Parameters and sensors

From literature analysis and field experience in testing IoT technologies, a considerable number of parameters have been identified that can be monitored with IoT sensors. 18 main parameters based on the literature (Talamo and Atta, 2019; Luna Navarro, 2021; de la Barra Luegmayer et al., 2022) and conducted experiences can be considered essential for the circular management of a façade system (Tab. 8). Although the opportunities offered by IoT are broader, this list can be considered exhaustive for the purpose of the research. The definition of these parameters is necessary for the subsequent development of key performance indicators that support the decision-making choices of the various players. Depending on the type of parameter, three main types of sensors were identified that could potentially be integrated into façade systems (Fig. 61): asset identification and geolocation, internal and external environmental monitoring, and monitoring of the assets operational status (Tab. 8).

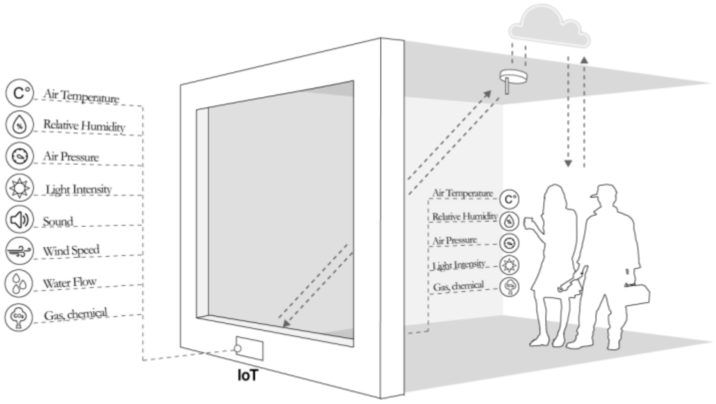


Figure 61: Potential parameters that can be monitored by an IoT-based façade system

Table 8: Types of parameters that can be monitored by an IoT-based façade

Type	Parameter	M.U.	Sensor technology
Tracking and identification	Identification	-	RFId (LF, HF, UHF), NFC, etc.
	Geolocalization	-	GPS
Environmental monitoring	Air Temperature	[°C] [K]	Thermometer (e.g. DHT), thermocouple, etc.
	Relative humidity	[%]	Relative humidity (e.g. RHT)
	Pressure	[Pa] [Bar]	Barometer, manometer, etc.
	Illuminance	[lux]	Luxometers (e.g BH1750)
	Sound	[dB]	Microphone (e.g. KY-037)

Asset monitoring	Wind speed	[m/s]	Anemometer
	Rain	[mm] [-]	Optic sensor, pluviometers
	Gases and chemical	[CO2] [µg/m^3]	CO2, NO2, PM sensor, etc.
	Surface temperature	[°C] [K]	Contact thermometer, infrared
	Humidity	[%]	RHT, Piezoresistive, etc.
	Cavity Pressure	[Pa] [Bar]	Barometer, manometer, etc.
	Surface Radiation	[W/m^2]	Pyranometer, pyrheliometer, etc.
	Vibration, speed and acceleration	[m/s]	Accelerometer, vibration sensor, etc.
	Air flow	[m^3/h]	Flowmeter
	Counter	-	Optical, RFId, etc.
	Presence	-	Presence, camera, etc.

The 3 parameters types can be defined as follows:

- *Identification and geolocation*. This type of sensor makes it possible to recognize an asset, access information, track, and geolocate it in space. These applications can be crucial in the production and installation phases (Copeland and Bilec, 2020) where continuous monitoring of material and product flows can generate greater process efficiency. Remote control of the production line, shipping stages, and construction site allows project managers to monitor the progress of a project taking timely corrective action (Niu et al., 2017). In addition, the automation of auto-identification processes of a façade component would allow a reduction in time, costs, and errors for repetitive tasks. Even during the operational phases, identification of the material characteristics of the asset and access to technical information allows a greater efficiency in the maintenance phases (Lin et al., 2014). Among these, RFId sensors represent the most suitable sensor type to tracking process and storing data (Costa et al., 2021). GPS systems are uncommon because the façade system, which is excluded for very short times such as transport to or from the site, refers to static assets.

- *Environmental monitoring*. The filter role of the building envelope implies special attention to internal and external microclimatic conditions. In the direction of the development of a "filter" that is increasingly adaptive to user needs and external stresses, the ability to monitor internal and external parameters makes it possible to gather fundamental inputs on which to optimize the work of the façade and feed the self-learning of control algorithms (Luna Navarro, 2021). In this perspective, the monitoring of environmental parameters with a higher spatio-temporal resolution would increase the adaptability of dynamic components ensuring greater comfort to building occupants and increase the accuracy of energy management and simulation models (Bottaccioli et al., 2020). For the latter, the relationship between phenomena such as temperature, humidity, illuminance, noise or air quality and the health of users is an example. With regard to outdoor environmental parameters, real-time monitored data, in addition to the regulation of HVAC systems, could be used at the micro-urban level to control the healthiness of outdoor spaces and assess the effect of the façade on the surrounding environment (Naboni et al., 2020).

- *Asset monitoring*. Sensors for monitoring the functioning of the façade system can be of a different nature. Depending on the complexity of the technology, the integrated systems, the characteristics of the building and the specifics of the area, different sensors can be adopted. "Condition-focused" sensors (Niu et al., 2017) are planned to continuously monitor the performance status of the asset. With a view to introducing new maintenance and facility management paradigms based on Big Data analysis (Azzalin, 2020; Atta, 2021), the monitoring of such parameters could enable new insights. For instance, sensors related to surface temperatures or cavity pressures could allow monitoring the performance of the asset from a technological and energetic point of view. Position sensors could detect any structural collapse of the system, or moisture sensors could identify any ongoing failures. This family of sensors is thus intended to monitor the functioning status of the façade system from an energy, structural, and technological point of view.

6.2.1 Sharing information

The IoT has the ability to generate and share data in new ways. Huge flows of information could be managed semi-automatically through the potential of smart devices and the network. In a highly fragmented market, the information management of an asset within a unified framework could provide huge benefits in terms of quality, transparency and resources employed. In the façade sector, as in the construction sector, many companies keep information on product, manufacturing methods, and operational data private and not all of this information is digitized and structured in a way that makes it easy to share (Giovanardi et al., 2023). Therefore, data sharing is still limited often due to the concurrent agenda of different players. This approach is today an obstacle for the transparent and life cycle oriented management of a building component (Dave et al., 2016). Therefore, the development of a collaborative work framework to support the information management of the asset is a pivotal action for the circular management of the asset (Fig. 62).

In this context, the adoption of tools that facilitate the exchange and storage of information between the actors of the supply chain must provide for full interoperability with the tools in use. Thus, the criticality is dictated by the fact that different players use different management software. To map the most recurrent ones and identify possible relationships with IoT technologies, the classification of software proposed by Charef (2022) is used. According to Charef (2022), information management tools can be classified into: Project Information Model (PIM), Asset Information Model (AIM) and Deconstruction Information Model (DIM). PIMs refer to the set of tools used during the façade design phase. Among them, BIM is considered the most suitable software to gather heterogeneous information when the LOD (level of detail) of the project is still low. It is used to assess spatial and architectural relationships with other building systems and during the design phase it drastically reduces errors and delays (Honic et al., 2019). In these early stages, the use of IoT is limited.

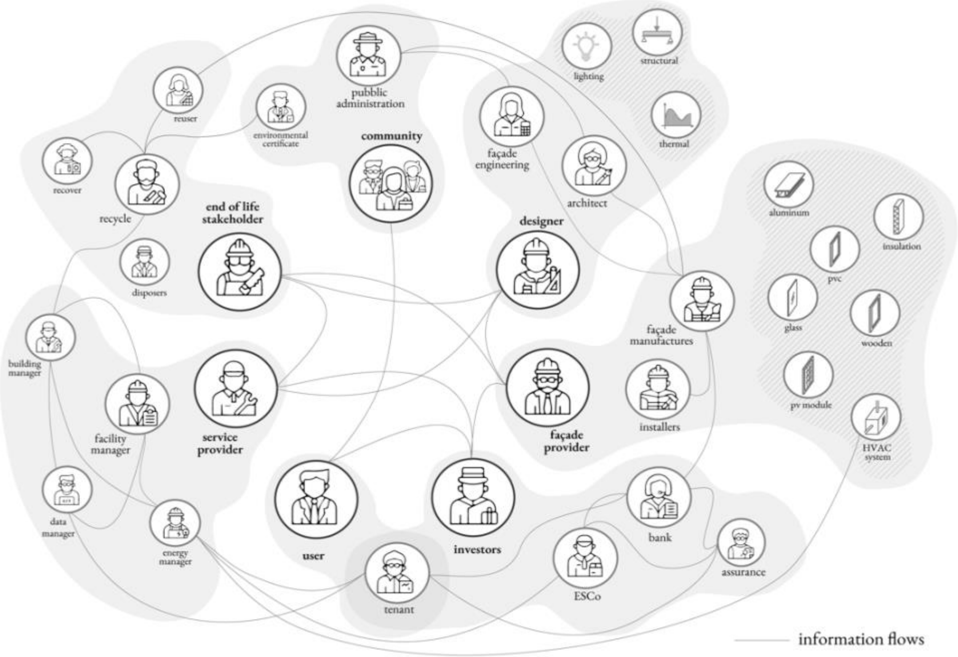


Figure 62: Information flows between façade stakeholders

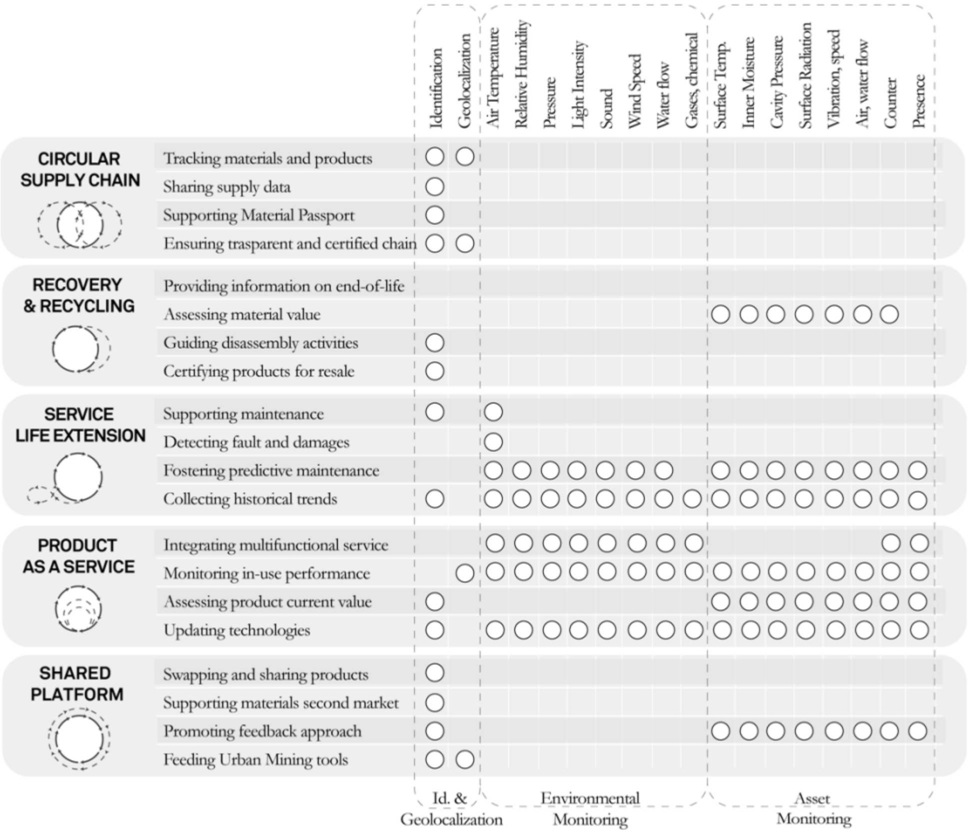
AIM includes all software and tools from the production of the assets to the utilization phase. During the executive design (e.g. mockup testing) and production phases, façade suppliers generally use software, often developed by the companies themselves, that can handle more detailed information and sometimes dialogue with numerical control machines such as those for extruding and cutting profiles or their assembly. AIMs are essential tools for project managers to monitor the progress of the job order and verify that the schedule is being met, ensuring significant cost and time savings (Demiralp et al., 2012). During production and delivery of the asset to the construction site, checklists are compiled to verify the asset's compliance with project and regulatory requirements. At these stages, the use of IoT can be envisaged for the remote management of site progress. Automated data on production, shipment monitoring or the construction site can provide key tools to increase process efficiency (e.g. reduce delays). During the use phase, facility management software should be used to schedule (and control) maintenance and cleaning activities. Furthermore, the recent trend to integrate dynamic components such as solar shading or photovoltaic panels has led to the widespread use of computer-based remote-control systems such as BMSs (Building Management Systems). In this context, sharing data on the performance of a system in real time can provide insights needed to optimize specific tasks or detect problems. Finally, DIMs refer to a set of emerging tools to manage the end-of-life activities of buildings and facilitate the circular management of façade materials. They are used to manage demolition phase activities, material separation, and disposed material (Charef, 2022). These, although not yet widespread in the market, could benefit from the efficiency and monitoring capabilities of IoT technologies to tackle different tasks. Indeed, an increased focus on "closing the loop" could incentivize the use of devices that certify products and processes.

6.3 Circular information requirements

After defining the opportunities of the IoT in data production and sharing, this step sets the information requirements imposed by the EC. To determine whether the IoT can meet the new circular information requirements, it is essential to clarify the specific information required by 5 CBMs and to establish the list of façade information. To this, an analysis of the relationship between 5 CBMs and IoT parameters is provided. Through a matrix identifying the relationship between parameters and CBMs, the link between data and goal is clarified. Finally, a list of information on the life cycle of a façade is proposed on the basis of the literature and the main experiences in the field of material passports (MP). In this sense, 12 types of information on the life cycle of a façade system are fixed to investigate the potential enabling factor.

6.3.1 Circular Business Models requirements

Based on the parameters that can potentially be monitored with an intelligent building envelope, the analysis of interconnections with CBM is a key action for the development of innovative systems. Through a matrix that identifies the relationship between information type and information purpose (CBM), the relationship between information and CE is clarified (Fig. 63). For each CBM, four main actions were selected as pivotal actions for achieving the target in the façade sector.



		Id. & Geolocalization		Environmental Monitoring								Asset Monitoring							
		Identification	Geolocalization	Air Temperature	Relative Humidity	Pressure	Light Intensity	Sound	Wind Speed	Water flow	Gases, chemical	Surface Temp.	Inner Moisture	Cavity Pressure	Surface Radiation	Vibration, speed	Air, water flow	Counter	Presence
CIRCULAR SUPPLY CHAIN	Tracking materials and products	○	○																
	Sharing supply data	○																	
	Supporting Material Passport	○																	
	Ensuring trasparent and certified chain	○	○																
RECOVERY & RECYCLING	Providing information on end-of-life																		
	Assessing material value											○	○	○	○	○	○	○	
	Guiding disassembly activities	○																	
	Certifying products for resale	○																	
SERVICE LIFE EXTENSION	Supporting maintenance	○		○															
	Detecting fault and damages			○															
	Fostering predictive maintenance			○	○	○	○	○	○	○		○	○	○	○	○	○	○	○
	Collecting historical trends	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
PRODUCT AS A SERVICE	Integrating multifunctional service			○	○	○	○	○	○	○	○							○	○
	Monitoring in-use performance		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Assessing product current value	○										○	○	○	○	○	○	○	○
	Updating technologies	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
SHARED PLATFORM	Swapping and sharing products	○																	
	Supporting materials second market	○																	
	Promoting feedback approach	○										○	○	○	○	○	○	○	○
	Feeding Urban Mining tools	○	○																

Figure 63: Matrix to identify the parameters required by each CBM

These can be defined as follows:

- *Circular supply chain*. Achieving a circular supply chain in the façade sector is a complex challenge as it involves a joint action of all actors in the supply chain. For markets that are still populated by small and medium-sized enterprises, this can be an obstacle if it is not imposed by regulatory obligations. This CBM covers aspects related to the traceability of components and processes (Bateman, 2015; Santana and Ribeiro 2022), efficient processes, and greater transparency (Kumar, and Shoghli, 2018), and supply chain coordination (He et al., 2020). These aspects require the use of identification and geolocalization IoT technology such as RFId and GPS. Direct access to asset supply chain information (e.g. production data, environmental impact, etc.) leads to greater transparency between customer and supplier. In this perspective, the customer's choice can be influenced by a greater commitment of the producer to environmental issues (He et al., 2020). Therefore, the development of an information infrastructure to facilitate the sharing of supply chain information and make it accessible to different players can be considered a crucial action towards the CE. The development of smart labels and digital systems to support the MP systems could foster companies to create a collaborative chain (e.g., consortia, cooperation, etc.).

- *Recovery and recycling*. The focus of this CBM is on the recovery and recycling of material flows. To facilitate façade reuse and recycling through up-cycling practices it is necessary to have of a detailed knowledge of the asset features (Minunno et al., 2018). Data on material composition and how a façade system is disposed of become crucial information. To comply with regulations concerning the recyclability of components, a clear picture of the physical and chemical characteristics of the asset is essential. For instance, having direct access to how a glass has been treated or the composition of an aluminum frame facilitates the reuse and recycling of the material. To achieve this CBM, a proper evaluation of an asset during operational stage can be crucial to design and guide end-of-life strategies. Furthermore, Valero et al. (2015) pointed out how the capability of monitoring deconstruction phases is essential to check material disposal procedures. In this perspective, transparency and certification of information are key features. Thus, the use of IoT technologies can support the "closing the loop" by facilitating the reuse of certified materials whose provenance and use is known.

- *Life Extension*. This CBM shifts the focus towards how the material is used and managed. Although activities related to circular design and production are key aspects in the development of durable façade systems, information on the external agents and management type open interesting scenarios in the use of IoT technologies. The long service life of a façade component implies that greater attention should be paid to the operational phases. During these stages, environmental and anthropogenic factors are the main influences on the durability of a façade system (Lacasse et al, 2020). In this perspective, the creation of historical data sets can facilitate the understanding of ongoing phenomena that are difficult to detect. This is the case, for example, of building or façade pathologies that if not properly monitored could imply negative effects on the whole system performance. In this regard, data analysis could (theoretically) allow predictive and proactive maintenance approaches (Chew and Gan, 2022). The increased complexity of façade systems, coupled with an ever-increasing integration of dynamic components, may require the use of such approaches in the future. In addition, quick access to asset data means improving efficiency and safety for maintainers (Snyder et al., 2018).

- *Product As a Service*. In PAaS models, data (and IoT) can be strong enablers (Bressanelli et al., 2018). Besides the identification and direct access of asset information, environmental and asset performance condition monitoring becomes key aspects (Azcarete-Aguerre et al., 2022). If the productivity of the product-service provider's investment is based on the performance of service provided, monitoring the façade behavior becomes an essential action to control the effectiveness of the investment and orient management strategies. Aware that, on the one hand, environmental inputs are the first factors to determine the functioning of the system and, on the other hand, monitoring of the specific conditions of components can facilitate proper management of the system, attention to parameters in the operational phase becomes essential. Furthermore, the creation of datasets and historical trends can enable the evaluation of the effectiveness of PAaS models over time, thus fostering their dissemination and optimization (Schaminee et al., 2020). By limiting the risk associated with long-term investments, data analysis may provide new tools on which to settle product-service and performance-oriented contracts. Furthermore, the large variety of parameters that can be monitored enables the supplier to develop customized products-service (e.g., air quality).

- *Shared platform*. Regarding the support provided by the IoT to the development of shared platforms, there are two main aspects to consider for façade sector. The first concerns the creation of platforms for identifying and quantifying material (e.g., building stock database, urban cadastre, etc.) to exchange materials in the end of product life (Giorgi et al., 2022) and facilitate second-hand markets. In this case, information about the asset is essential data for any action. Identifying material types and quantifying dimensions and volumes are prerequisites for any action aimed at fully exploit the value of the material. This approach, if thought on a large building stock, can support the definition of medium- and long-term strategy. The second concerns the introduction of shared platform for collecting feedback. In this case, data on the asset usability, performance, or comfort can be shared between different players. Economic feedback related to the effectiveness of the investment or technical feedback related to usability become crucial data for service optimization.

6.3.2 Circular façade information requirements

Selecting which of façade life cycle information is needed to enable circular approaches is essential. Defining the primary information about a long-lasting asset in a highly fragmented market is a complex challenge (Santana and Ribeiro, 2022). Indeed, as anticipated in *Chapter 4* (cf. 4.2), a façade system is generally designed to last more than thirty years and can incorporate and generate a huge amount of information.

The proposed life cycle information list is presented in a hypothetical scenario in which data is easily accessible to all players. Several European studies are supporting the development of a building MP that would collect and maintain asset information in a single and accessible platform. For this reason, the proposed list comes from the analysis of the main MP experiences and the literature review. In this perspective, the European BAMB project can be considered a forerunner. Promoting the idea of a MP of building components, the project aims to systematize the asset life-cycle information in a single framework. This, identified as “a data set describing the characteristics of materials and components in products and systems” (Mulhall et al., 2017), is considered a key strategy for the widespread reuse and recycling of building components. Knowing the detailed information about a product’s chemical and physical composition is considered crucial for its proper reuse and for maximizing its value. Other initiatives in the AEC sector are also working towards this goal, such as the Declare Label[18] developed by the International Living Future Institute and the Madaster tool. Declare is a voluntary platform to share and find environmentally sustainable and health-oriented building products, while Madaster tool is the result of a 2018 Horizon project that led to a creation of an online library of information on materials and products. The platform provides information about the building

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[18] Declare Label. https://declare.living-future.org

components and their location, as well as their impact on circularity and the environment with the aim of creating a building materials cadaster (Madaster, 2020).

The façade life-cycle information list is settled starting on different MP experiences and academic literature. Although, different approaches are used to organize the information ontology and the data collection process, the analysis of these can provide a life-cycle oriented information set. For example, in BAMB MP, life-cycle information is divided into "physical", "chemical", and "production" data for different levels of detail (e.g. systems, products, components, ingredients). The first includes data on the asset's features and performance (e.g. dimensions, structural data, thermal, light and fire resistance capacity, lifespan, recyclability rate, etc.). The "chemical" section mainly relates to the collection of environmental and product certifications (e.g. LCA, LCC, social assessment, material criticality, etc.). Finally, the "production" one collects detailed data on the supply chain process (e.g. timing, company information, etc.). A slightly different structure is provided for the Madaster platform. In this case, the physical dimensions and quantities of the product are the main information of the MP. The asset description, geometric features, and material information are organized in a graphical interface that allows a quick overview of specific circular indicators, such as the recyclability and reusability rate of the entire building (Madaster, 2020). From the different MP ontologies and BIM-based workflows in the literature, the interest in asset information extends to different fields of application. In the operational phase, information on maintenance activities, safety (Atta et al., 2021), contracting (D'Angelo et al., 2022), static behavior (Bertin et al., 2020), and systems providers companies (Kedir et al., 2021) have emerged as crucial to manage the asset by optimizing resources. Regarding the end-of-life phase, on the other hand, information on the building components, such as reuse and recycling capabilities (Iacovidou et al., 2018), chemical composition and disassembly guide (Honic et al., 2019) are needed to preserve the value of the asset and lead worker activities. Additional information, such as user feedback for comfort (Luna Navarro, 2021), is added as it is closely related to the IoT opportunity. Based on these experiences, the main façade life-cycle information has been settled and classified in 4 main types. Contractual, product, process, and service information are divided in 12 domains (Tab. 9) according to the purpose of information. Data specifications are explained to provide a more comprehensive overview.

Table 9: Façade life-cycle information list

Type	Domains	Specification	References
Contract	Asset	type, ownership, responsibilities, contract timing, contract sale, assurance, rewards, financing, asset end-of-life responsibility etc.	(Heinrich and Lang, 2019), interviews
	Service	design and tender, construction commissioning, facility management services, end-of-life, cascading for testing, etc.	(Heinrich and Lang, 2019), interviews
Product	Technical features	ID, brand name, general description, product image, warranty, cost, design, construction, and as built drawings, dimension, weight, materials and chemical properties, etc.	(Heinrich and Lang, 2019; Madaster, 2020; Honic et al., 2019; D'Angelo et al., 2022)
	Declaration of performance	air permeability, watertightness, conductivity, thermal transmittance, light transmission, sound transmission, seismic resistance, fire resistance, load resistance, expected service life, etc.	Heinrich and Lang (2019)
	Certification and labeling	CE, Environmental Product Declaration (EPD), Life-Cycle Assessment (LCA), Life- Cycle Costing (LCC), on- site testing, state-of-the- art installation, etc.	(Heinrich and Lang, 2019; Madaster, 2020)
	Guide and instruction	assembly guide, maintenance guide, cleaning instructions, disassembly guide, end-of- life guide, etc.	(Heinrich and Lang, 2019; Atta et al., 2021; Kedir et al., 2021), interviews

Process	Supply chain	supply companies, date and delivery, factory production control, etc.	(Medaster. 2020; Kedir et al., 2021)
	Delivery and construction	delivery companies, date and delivery, installers, workers information, safety, etc.	(Honic et al., 2019; Kedir et al., 2021)
	Operational and management	facility management companies, maintenance status, cleaning status, energy production, static behavior, current status, etc.	(Iacovidou et al., 2018; Bertin et al., 2020; Kedir et al., 2021)
	End-of-Life	disassembly companies, date and timing, material recycled, reused and disposed, etc.	(Iacovidou et al., 2018; Madaster, 2020; Atta et al., 2021; Kedir et al., 2021; Charef, 2022)
Services	Integrated user-service	HVAC systems regulations, indoor/ outdoor comfort, automation systems, etc.	(D'Angelo et al., 2022), (Luna Navarro, 2021)
	Feedback	user interaction feedback, investment, design, product, and process feedback, etc.	(Luna Navarro, 2021)

More precisely, the 12 information domains can be classified as follows:

- *Asset contract*. This information mainly refers to data related to the sale of the good. Direct access to information on the façade contract such as the identification of the parties involved, the specifics of the system, and how the information is shared are essential to establish the environmental ownership and responsibility of the product. The traceability and sharing of this information can be supported by intelligent tags that ensure the transparency and reliability of the information contained.

- *Service contract*. Similarly, access to contractual information on the exchange of services provided during the life of the good can be decisive in making the market more transparent. Access to service contract data such as information concerning the designers or operators of the good ensures complete traceability of the product, thus reducing the gap between consumer and service provider. These could also refer to the exchange of services between B2Bs, as in the case of sharing certifications.

- *Technical features*. Information on façade types, dimensions, weights, and material properties are necessary to undertake most actions during the façade life cycle. Direct access to information such as the type of frame, the type of double glazing used (e.g., glass thickness), the glass treatments used, the type of insulation in the spandrel panel, integrated elements (e.g. types of shading) has direct effects on the optimization of asset management and evaluation processes. Detailed technical information (e.g., as-built drawings and technical specifications) is crucial data in the utilization and end-of-life phases for service contracts (e.g., cleaning and maintenance, energy audits, preliminary verification of disposal costs), for the valuation of assets, and for making facility management activities more efficient.

- *Guidance and instructions*. Information on how to install, maintain and dispose of a façade system is crucial to reduce time-consuming activities and increase asset quality. Maintenance personnel spend a not insignificant amount of time tracking down information on assets to replace systems and components. Furthermore, the increasing complexity of façade systems, which integrate dynamic and multifunctional systems such as automatic shading, opening and mechanical climate control, makes maintenance tasks more frequent and difficult. Keeping information regarding construction, management, and operation instructions in a single framework would ensure a more rational management of the asset.

- *Performance declaration*. Information on the declaration of performance is essential to meet regulatory and design requirements. Data on air permeability, water impermeability, conductivity, thermal transmittance, light transmission, fire resistance and load resistance are the most common. Tracking and collecting this information in a single, open-access platform would be an advantage for project and construction managers (e.g. during acceptance of materials and components at the construction site). Furthermore, the use of IoT for certification of monitoring information becomes essential in performance-based procurement, where the performance parameter becomes the means of awarding contracts.

- *Certifications*. Currently, product environmental certifications data are mainly used in the design phase. Here, product and process certifications such as environmental declaration, recyclability, or recycled content are increasingly required for building permits and sustainability assessments. In this context, transparent, digital, and open access management of certified information is a central aspect to foster circular markets and verify the materials compliance.

- *Supply chain*. Supply chain traceability information can greatly increase the façade system value. Sustainable chain information, recyclability of products, recyclable content, low energy impact and traceability information are matched by customer interest. This attention is due, on the one hand, to the recent update of national regulatory frameworks and, on the other, to increased public awareness of environmental and economic issues. Knowing who produced a good, where, and when is also information of interest in the façade sector. A controlled and transparent supply chain therefore becomes a competitive factor for façade manufacturers to demonstrate a company's environmental commitment.

- *Logistics and construction*. Data regarding production and installation processes can lead to huge time and cost savings. Façade shipping and site management are still the main tasks of façade project managers, with a strong impact on project success. In this sense, real-time monitoring of the production line and information on construction site logistics is essential information to keep the project on schedule.

- *Operational and management*. Monitoring the operational and management phases of façade systems should be particularly effective in optimizing specific tasks and defining their current value. For this reason, the traceability of maintenance, cleaning, and spaces utilization of building can ensure the proper execution of provided service activities. Historical data on building activities can be used to estimate the remaining façade service life and guide the manager’s decision-making process. In addition, such information can be essential to define the asset value from an economic point of view.

- *End-of-life*. Information on the companies involved, disposal protocols, selective material separation methods, end-of-life management plans, transport and disposal of materials are essential to address material disposal regulations and to verify the proper “closure” of a circular process. Towards a fully circular chain, more attention in end-of-life data will also be given from new players in the recovery and reuse of building components.

- *Integrated services*. Monitoring indoor comfort, automating components, and creating customized integrated services requires the management of massive amounts of data. An IoT infrastructure that enables new functionalities for the enclosure system is a key aspect to increase the value of the asset. In this perspective, the management and sale of service information can provide manufacturers with new data on which to structure their commercial offers and customers with new services to exploit their full value.

- *Feedback*. Certified information on the effectiveness of products and processes could provide customers, designers, façade suppliers, and investors with data to evaluate and optimize their tasks. Gathering a large amount of data is a prerequisite for continuously updating technology and attracting new investors. Data on product behavior in operation and user interaction can reduce investment risk and support the creation of new performance-oriented contracts.

6.4 The enabling factor

The enabling factor of the IoT arises from the relationship between IoT opportunities and CBM requirements. The systemization of the information flows, actors, and information management tools presented above allows the relationship between the different aspects to be clarified (6.4.1). Through a diagram identifying the information flows of the front-end systems, the enabling action of the IoT is clarified. Based on this, three primary Strategies and nine potential IoT-enabled Actions have been identified. The ability of IoT technology to process large amounts of data and fulfill information needs for implementing circular approaches make these actions potential areas of study for the façade industry. Through this framework, it is possible to envision the effects of data-driven approaches using IoT technology in the façade sector. Future (and not too distant) scenarios are proposed to stimulate reflection on the topic.

6.4.1 Façade life cycle information flows

In the Figure 64, the information flows are organized in a life-cycle diagram (x-axis) where, on the y-axis, the different types of data should be read horizontally. In this way, a better emphasis is laid on the time in which information is produced and exchanged. Mono or bi-directional arrows show the information flows among different stakeholder families (white boxes). For design and production, in- use, and end-of-life stages, an information management tool collects hypothetically all the information needed and allows different actors to access information.

From the design phases to the production of the façade system, the exchange of data takes place mainly between designers and manufacturers in a bidirectional way. In many cases, the development of customized façade systems is done in collaboration between architect and manufacturer, triggering constant information flows. On the one hand, the designers match functional and aesthetic requirements, on the other hand, the manufacturers provide the technical know-how necessary for the development of the system. The role of the investors in this first phase mainly concerns the sharing of contractual aspects concerning how the project will be financed. In the second phase, the operational stage, the mainly information sharing occurs between the manufacturer, customer, and service provider. The former is generally required to provide as-built drawings, environmental certifications, product tests performed, and data on supply chain companies. Service providers often start from the technical data of the property (e.g. drawings, dimensions, types of materials, etc.) to design their offer and organize their work. However, the exchange of information between manufacturers and service providers is still very limited and often the data produced remains internal to companies for private use. In this phase, the user has a dual role in the exchange of information. On the one hand, the user is a key element in the conclusion of after-sales contracts with service providers, on the other hand, the user can produce large volumes of information to trigger feedback approaches on the use of the product-service. Finally, information regarding the type and quantity of the good, how it is disposed of, the state of preservation and the maintenance activities carried out over the years can facilitate the end-of-life management. In this respect, the interest in the quantity of material stored in the city and the need for renovation would be of interest to the community, too. The latter, identified both in the community living in the city itself and as a public body that must stipulate rules and incentives to regulate material flows, can refine its knowledge of the existing building stocks and guide its actions on the basis of the collected data.

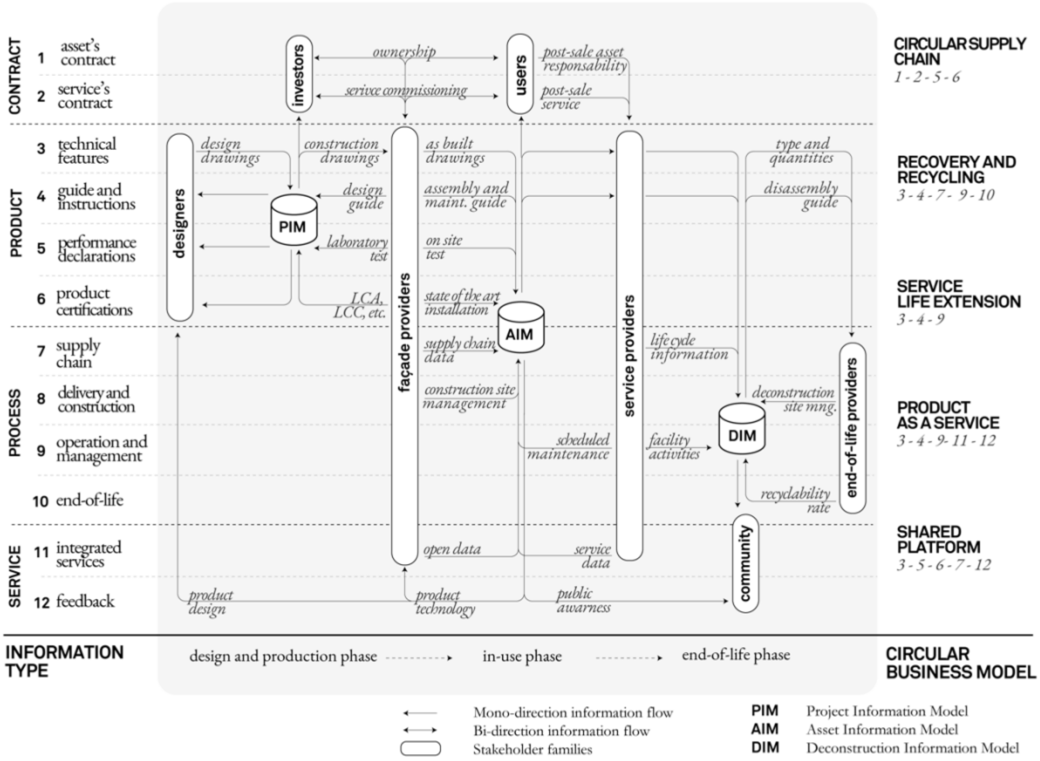

Figure 64: Façade information flows, organized per information type and stakeholders along the façade life-cycle stages (source: Giovanardi, 2023)

6.4.2 Three circular Strategies

The enabling role of IoT technology is provided by the value of the information produced. Information about a product's life cycle is essential to support stakeholder decision-making, enable alternative models, and verify their sustainability once started (Ingemarsdotter et al., 2019). Recent advances in data analysis allows a greater attention on topic. The descriptive, diagnostic, predictive, or prescriptive analyses supported by data analysis opens up a wide range of applications to increase our knowledge of the asset. Knowing phenomena related to the interaction between the built and human environment, analyzing the relationship of the different factors at play, or predicting the occurrence of phenomena can thus increase the rationality of the activities with which an asset is managed. In the façade sector, three main Strategies enabled by IoT technology have been identified based on the scope of information. The transition to an intelligent, transparent, and collaborative supply chain, process (and product) optimization, and the creation of new values are key areas for the circular transition. Despite, the three Strategies, have several aspects in common, they have been separated to make the results more understandable.

The purposes of each Strategies can be described as follows:

- *Smart, transparent, and circular chain.* The use of IoT in production and information sharing between supply chain actors is the first Strategy. The increasing focus on certifying supply chains that ensure sustainable and circular management of goods requires the management of new information flows (Abdel-Basset et al., 2018). The transparent management of this data therefore requires the use of appropriate tools to verify its reliability and ensure its usability. By using IoT to increase control of the supply chain, companies will be able to respond to increasingly stringent regulatory compliance and signal their commitment to the transition to CE (Kumar, and Shoghli, 2018). Data on zero-waste, short supply chain, or low carbon footprint processes will be able to respond to the needs of an increasingly informed and aware customer.

- *Product and process optimization.* The use of data is indispensable for product and process optimization. The introduction of data-driven approaches in the design of complex systems and the provision of services has significantly increased the effectiveness of actions taken. Therefore, at all stages of the life cycle, sharing and processing data on the efficiency of an asset can enable corrective actions aimed at reducing waste. In this perspective, a structured knowledge of the data collected during the operational phase may even lead to the activation of predictive and prognostic actions in the management of the asset (Chew and Gan, 2022). New performance-based contracts could reward (in terms of revenues) the quality of the products produced. In this way, IoT can support a reduction in resource consumption, waste, and climate-changing gases throughout the life of the technological system.

- *Increase and preserve asset value.* Information can increase the value and functionality of a physical asset (Bateman, 2015). The intelligent management of an asset's information can generate value by sharing it

> among multiple actors. In this case, the IoT can enable information flows that offer new dematerialized services. The introduction of these could trigger, as in the case of dedicated services or feedback on how an asset is used, new revenues for actors. In this perspective, the façade system includes new functionalities that aim to create value in the market and facilitate the preservation of this over time. The scalability of data and its use by several actors at the same time considerably broadens perspectives on the subject.

Based on the scheme presented in Section 6.4.1, the 3 Strategies can be identified through the diagram in Figure 65. Although the fields of application of these strategies are depicted with 3 colored boxes, the boundaries of these must be understood to be broader and more flexible.

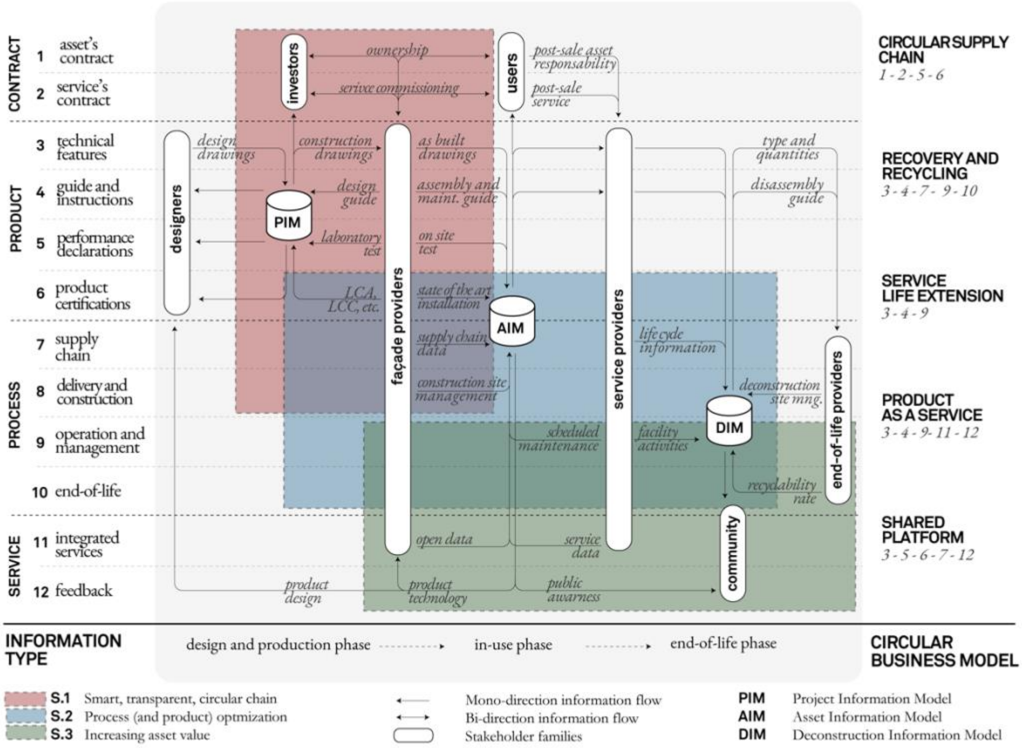

Figure 65: The 3 Strategies in façade life cycle information diagram

6.4.3 Nine circular IoT-enabled actions

In the façade market, the introduction of IoT generates stimulating scenarios in terms of product and process innovations. Faster access to information and data production are crucial Actions for enabling circular transition (CE-IoT Consortium, 2020). From the relationship between IoT opportunities and CE requirements, nine actions enabled by the IoT can be pointed out. These are to be understood as potential innovative actions in which the use of the IoT would trigger incremental actions (improvement of an existing functionality) or disruptive actions (creation of new ones). Although these actions are at different stages of maturity, the recent and rapid progress in the field of information technologies allows the foreshadowing of future scenarios.

- *Action 1.* Record, store, and update the life-cycle information of the good directly in the product. Through smart labels able to organize and easily share the information contained in the building components with different stakeholders, the problem of information retrieval would potentially be solved. Indeed, while the lack of information on an asset is still considered a barrier to the circular transition (Hartwell et al., 2021), the development of RFId, or NFC, smart labels could replace the current paper-based systems. The label would be transformed into an intelligent memory into which information of various kinds (contractual, product, process, and service) would flow. Producer, customer, or maintainer "scanning" the façade could thus have a complete biography of the asset. In addition to the storage of technical information (e.g. as-built drawings, certifications, etc.) and supply chain information (e.g. where it was produced, by whom, etc.), such applications will allow during the management phase to continuously update information about the asset. The frequency of cleaning, number of maintenances, or types of facilities activities can provide useful data to assess the asset value. The benefits of a smart label have direct effects on all 5 CBM presented, especially for business models aiming at the implementation of the circular supply chain and recovery and recycling. This approach could foster cooperation and the creation of circular consortia that show their commitment through a smart label.

- *Action 2.* LCA support through process monitoring. In the façade sector, more and more attention is being paid to the use of products with a limited environmental impact. Driven by a regulatory trend that rewards low-energy and carbon-neutral products, the demand for certified products has increased dramatically. In this context, manufacturers are voluntarily providing environmental product certifications (e.g., EPD, FSC, Nature Plus, etc.) obtained by third-party auditors on a sample product. The environmental footprint of all processes required to transform a resource into a finished product is assessed on the basis of energy and resource consumption and the production of climate-changing gases. Currently, the main life-cycle oriented certifications, mainly required for the design phases, only refer to the transformation of the good, excluding the transport, installation, management, and end-of-life phases from the count. In this context, the development of a label that reports (and updates) the impact of the good over time can be crucial for the evaluation of the good in its life cycle. Thus, supporting the development of carbon accounting tools (Sangiorgio, 2022), the ability to track the real impact of the good could fuel new business models and government incentives.

- *Action 3.* Systematizing a knowledge base about the materials stored in our buildings (and cities) is an essential issue for any circular strategy. Developing a knowledge crucial for action means, first, being able to quantify and classify the material in-use we have. Based on this, circular scenarios and strategies can be developed to incentivize the reuse and recycling of materials, limit resource consumption, or activate sharing platforms to fully exploit the value of matter. The use of IoT in digitizing the built heritage can be decisive. As with the support of traceability of life-cycle oriented processes, the introduction of digital labels can support the inventory of resources (Honic et al., 2019). More detailed knowledge may be crucial for medium- and long-term strategies. Knowing how the volume of glass panels are present in a building stock (or in a city), the type (e.g. surface treatments), and the age of installation serves, for example, to plan (more carefully) renewal rates. Thus, the digitization of façade components could support large-scale property owners in activating energy and technology retrofit processes by identifying the end-of-life of the asset in advance. In this view, the digitalised façade materials register may in future support innovative CBMs such as the certified sale of materials before they reach their end-of-life. A greater focus on materials in use will be increasingly felt by consumers and manufacturers given the prospects in the scarcity of resources per capita.

Action 4. The introduction of IoT in the production and construction phases represents one of the most suitable aspects of technology. The monitoring of production processes, the control of key performance indicators or the support for robotics or addictive manufacturing expand opportunities (Cagno et al., 2021). From a circular perspective, the transition to a digitized production system means reducing energy consumption, emissions, and limit waste. In this perspective, Action 4 aims at the development of integrated sensors for self-identification and geo-localization in façade systems to enable digital and automatic fabrication in which the "things" (machines and façade system) communicate directly with each other. Thus, the intelligent building site will automatically recognize when the intelligent façade module has arrived on site and update the action plan in real time. Automated installation machines and robots will recognize the façade module through the identification label and support (or replace) highly specialized labor during installation. Initial experiences in the field of automated installation are showing real interest on the part of manufacturers (Iturralde et al., 2022). Automatic recognition by the crane and positioning of the curtain wall module in the building grid can lead to significant advantages in terms of site speed. The use of sensors for tracking and geolocation can therefore enable more efficient work. In addition to the advantages related to the concept of "reduction", site automation also involves aspects of worker safety and well-being.

- *Action 5.* In the operational phases, the use of IoT will be mainly aimed at monitoring the performance and supporting the FM activities. In the operational phase, environmental data will then serve multiple purposes. (Bottaccioli et al., 2020) For example, the monitoring of temperatures or solar radiation will, on the one hand, be able to regulate HVAC systems with greater resolution, and on the other hand, guide the choices of maintainers with respect to intervention priorities. Smart façade systems will be able to change their physical-optical characteristics based on locally monitored data in real-time and analyzed through self-learning algorithms. In this way, the reduction of energy consumption and climate-changing emissions will provide the main benefits in economic and environmental terms. Regarding the FM main activities, the monitoring of indoor and outdoor parameters will make it possible to structure predictive and proactive maintenance schemes where, based on collected environmental data, usage patterns, and system characteristics, advanced data analysis will anticipate failures and damages. For instance, if a façade is more exposed to solar radiation and fluctuating temperature trends, this will mean that the external seals will (probably) be more damaged. The study of the parameters that can be monitored and the spatio-temporal granularity of the data will strongly depend on the type of building, the boundary conditions, and its mode of use. For this reason, the development of an integrated IoT system that can monitor key parameters to ensure the proper functioning of the façade system will have to be developed on a case-by-case. These aspects are crucial to prolonging the life of the asset.

- *Action 6.* The use of IoT to support the disassembly, separation, and end-of-life management phases appears to be the application field with the highest growth margins (Charef, 2022). Indeed, the processes of disassembly, selective separation and sending materials to different supply chains represent a still non-existent field of application in which information flows are necessary to meet regulatory compliance, supply chain control, and process optimization. The development of IoT systems for the self-identification of materials or components can be a strong enabler. As in the case of installation, rapid access to information on how the asset should be disposed of and how individual components treated can guide disassembly actions and ensure the full reusability of façade components. The monitoring of the proper material disposal and its reintroduction into production processes could enable the development of certification systems to guarantee the effectiveness of "closing the loop". More detailed and transparent information on the end-of-life of façade components would allow a better understanding of the problem. Even today, aggregated data on C&D waste production do not allow the assessment of possible corrective strategies. In the circular perspective in which façade systems will be disposed of more and more accurately as they retain more and more value, the use of IoT technologies will enable full knowledge of them and guide how they are disposed of, managed and revalued.

- *Action 7.* A new aspect enabled by digital technologies is the introduction of feedback processes. The development of an IoT-integrated façade able to interact with the user and record a series of events describing how the asset performs and is used is a highly attractive outlook. Especially for service-based CBMs, having full knowledge of how a product-service is used can, on the one hand, provide a set of historical data to guide the redesign of the asset, and, on the other hand, support insurance practices for the proper management. For example, these actions have a particular application in comfort management. Triggering occupant feedback processes and counting the number of activations of a screen can indicate how much the rooms were used and how they functioned. The ability to record such information can support the implementation of user-oriented CBM (Giovanardi et al., 2023). Feedback of a technical, economic or utilization nature can become information of interest to manufacturers, property developers and credit and insurance providers. In this way, the dissemination of feedback on a large scale could foster the development of the technology in a circular perspective. The use of IoT devices to create operational feedback enables a new way of conceiving and interacting with the façade system.

- *Action 8.* The development of a digitally integrated system offers the possibility of managing the asset in a new way. Management, analysis, and simulation tools can be constantly fed and calibrated on real-time monitored data. By drastically reducing the distance between the real object and virtual models, the ability to collaborate with the most advanced simulation tools increases the value of the asset. In this perspective, the emergence of Digital Twins for intelligent building management could find new input data producers from smart components (Çetin et al., 2021). In the perspective of a complete digitization of the building sector, IoT-integrated components enable virtual twins for evaluation and simulation. The data provided by a façade system could thus ensure a higher level of digitization of the building by facilitating the comparison of alternative scenarios and the current assessment of the value of the asset. For investors and managers, these aspects are central to the valuation of investments. In terms of CE, the fundamental role of the building envelope in the energy-environmental balance of the building system promises a more rational management of the asset. The value of the asset would thus not be limited to in-use performance but would extend to the compatibility of the asset with the most advanced management and simulation systems.

- *Action 9.* The possibility of monitoring aspects of our lives broadens perspectives on the topic of IoT integration. In the circular perspective, a smart façade system capable of providing intangible services to the user represents a potential innovation aspect (Bressanelli et al., 2018). The introduction of new services transforms not only the asset itself, but also the role of the producer into a service provider. IoT support for the management, monitoring, and control of new integrated services could enable new revenues for producers and new contractual schemes. For example, the introduction of air quality sensors, which have a negligible cost compared to façade technology, could generate additional revenues in service management. Especially for high-risk buildings (e.g. hospitals, factories, etc.), air quality data could become valuable. Based on this data, new after-sales schemes based on the performance of the services offered (e.g., comfort level) could take place. In the circular perspective, the development of integrated IoT-based services would increase the value of the asset by potentially enabling new PAaS models and the creation of shared platforms.

6.4.3 Research implications

The research implications and barriers to IoT deployment in the façade sector are shown in the box at the bottom of the framework. On the left-hand side, the technical implications of integrated systems development are presented on the basis of findings from the opportunities offered by the IoT. On the other side, the managerial implications imposed by the adoption of CBMs are considered as key aspects for the fulfilment of circular requirements. Finally, in the middle part below, the nine IoT-enabled actions, gaps and barriers to trigger an IoT-oriented innovation process are outlined.

Technical aspect. Among the most relevant technical aspects, there are two main issues: physical-digital integration and the reliability of the data produced. For the former, the greatest challenge is to rethink objects that were not designed to integrate the digital component. Although the peculiarities of each case impose the development of ad-hoc technologies, some criteria can be considered common to solve the issue of physical-digital integration:

- *Accessibility*. Accessibility to the sensor, tag, or integrated device must be guaranteed to facilitate its use and management over time.

- *Maintainability*. The ability to replace, repair, and upgrade the IoT device without compromising the functionality of the entire system is a key criterion for digital integration.

- *Energy power supply*. Power supply modes (e.g., integrated battery, cable, etc.) must be considered depending on the type of integration and sensor consumption (mainly dictated by the sampling rate).

- *Data shareability*. The possibility of sharing information via the network implies that there is no physical shielding between the sensor emitting the signal and the receiving antenna. In the case of façade systems, aluminum frames and low-emission glass are two potential major obstacles.

- *Aesthetic integrity*. The IoT device must be aesthetically integrated into the physical system. This can have significant repercussions on the customer's choice and compliance with the aesthetic canons of the building.

As far as data aspects are concerned, we can mention:

- *Data reliability*. The use of generally low-cost sensors or the access of many players implies a lower reliability of the collected data. Studying solutions (e.g. calibration algorithms and blockchain) for recording certified data can be a rewarding aspect of the system.

- *Granularity*. Identifying the spatio-temporal resolution of the data means identifying the minimum number of sensors and sampling frequency to obtain certain information.

- *Storage*. How to store large data streams can be a problem for long-lived systems. Managing large data sets may generate negative environmental impacts greater than the benefits generated.

- *Interoperability*. The ability to exploit the data produced through the main design and management tools is still an unresolved issue. The development of common communication protocols could ensure a smoother sharing of data.

- *Privacy and data security*. Managing private data securely is of great interest to companies and property owners. Developing solutions that ensure this can be crucial in the adoption of IoT and cloud-based tools.

Managerial aspect. There are several managerial aspects to be taken into account in the development of IoT-oriented innovations. These include:

- The need to develop ad hoc CBMs in which information gains value and becomes a commodity. This mainly implies an effort on the part of companies in rethinking post-sale services.

- Transdisciplinary know-how is a key aspect for company growth. The development of innovative and scalable technologies requires (often) the training of new professionals within the company.

- Determining who has the legal authority to access and use the data for their own purposes is an issue that needs to be resolved. Contractual formulas should make explicit the responsibilities of the different players.

- The management of sensitive data. The monitoring of the private sphere and the sharing of corporate information must be regulated to ensure a transparent supply chain without compromising privacy.

Gap and barrier. From technical and managerial implications, from the analysis of the literature, and from interviews with professionals in the field of façade, the main barriers can be identified. Besides a cultural and systemic gap in the evolutionary aspects that characterize the whole construction sector, the following barriers refer to the precise context of IoT technologies in the façade sector. These can be summarized as follows:

- *Fragmented supply chain*. At least in the European market, the façade sector is characterized by a few large players and a myriad of small and medium-sized companies. The fragmented supply chain results in an articulated and complex market. Proposing innovations that should be adopted by all players can be a major obstacle for technology diffusion.

- *Economic benefits difficult to assess*. One of the most critical aspects noted is the difficulty of assessing the benefits from an economic and environmental point of view over time. The long-term feature of circularity and information lead to limited interest from companies and investors. Studying CBMs with faster payback times is necessary to trigger interest in IoT solutions.

- *Service life*. The service life of sensors and façades is very different. This implies that the system must be designed so that the IoT device can be replaced, repaired, and upgraded over time. The rapid obsolescence of IoT technologies is identified as a limiting factor for investors and developers.

- *Time-limited responsibilities*. In the current model, the limited environmental responsibility of supply chain actors imposes limited interest in the development of life-cycle oriented systems. In this context, regulatory developments could impose greater interest in the topic.

- *Lack regulatory framework*. The lack of a common LCA-oriented framework related to the circularity of the building component is a deterrent factor for an IoT-driven circular transition. Impositions regarding the percentage of recycled material in components or the way in which it is recycled do not allow the opportunities of the CE to be fully exploited.

6.5 Validation Process

After presenting the framework and defining the characteristic aspects to initiate an innovative process, it was validated with a number of industry professionals. The objective of the validation process is twofold: firstly, to confirm (and if necessary update) the elements of the framework and, secondly, to prioritize the nine actions according to the interests of the different market players. This process makes it possible to define the main research development trajectories according to the real needs of the sector.

6.5.1 Methodology

The last step of the research is the validation of the framework. The validation, carried out with some professionals in the field, has a twofold objective: firstly, to confirm (and if necessary update) the elements of the framework and, secondly, to prioritize the nine actions with respect to the overall objective of the research (innovations that enable the EC). Based on a scoring system given by the feedback from the different market players, first qualitative considerations can be made.

Before presenting the steps of the prioritization process, it is necessary to show the decision tree used for the purpose of the research (Fig. 66). According to this diagram, there are three main layers: (i) the Goal, i.e. the final objective, (ii) the Strategies to achieve the goal, and (iii) the Actions necessary to enable the Strategies. The division of the Actions into triplets follows the pattern of the framework. Actions 1,2,3 serve to enable Strategy 1, Actions 4,5,6 Strategy 3 and Actions 7,8,9 Strategy 3. For example, the construction of a short, transparent and circular supply chain (Strategy 1) can be facilitated by the development of a material tracking system, or, the optimization of products and processes (Strategy 2) can be enabled through the monitoring of production and installation phases. The evaluation of the Actions, although they have aspects in common with several Strategies, are only considered for the proposed Strategy.

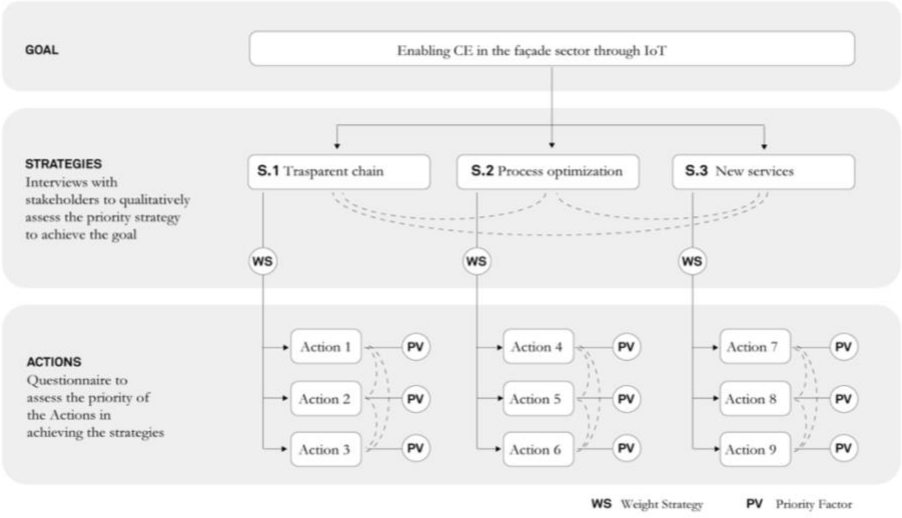

Figure 66: Validation process decision tree

Having defined the decision tree, the validation process was structured in four main steps (Fig. 67):

- Step 1. Nine structured interviews aim to identify the priority of the Strategy against the Goal. By identifying the weight of each Strategy, it will be possible to weigh the results of each Action against the Goal. At the end of this step, the Strategy Weight (WS) factor is defined.
- Step 2. A questionnaire submitted to 15 professionals prioritises, for each Strategy, the three Actions by comparing them with each other.
- Step 3. The data from the questionnaire are processed through an Analytical Hierarchical Process (AHP) software in order to identify the Priority Vector (VP) of each Action.
- Step 4. Finally, the Priority (P) of the different Actions is established through the formula:

$$P = WS \times VP$$

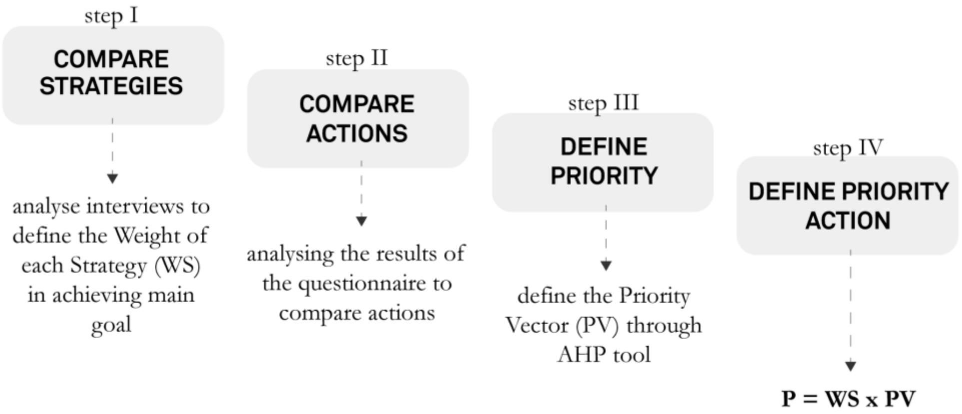

Figure 67: Validation steps

The selection of professionals for the interviews and questionnaire was mainly made among members of the European Façade Network[19], a European network of experts in the field of design, engineering, and construction of the

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[19] European Façade Network. https://www.europeanfacadenetwork.eu

building envelope, participants to FACE - Façades Architecture Construction Engineering[20] master's course, and researchers involved in the Architectural Façade and Product Research workshop[21] organized by the Façade Research Group of TU Delft. Among the limitations of the validation process, it should be mentioned that the number of interviews and questionnaires does not allow a statistical and quantitative analysis of the results. Furthermore, the unevenness of the roles in the sector of the questionnaire participants could affect the interest of the different Actions. However, for the purposes of the research, the data obtained can still be considered useful for qualitative evaluations.

The interviews and questionnaire were conducted remotely between September and December 2022.

6.5.2 Interviews

Nine professionals, including manufacturers, certifiers, service providers and researchers, were involved in the interviews (Tab. 10). Selected as being closely related to the research topics, the interviews lasted on average about one hour and took place online on the Teams or Google meets platform. Five out of nine interviews were recorded, with the permission of the interviewees, for later editing. To guarantee the privacy of the interviewees, they will be indicated in the text through the company in which they work.

The structure of the interview follows a precise pattern. After an initial introductory part in which the current research and the objective of the interview are presented, the interviewee is asked four questions. The first two are multiple choice questions and are designed to find out which of the three strategies was the most interesting from the perspective of a circular transition. Whereas the last two questions are open-ended and are aimed at identifying the main actors in the system and barriers in the development of integrated systems. The questions were formulated as follows:

Question 1 - *Which of those listed is a priority aspect in ensuring the circular transition in the façade sector?*

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[20] FACE Course. https://www.facecamp.it/partners/eurac-research/

[21] AF&P Workshop in TU Delft. https://facadeworld.com/2022/11/07/architectural-facade-and-product-research-group-meeting/

Question 2 - *Which of the listed ones represents a priority aspect in increasing and preserving the value of the asset?*

Question 3 - *Which player has a central role in promoting product and process innovation?*

Question 4 - *Which barriers hinder the diffusion of innovative IoT-based products in the façade sector?*

The analysis of the answers was carried out qualitatively. Through the order expressed by the respondents for the first two questions, a score was assigned to each Strategy (0.063 non-priority, 0.313 neither priority nor no priority, 0.625 priority). The multiplication of the different factors for the 9 respondents made it possible to define the priority Strategy.

Table 10: List of interviewer

ID	Stakeholders type	Company	Data interview
I.1	Researcher	Politecnico di Torino	05.12.2022
I.2	Researcher	EURAC	11.11.2022
I.3	Façade consultant	AI Engineering	04.11.2022
I.4	Developers	SKANSKA	09.11.2022
I.5	Developers	GearCraft Real Estate	23.11.2022
I.6	Manufacturer	Focchi S.p.a.	18.10.2022
I.7	Manufacturer	Alkondor Hengelo B.V.	14.11.2022
I.8	Service Provider	Physee	17.11.2022
I.9	Certification institute	International Living Future Institute	02.11.2022

6.5.3 Questionnaire

Fifteen professionals participated in the online questionnaire, managed via the Microsoft Form platform. With the aim of clarifying the PV for each *Actions* of the three circular *Strategies*, designers, consultants, researchers, and professionals in façade manufacturer expressed their opinion through closed questions.

The questionnaire was structured in 4 main sections. After an introductory part in which the objective of the research and the modalities of the questionnaire were clarified, the first section aimed to identify the personal information of the participant. The role within the industry, the size of the company, and familiarity with CE and IoT topics serve to interpret the answers and make an initial set of considerations on the maturity of the topic.

The following sections refer to the 3 *Strategies* proposed by the decision tree. For each *Strategy*, the participant was asked to prioritize by comparing the Actions in pairs. The comparison of each *Action* with the others for the same *Strategy* (e.g., Action 1 vs Action 2, Action 1 vs Action 3, Action 2 vs Action 3) was set through a numerical score. A slider with values ranging from 1 to 5 allowed to express for each comparison the priority and by how much. For example: a score of 5 meant that Action X was extremely higher priority than Action Y, a score of 4 meant that Action X was higher priority than Action Y, 3 of equal importance, 2 meant Action Y was higher priority than Action X, while 1 meant Action Y was much higher priority than Action X.

The pairwise comparison approach follows the rules of the AHP model, a multi-criteria decision analysis methodology developed in the 1970s, which allows the best alternative to be selected from a discrete set of alternatives (Saaty, 1990). The method is based on both quantitative and qualitative values and judgements of individuals and groups, determined according to a multi-level hierarchical structure to obtain priorities. The scale of criteria (1 to 5) was chosen according to the questionnaire management platform (Microsoft Form) and the purpose of the research.

The questionnaire was completed anonymously. The full questionnaire is provided in the Annex section.

6.5.4 Results

Interviews. The interviews confirmed the actions and structure of the framework. The different interests of the stakeholders' agendas revealed different views on the topic of EC and IoT. The analysis of the interview responses served to clarify which strategy was favored to achieve the main objective and which aspects characterize the development of innovative processes.

In particular, the most significant aspects for each question are summarized below.

Question 1 - Which of those listed is a priority aspect in ensuring the circular transition in the façade sector?

Option A - *Work on the supply chain to reduce consumption (Strategy 1)*

Option B - *Encourage re-use and recycling of components (Strategy 2)*

Option C - *Rethink the whole model by creating new values (Strategy 3)*

All respondents agreed that such a complex problem cannot, of course, be solved by single strategies. The main paradox underlying the circular transition lies in the fact that we should, first of all, reduce demand (i.4). However, this conflicts with the core business of all actors in the sector. Therefore, (i.4-5) are convinced that we need to completely rethink the current market paradigm in order to initiate the circular transition. New CBMs could create new forms of profitability that do not impose heavy consumption of resources. Although most of the respondents find it interesting to rethink the entire industry through new CBMs (e.g. Façade As a Service), the same respondents are convinced that these models are still far from being introduced into the market (I.9-2-3-1-6). From the analysis of the respondents' answers, two main points of view emerged. The first, identifies actions that can facilitate the creation of a transparent, collaborative, and circular supply chain (Strategy 1) as the main challenges to be faced in the future (i-1-3-4-7). Despite important progress has been made in the sector over the last ten years, there is still significant room for improvement on the reduction of energy consumption and waste reduction (e.g. building material packaging) (I.2-I.7). In this respect, encouraging the development and dissemination of environmental certifications and protocols that push companies to reduce their environmental impact can be decisive in the circular transition (I.3-9). The voluntary adherence of actors in the system could anticipate the slow imposition of regulations.

The second point of view identifies end-of-life as the main area to work on (I.2-6-8). Encouraging the reuse and recycling of materials requires the implementation of a supply chain to recover material at the end of its life cycle. Today, the low value of C&D waste materials and the high costs of selective disassembly (I.2) make it difficult to close the loop. Developing strategies that reduce these costs by facilitating the separation of components may therefore be crucial for the circular transition.

Table 11: Priority of strategies for different stakeholders (Question1)

	I.1	I.2	I.3	I.4	I.5	I.6	I.7	I.8	I.9	WS
Strategy 1	0,625	0,313	0,625	0,625	0,063	0,313	0,625	0,063	0,625	0,431
Strategy 2	0,313	0,625	0,313	0,063	0,313	0,625	0,313	0,625	0,313	0,389
Strategy 3	0,063	0,063	0,063	0,313	0,625	0,063	0,063	0,313	0,063	0,181

Question 2 - Which of the listed ones represents a priority aspect in increasing and preserving the value of the asset?

Option A - *Increase knowledge on product (Strategy 1)*

Option B - *Knowing the performance of the asset in use (Strategy 2)*

Option C - *Introducing new services and functionalities (Strategy 3)*

The second question aims to identify how digital innovations can be adopted by the market. Here, the majority of respondents (I.1-4-6-7-9) place specific interest on the use of technology for process optimization. Among these, monitoring of usage phases emerged as a new potential disruptive area. For example, the information gap between what is designed and what a system performs is an area of great interest to researchers, consultants, developers, and practitioners in the field of certification. Since there is no device today that monitors system performance, evaluations of operational phases always rely on simulation models or analysis of the system as a whole (envelope, systems, and utilities) (I-1-2). Knowing the performance of the asset would allow, according to some, to identify the specific behavior of a part of the system (I.2) and to structure new after-sales contractual relationships that protect customers (I.3-9). Furthermore, monitoring the performance status of an enclosure may facilitate the introduction of predictive and proactive maintenance schemes (i.7).

Respondents placed special emphasis on the use of information technology for the information management of the asset (i.2-3-4-5). Support in the digitization of the built environment is according to some a key aspect to achieve a higher level of efficiency. A structured information management of the asset implies a higher speed in the activities related to its management and related investments (I.5). Finally, the introduction of technologies to preserve and maintain the value of the asset is an essential strategy for (i.4-6). On the one hand, the introduction of new devices to ensure the effectiveness of what has been designed and, on the other hand, the introduction of new ones represents an enabling aspect for the IoT. In particular, for wellbeing and user experience aspects, the use of the IoT may prove to be central.

Table 12: Priority of strategies for different stakeholders (Question 2)

	I.1	I.2	I.3	I.4	I.5	I.6	I.7	I.8	I.9	WS
Strategy A	0,313	0,063	0,625	0,063	0,625	0,313	0,625	0,625	0,313	0,396
Strategy B	0,625	0,625	0,313	0,625	0,313	0,063	0,063	0,063	0,625	0,368
Strategy C	0,063	0,313	0,063	0,313	0,063	0,625	0,313	0,313	0,063	0,236

Question 3 - Which player has a central role in promoting product and process innovation?

To answer number 3, respondents gave different answer. Although all were aware that regulatory action is necessary, respondents identified demand-side producers as the main actor in initiating this transition. Large developers and large private customers now have the bargaining power to impose strongly circular aspects in design (I.1-2-3-6-7-8-9). Manufacturers and designers now have the task of responding to this need by developing innovative integrated systems. In the context of the development of new business models, the role of banks and credit institutions can also be decisive (i.5). The management of financial flows is a key aspect in economic sustainability. The joint action of several players and the creation of consortia in this case can facilitate the innovation process.

Question 4 - Which barriers hinder the diffusion of innovative IoT-based products in the façade sector?

Respondents provided a detailed set of barriers in the market today that limit the development of integrated IoT systems. First, the quantification of benefits in economic and environmental terms is unclear (i.1-3-4-5-6). The high efficiency of the current supply chain and information management tools (I.6) complicates the introduction of new technologies in a fragmented and articulated supply chain. These are followed by the problems of physical integration. In addition to the need to rethink the technological component, physical integration implies new professional skills and knowledge for the company. Related to this is also the issue of the useful life of the technology (i.7). The rapid progress of information technologies leads to a rapid obsolescence of information management systems. Finally, speaking of data and low-cost IoT technologies, an as yet unresolved issue concerns the reliability and value of data (i.9). Solving these problems could enable greater interest on the part of the supply chain.

From the first step of validation process, Strategy 1 (collaborative, transparent, and circular supply chain) represent the strategy more important for achieving the *Goal*.

Questionnaire. 7 designers and consultants, 4 researchers, 2 façade manufacturers, a developer, and a service provider answered the questionnaire. The average response time to the questionnaire was 22 min. The breakdown according to company size shows that 5 candidates come from companies with between 1 and 10 employees, 5 between 10 and 50, and 5 above 50. Prior to analyze the results of the questionnaire on prioritized action, it was necessary to identify the participants' knowledge of the problem. Most of them (60%) stated that they were extremely confident or trusting on the topic of the CE. 5 (33%) respondents expressed a neutral opinion, while 1 respondent stated that they did not feel confident about the topic. Regarding knowledge of the IoT, 7 respondents (46%) felt confident or extremely confident about the topic, 5 neutral (33%) and 1 not confident.

The comparison of *Actions* is reported by *Strategies.* The values shown in the Table 10 are the weighted results of the questionnaire.

For *Strategy 1*, respondents expressed greater interest in the development of strategies to support environmental certification (*Action 2*). This was followed by the adoption of IoT to increase the traceability of the building component (*Action 1*), and finally, the use of technology to create databases and materials cadastre (*Action 3*).

Regarding *Strategy 2*, the results show that greater interest is placed in monitoring the operational phases (Action 2). This is followed by actions related to production and construction (Action 1) and, finally, end-of-life aspects (Action 3).

Finally, regarding *Strategy 3,* the develop of innovative product aimed at increase interoperability with digital simulation tools systems is the priority (Action 2). This is followed by support for feedback processes (Action 1) and, finally, the introduction of new dematerialized services (Action 3).

Table 13: Actions comparison

Action X	vs	Action Y	X>>Y	X>Y	X=Y	Y>X	Y>>X
Action 1		Action 2	0,10	0,29	0,24	0,37	0,00
Action 2		Action 3	0,09	0,13	0,04	0,65	0,09
Action 1		Action 3	0,26	0,51	0,09	0,06	0,09
Action 4		Action 5	0,00	0,14	0,19	0,49	0,19
Action 5		Action 6	0,09	0,48	0,09	0,34	0,00
Action 4		Action 6	0,09	0,28	0,19	0,35	0,09
Action 7		Action 8	0,38	0,21	0,33	0,07	0,00
Action 8		Action 9	0,00	0,45	0,25	0,30	0,00
Action 7		Action 9	0,10	0,50	0,24	0,07	0,10

These results were used to calculate the PV via an online AHP software. The final evaluation of each action involves multiplying the weight of the strategy (interview result) by the priority factor (questionnaire and AHP result). The action with the highest value will be the one that responds most concretely to the criteria imposed by the market.

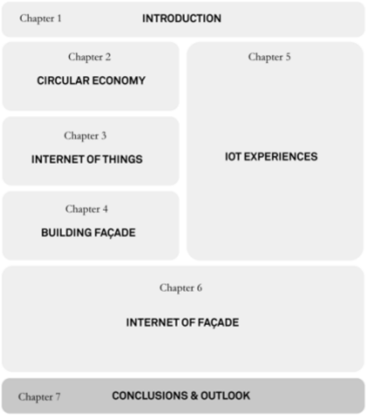
Table 14: Results of validation process

Strategy	Weight Strategy	Action	Priority Vector	Action Priority
Strategy A	0,413	Action 1	0,416	0,172
		Action 2	0,458	0,189
		Action 3	0,126	0,052
Strategy B	0,378	Action 4	0,249	0,094
		Action 5	0,594	0,225
		Action 6	0,157	0,059
Strategy C	0,208	Action 7	0,387	0,081
		Action 8	0,443	0,092
		Action 9	0,169	0,035

The results identify the priority order of the 9 *Actions* to achieve the Goal (enabling the CE). The Action Priority was obtained by multiplying the WS by the PV. In this way, it was possible to assess the priority of each *Action* taking into account the weight of the Strategy. *Action 5* (performance monitoring in the use phase) obtained the higher score. Subsequently, an high interest of practitioners is towards the *Action 2* for the development of solutions to support environmental certification and *Action 1* in tracking and sharing product information. It should be noted that the results of the validation process may have been influenced by the different technological maturity of the actions. For some, more mature actions might seem more likely to create environmental and economic benefits.

Chapter 7

Conclusions and Outlook



Chapter 7 closes the research by summarizing the main insights of this thesis. A critical reflection on the future of this research is presented to initiate a discussion on the relationship between technology, information in the perspective of enabling EC. From the results of the framework and validation process, research trajectories are outlined through the identification of a sensor capable of monitoring the performance of the asset in use.

7.1 Towards a digital and integrated façade

The impact of resource consumption and waste generation on the metabolism of urban settlements determine the need (and the urgency) for developing alternative usage and consumption patterns. In this scenario, the transition to the CE is an imperative action that implies the adoption of a new economic paradigm in which economic and environmental interests are rebalanced. Considering the slowness of the regulatory framework to act on economic-environmental decoupling, product and process innovations emerge as pivotal actions to trigger the circular shift. This research is thus aimed at exploring the opportunity provided by IoT technologies as a driver for circular innovations in the façade sector. At the conclusion of this experience, some considerations can be made.

Firstly, it is crucial to clarify the meaning of CE. As explained in *Chapter 2*, CE should not be intended as a set of practices aimed exclusively at material recycling, but rather as the development of systemic and advanced models able to replace the "take-use-dispose" model. Nowadays, one of the main challenges in the construction sector is to maintain and preserve the economic and environmental value of materials and resources as long as possible. Innovative CBMs must be rapidly developed to enhance the competitivity of circular approach from an economic, environmental, and social point of view. In this regard, as reported in *Chapter 3*, the rise of IoT technologies can be considered a unique opportunity. Lessons learnt from other industries indicate how the IoT technology can be a disruptive technology for rethinking process and increasing knowledge. The relationship between CE and IoT is thus analyzed in a strategic sector for innovation in the construction industry, the façade sector. As reported in *Chapter 4*, through the analysis of the curtain wall technology paradigm, the technical and functional requirements for the development of an innovative, circular, and digitally integrated system have been established. From the practical experiences (*Chapter 5*), the technical and management implications of physical-digital integration are investigated. The way in which data is collected (spatio-temporal granularity of data) and the value of the information are key aspects that need to be addressed in future research.

Having clarified the theoretical context, the "Internet of Façade" is proposed to provide a broad overview of the opportunities generated by the IoT. Three main strategies and nine potential innovative actions are identified to answer the research question:

Can (and how) the IoT enable the Circular Economy in the façade sector?

The answer is yes, but under certain condition.

The ability to transform façade into "smart" component introduces new opportunities to address the challenges imposed by the circular transition. By producing and sharing data on the life cycle of a façade system, crucial knowledge can be gained to guide circular asset management. From the proposed framework, three main strategies emerge as potential application domain for IoT technologies. The first concerns the creation of a transparent, collaborative, and circular supply chain, where the IoT became crucial to support the product "biography" and the sharing of information among different players. The storing of product data within IoT-based labelling seems to be an emerging prospect for increasing the efficiency of product identification processes, increasing transparency towards consumers, and actively involving stakeholders in the circular transition. The second strategy refers mainly to the IoT's ability to monitor. The adoption of IoT in this case can be to track shipping status, construction (or deconstruction) phase, operational energy performance, or support maintenance activities. Thus, large datasets can be reprocessed with advanced analysis tools to support a more rational use of resources. In this perspective, predictive and proactive action stimulates interesting scenarios in the management of façade systems increasingly subjected to anthropogenic and environmental stress. Finally, the use of IoT is hypothesized for the creation of new values. In this context, the circular approach is manifested in the development of new integrated and dematerialized services able to the meet the customer needs. Towards this scenario, the wide panorama of IoT technologies offers the development of highly customized technologies.

However, these actions are not sufficient to enable innovations that support the CE transition.

Along with the development of the CE regulatory framework, the design of new CBMs is crucial for the adoption of IoT innovations by the market. An industry that is still strongly set on the linear model, in fact, limits actors' interest in such strategies. This is due to a low value of information about the asset and façade lifecycle processes in the traditional economic model. Triggering a digital and circular transition therefore means developing new CBMs in which produced information flows play a crucial role in rationalizing (material and economic) resources and building relationships among different stakeholders. For example, the potential of smart labels capable of storing and information is hampered by the limited environmental liability of each actor over time. In the current linear model, manufacturers and supply chain actors are interested in traceability information for short periods, generally related to post-sale insurance contract. While moving towards a circular transition, interest in traceability aimed at storing essential information and certifying the impact on the environment will emerge strongly. This, in addition to facilitating actions relying on access to asset information (e.g., maintenance) will lead to the recognition of the economic and environmental value of a component at end-of-life enabling new uses. As for actions enabled by monitoring environmental, performance, and usage parameters, the biggest hurdle to overcome a real adoption of IoT technologies is the assessment of the benefits from an economic and environmental perspective. For example, the underestimation of the issue of falling façade system performance over time is partially linked by users' lack of awareness (and their difficulty in monitoring process). In order to extend the useful life of the asset, the focus on integrated IoT monitoring systems will grow significantly if it is supported by the development of new CBMs based on performance-oriented contracts. In this perspective, the development of PAaS models in the façade sector will drive the rapid development of IoT sensors that facilitate continuous monitoring of the asset allowing manufacturers to keep track of the effectiveness of their investment.

Once these innovative approaches are enabled, the creation of large heterogeneous datasets will feed platforms where sharing of information and know-how will foster of second-hand markets.

7.1.1 Research limitations

Before considering the technical implications of the research, it is necessary to highlight the limitations of the methodological approach used. First of all, with a view to initiating a process of innovation in the sector, the purely theoretical hypotheses put forward should be verified with advanced market analyses and a thorough investigation of the patents and technologies already in use by individual companies. Such aspects, often private information in companies, would be necessary to "ground" the ideas developed. Within this research, in fact, the topic of innovation is dealt with horizontally by trying to hypothesize possible scenarios. Although in the validation part of the thesis there was a discussion with stakeholders from the sector, the small number of participants leads to qualitative conclusions.

Furthermore, it should be emphasized that a large part of the research involved practical experiments aimed at investigating potential use. From this point of view, two limitations emerge from a methodological point of view. The first concerns the choice of the sensors used. The time and resources available to develop ad hoc sensors were not sufficient for the research, thus it was decided to use sensors available to the research group. As mentioned in the conclusions, these parameters are intended as an example of data that could be obtained. Furthermore, in order to obtain meaningful datasets for which information could be extrapolated, longer monitoring campaigns were required on more significant case studies with respect to the research topic. For example, the assumptions made in the three monitoring campaigns (cf. Chapter 5) should be validated with the technologies of curtain wall systems.

From a cultural, technical and management point of view, the research shows that some issues still need to be addressed to trigger the development of innovative systems that support the circular transition. First, the long-term economic and environmental benefits need to be further investigated, since the lack of experience in this context is a significant obstacle to development of integrated technologies. Further research needs to be developed to assess the long-term economic and environmental benefits. The almost non-existent experiences in this context are a major barrier to the development of integrated technologies. In addition, further investigation must be conducted in ensuring the truthfulness of the data. Besides verifying the correctness of the data, further investigation into cybersecurity and privacy is necessary, as the handling of private data can be a very sensitive issue for users. The security that the processed data is stored correctly can be an incentive for companies and real estate owners to start the digitization process. Second, as previously mentioned in the experiments chapter, interoperability of data communication protocols with the main asset management software is a key aspect. Today, the presence of different protocols means that communication between IoT systems and management software such as the BMS is difficult. Nowadays, these last two points can be seen as technical obstacles to be addressed by political action with a view to fostering industrial cooperation towards unified standards. Third, issues related to physical-digital integration still need to be resolved. In this respect, as a matter of example, the different lifespan of a sensor compared to the one of a façade components is a key issue in the design of integrated systems. The shorter lifespan of IoT systems requires them to be easily repaired, maintained, and replaced during the life of a façade.

Finally, the impact of digital technologies and data management on the environment should be taken into account. Increased consumption of resources, critical raw materials, and high energy consumption for running data centers and simulation tools require further analysis on the life cycle of the digital component.

7.2 Future scenarios for IoT-based façade

In addition to confirm the theoretical framework, the validation process served to identify the future trajectories of this research. Despite the small number of stakeholders involved in the validation process, some initial and qualitative considerations can be made. The prioritization of the nine actions indicated the aspects that best meet the needs of the stakeholders. Based on these insights, a hypothesis on the development of an integrable technology is proposed.

Towards an ecological and circular transition, stakeholders expressed a particular interest in using IoT to monitor the asset performance during the use phase (Action 5). Therefore, it can be assumed as the main direction of this research. An innovative IoT system for façade systems will allow the monitoring of environmental (e.g., carbon accounting), energy (embodied and operational energy) and technological (e.g., remaining useful life) performance of the system in use. As mentioned above, this requires a CBM that fully exploits the value of the information. From this perspective, the development of aftermarket services and performance-based contracts will give new economic and environmental meaning to asset performance data. Hypothetically, the relationship between service producer/provider and customer will be governed by an agreed fee in which system performance (e.g., energy savings, comfort, maintenance, etc.) will represent the former's profits.

Moving toward IoT sensor features, this should follow the following requirements. The engineer-to-order nature of façade systems implies the development of a smart modular component in which the type of parameters monitored is chosen according to the level of "intelligence" required by the customer. As discussed above, the spatial and temporal granularity of the data suggests to the development of a semi-integrable component that can be added and positioned (and continuously reconditioned) without changing the façade technology. A computer board within the component acts as the "brain" of the façade and gather data from different perceptual nodes (sensors). In this case, the organization of heterogeneous data is managed by a datalake interoperable with leading analysis and simulation tools. Within the smart component, temperature, humidity, and solar radiation sensors will represent the minimum functionality of the system, as these are the parameters that enable most of the functionalities of an intelligent façade system. The modular feature of the component thus makes the technology highly scalable. The addition of new perceptual nodes will expand the functionality of the asset according to the actual needs of the customer. A passive RFId tag integrated into the smart component case will store all the asset's biographical information, offering the possibility for different players to update it over time. This will provide direct access to the biographical and technical information (e.g., the volumes of material used or material properties) of the façade, thus facilitating evaluations of the asset over time and solving the problem of information loss over time. A battery powered by a photovoltaic panel will allow the sensor to be energy self-sufficient, enabling greater application versatility.

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Annex

Questionnaire: "IoT for driving Circular Economy in the façade sector"

Made with Microsoft Form.

List of question.

Personal information.

1. Which type of stakeholders would you identify with?
2. What is the size of your company/studio/research group?
3. How confident are you with the Circular Economy topic?
4. How confident are you with the Internet of Things (IoT) topic?

Strategy 1. "Moving towards a smart, transparent, and circular chain means foster a systemic, certified, and collaborative market in which material flows are kept within closed system. To foster this STRATEGY, three main IoT-enabled ACTIONS have been identified:

- *Action A*. Foster supply chain traceability through monitoring and collection of asset information.
- *Action B*. Ensure product/service quality by supporting certification processes.
- *Action C*. Promoting a digital and certified supply chain through smart contract and automated payments"

5. Select the sentence you consider most appropriate in promoting a "smart, transparent, and circular chain". Action A vs Action B
6. Select the sentence you consider most appropriate in promoting a "smart, transparent, and circular chain". Action B vs Action C
7. Select the sentence you consider most appropriate in promoting a "smart, transparent, and circular chain". Action C vs Action A

Strategy 2. Producing and managing large volume of data allow to monitor and optimise long-lasting and complex processes. From diagnostic to predictive and proactive analyses, advanced data analysis can drastically increase product and process efficiency. Three are the main stages in which optimization can be applied:

- *Action D.* Production and construction (e.g. monitoring production line, geolocalize façade module in shipping and construction site, etc.)
- *Action E.* In-use (e.g. supporting facility management, recording maintenance activities etc., predictive maintenance, etc.)
- *Action F.* Deconstruction and end-of-life (e.g. guiding disassemble activities, track end-of-life material, etc.)

8. Select the sentence you consider most appropriate. At what stage do you consider it a priority to take action to "Optimise Products and Processes"? Action D vs Action E
9. Select the sentence you consider most appropriate. At what stage do you consider it a priority to take action to "Optimise Products and Processes"? Action E vs Action F
10. Select the sentence you consider most appropriate. At what stage do you consider it a priority to take action to "Optimise Products and Processes"? Action F vs Action D

Strategy 3. The information produced by the IoT can increase the value proposition of the asset. Data produced over façade service life can guide decision-making and create new potential revenues for companies. To foster this STRATEGY, three main IoT-enabled ACTIONS have been identified:

- Action G. Monitor the façade during in-use phase to guide asset management and redesigned (e.g. failure feedback, loss of performance, etc.)
- Action H. Introduce new customised services for users (e.g. air quality monitoring, automated components, etc.).
- Action I. Support the creation of databases and digitised know-how for circular asset management (e.g. material register, material passports, etc.).

11. Select the sentence you consider most appropriate to "enhance and preserve asset value". Action G vs Action H
12. Select the sentence you consider most appropriate to "enhance and preserve asset value". Action H vs Action I
13. Select the sentence you consider most appropriate to "enhance and preserve asset value". Action I vs Action G

14. If you want to leave any comments, questions...

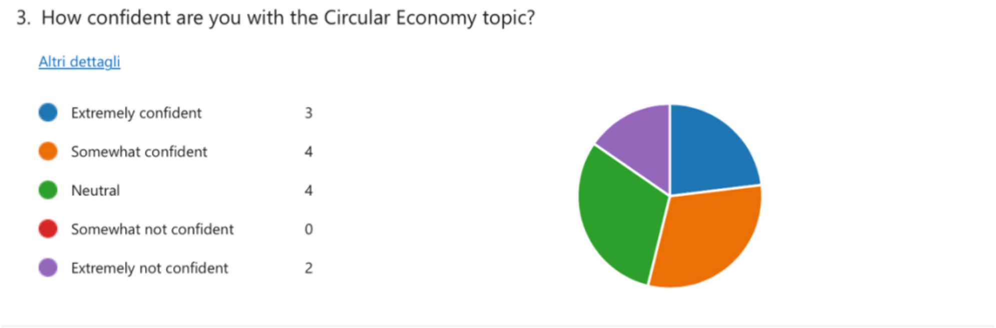
Questionnaire results.

1. Which type of stakeholders would you identify with?

●	Designers & Consultants	7
●	Façade Manufacturers	2
●	Service Providers	0
●	Developers & Investors	0
●	Public & Certification Authority	0
●	Researchers	4

2. What is the size of your company/studio/research group?

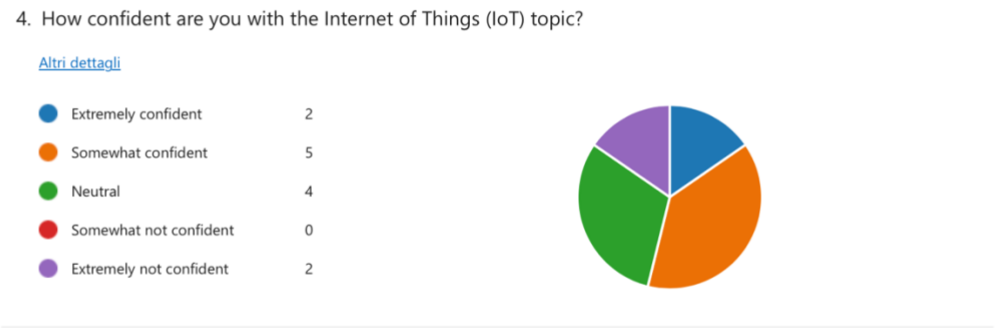
●	1 to 10	4
●	10 to 50	4
●	> 50	5



3. How confident are you with the Circular Economy topic?

Altri dettagli

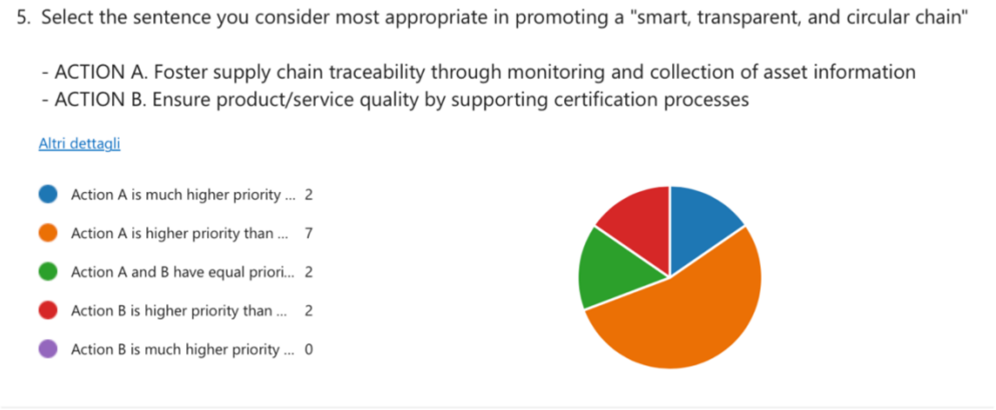
● Extremely confident	3
● Somewhat confident	4
● Neutral	4
● Somewhat not confident	0
● Extremely not confident	2



4. How confident are you with the Internet of Things (IoT) topic?

Altri dettagli

● Extremely confident	2
● Somewhat confident	5
● Neutral	4
● Somewhat not confident	0
● Extremely not confident	2

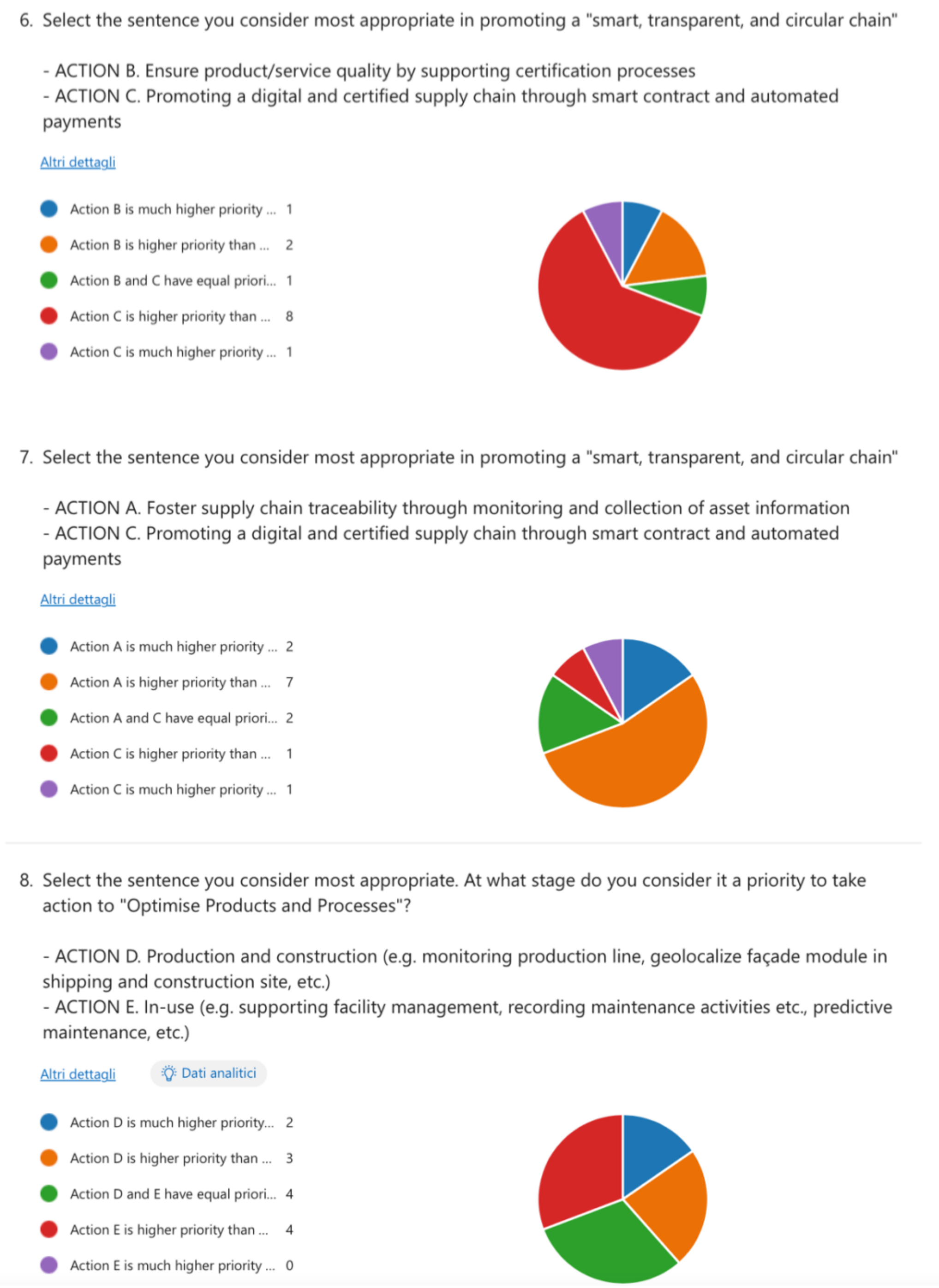


5. Select the sentence you consider most appropriate in promoting a "smart, transparent, and circular chain"

- ACTION A. Foster supply chain traceability through monitoring and collection of asset information
- ACTION B. Ensure product/service quality by supporting certification processes

Altri dettagli

● Action A is much higher priority ...	2
● Action A is higher priority than ...	7
● Action A and B have equal priori...	2
● Action B is higher priority than ...	2
● Action B is much higher priority ...	0



6. Select the sentence you consider most appropriate in promoting a "smart, transparent, and circular chain"

- ACTION B. Ensure product/service quality by supporting certification processes
- ACTION C. Promoting a digital and certified supply chain through smart contract and automated payments

Altri dettagli

●	Action B is much higher priority ...	1
●	Action B is higher priority than ...	2
●	Action B and C have equal priori...	1
●	Action C is higher priority than ...	8
●	Action C is much higher priority ...	1

7. Select the sentence you consider most appropriate in promoting a "smart, transparent, and circular chain"

- ACTION A. Foster supply chain traceability through monitoring and collection of asset information
- ACTION C. Promoting a digital and certified supply chain through smart contract and automated payments

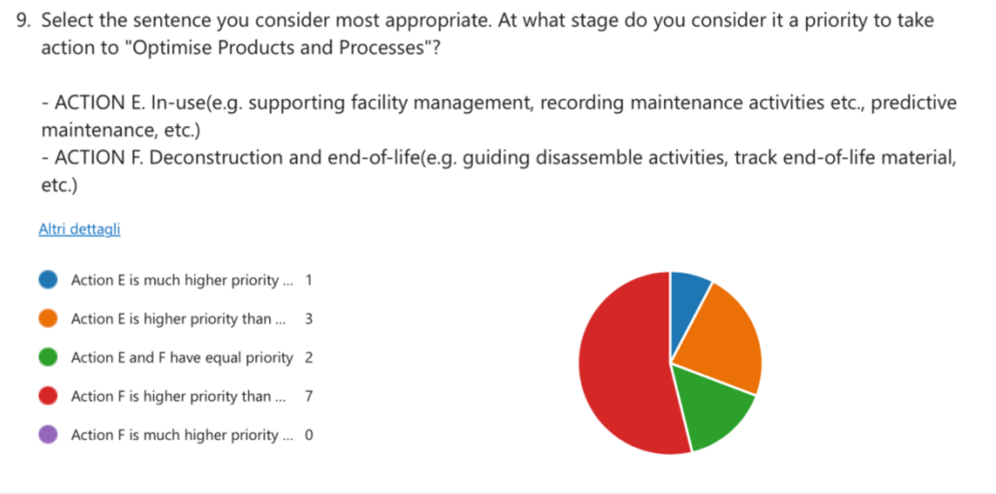
Altri dettagli

●	Action A is much higher priority ...	2
●	Action A is higher priority than ...	7
●	Action A and C have equal priori...	2
●	Action C is higher priority than ...	1
●	Action C is much higher priority ...	1

8. Select the sentence you consider most appropriate. At what stage do you consider it a priority to take action to "Optimise Products and Processes"?

- ACTION D. Production and construction (e.g. monitoring production line, geolocalize façade module in shipping and construction site, etc.)
- ACTION E. In-use (e.g. supporting facility management, recording maintenance activities etc., predictive maintenance, etc.)

●	Action D is much higher priority...	2
●	Action D is higher priority than ...	3
●	Action D and E have equal priori...	4
●	Action E is higher priority than ...	4
●	Action E is much higher priority ...	0

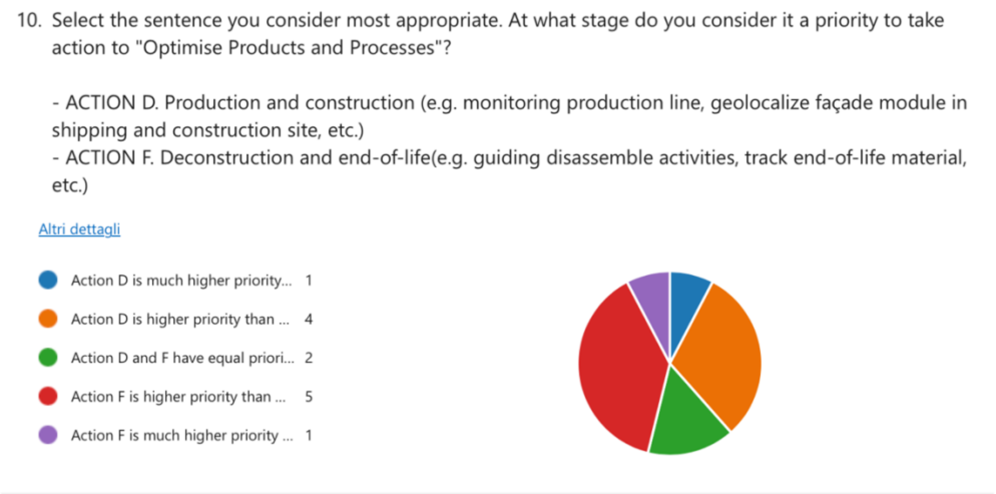


9. Select the sentence you consider most appropriate. At what stage do you consider it a priority to take action to "Optimise Products and Processes"?

- ACTION E. In-use(e.g. supporting facility management, recording maintenance activities etc., predictive maintenance, etc.)
- ACTION F. Deconstruction and end-of-life(e.g. guiding disassemble activities, track end-of-life material, etc.)

Altri dettagli

● Action E is much higher priority ...	1
● Action E is higher priority than ...	3
● Action E and F have equal priority	2
● Action F is higher priority than ...	7
● Action F is much higher priority ...	0

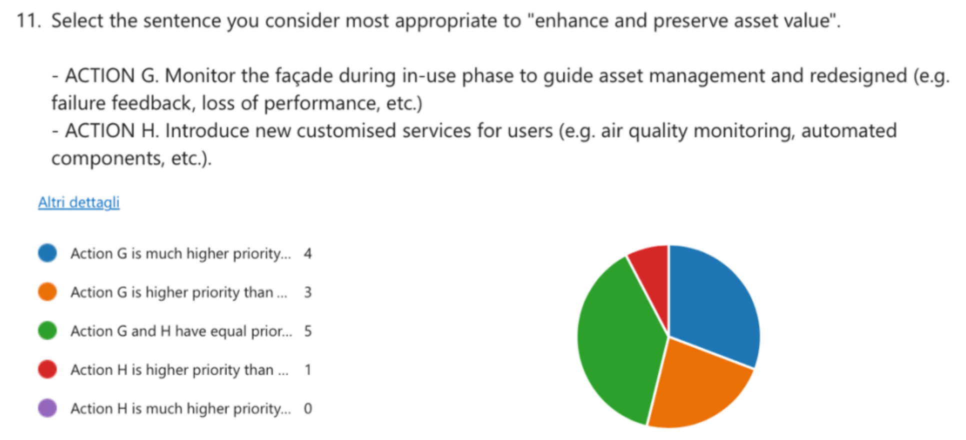


10. Select the sentence you consider most appropriate. At what stage do you consider it a priority to take action to "Optimise Products and Processes"?

- ACTION D. Production and construction (e.g. monitoring production line, geolocalize façade module in shipping and construction site, etc.)
- ACTION F. Deconstruction and end-of-life(e.g. guiding disassemble activities, track end-of-life material, etc.)

Altri dettagli

● Action D is much higher priority...	1
● Action D is higher priority than ...	4
● Action D and F have equal priori...	2
● Action F is higher priority than ...	5
● Action F is much higher priority ...	1

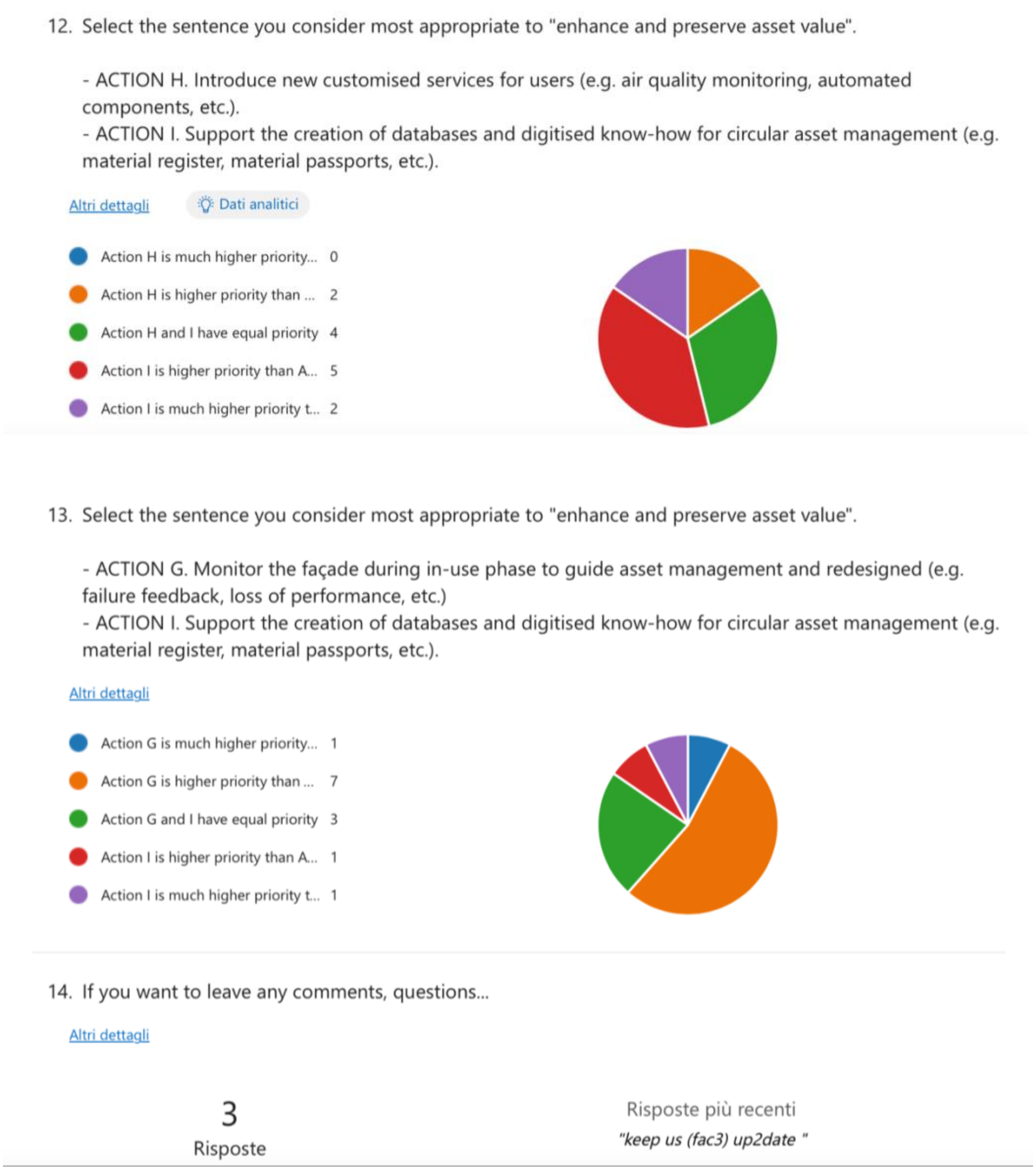


11. Select the sentence you consider most appropriate to "enhance and preserve asset value".

- ACTION G. Monitor the façade during in-use phase to guide asset management and redesigned (e.g. failure feedback, loss of performance, etc.)
- ACTION H. Introduce new customised services for users (e.g. air quality monitoring, automated components, etc.).

Altri dettagli

● Action G is much higher priority...	4
● Action G is higher priority than ...	3
● Action G and H have equal prior...	5
● Action H is higher priority than ...	1
● Action H is much higher priority...	0



12. Select the sentence you consider most appropriate to "enhance and preserve asset value".

- ACTION H. Introduce new customised services for users (e.g. air quality monitoring, automated components, etc.).
- ACTION I. Support the creation of databases and digitised know-how for circular asset management (e.g. material register, material passports, etc.).

● Action H is much higher priority...	0
● Action H is higher priority than ...	2
● Action H and I have equal priority	4
● Action I is higher priority than A...	5
● Action I is much higher priority t...	2

13. Select the sentence you consider most appropriate to "enhance and preserve asset value".

- ACTION G. Monitor the façade during in-use phase to guide asset management and redesigned (e.g. failure feedback, loss of performance, etc.)
- ACTION I. Support the creation of databases and digitised know-how for circular asset management (e.g. material register, material passports, etc.).

● Action G is much higher priority...	1
● Action G is higher priority than ...	7
● Action G and I have equal priority	3
● Action I is higher priority than A...	1
● Action I is much higher priority t...	1

14. If you want to leave any comments, questions...

3
Risposte

Risposte più recenti
"keep us (fac3) up2date "