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Internet of Things for building façade traceability: A theoretical framework to enable circular economy through life-cycle information flows

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ABSTRACT

Traceability is considered a crucial requirement to enable Circular Economy (CE). Product and process life-cycle data can facilitate circular asset management preserving the asset's value over time and reducing resource consumption. Many scholars point out how the loss of traceability data, lacking information reliability, and unstructured data are still barriers to the widespread application of CE. In the building façade sector, an increased interest on traceability is dictated by a growing demand for environmental product certifications. However, these aspects are often limited to collect data at supply chain stage, thus neglecting a huge amount of information produced during the asset service life. To foster an accessible and life-cycle oriented asset traceability, this research investigates the Internet of Things (IoT) as a potentially disruptive technology for supporting information management. The objective of this work is twofold: (i) to identify what façade life-cycle information is needed to promote CE and (ii) to clarify the enabling role of IoT in tracking, storing, and sharing such information. Through a scoping review combined with interviews to professionals, a theoretical framework structured on four key elements (stakeholders, information list, information management tools, and IoT) is proposed to fill the literature gap and support façade industry in the circular transition. Further research will have to be conducted to face the digital-physical integration issues and develop business models able to fully exploit traceability information value.

1. Introduction

Traceability refers to the "ability to trace the history, application or location of an object by means of recorded identifications" (ISO 9000: 2015), where "object" includes tangible and intangible entities. Until a few years ago, the issue of traceability has been investigated mainly from the perspective of quality and safety, rather than sustainability (Katenbayeva et al., 2016). Nowadays, product and process traceability are emerging as key information in driving the transition toward the Circular Economy (CE) (Danish Business Authority and Ellen MacArthur Foundation, 2021), and meeting the "Sustainable Consumption and Production" goal by optimizing resource consumption and waste generation (SDG12) (United Nations, 2015). According to this assumption, the circular management of an asset and the preservation of its value over time may depend heavily on the amount and type of information we have. In the construction sector, an increased focus on traceability and CE is manifested by recent widespread adoption of product environmental labels (e.g. Environmental Product Declaration, Declare Label, etc.) and the Material Passport (MP) (BAMB, 2020). This latter, 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 in European policies for promoting the reuse and recycling of building products. Such approach, aimed at tracking the materials source, recording their manufacturing processes, and preserving this information over time, acquires a greater value for complex and long-lasting building components, such as building façade technology.

The façade, defined as the (mostly) vertical element that constitutes the physical enclosure of the occupied areas of a building, is a crucial technological subsystem for more energy- and resource-efficient buildings. Its role is not limited to the building structure, but it is an integral element determining the building's appearance, functionality (Knaack

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et al., 2007) and sustainability. Indeed, they could cost up to 30% of the overall building construction cost (Klein, 2013) and contribute between 10 and 20% of the total embodied carbon emissions (ARUP, 2022). For these reasons, the transition to circular façade construction and management practices can be intended as a pivotal action for the transition of the entire construction sector.

Currently, the objective of life-cycle oriented traceability to rationalize resource consumption and exploit the residual value of materials implies, in addition to regulatory action, the updating of methodologies and supporting tools. The management of large information flows over time pushes toward the adoption of the latest Information and Communication Technologies (ICT). These are effective tools in achieving goals in scarce resources condition and creating a cross-cutting knowledge essential to the action. Among these, the Internet of Things (IoT) is emerging as one of the most suitable technology for facing traceability issues for building components. Its capability in tracking, collecting, and sharing information over complex and long-lasting processes promises interesting scenarios in driving a wide-spread application of circular strategies (Govindan and Hasanagic, 2018; Norouzi et al., 2021). Indeed, many scholars point out how the loss of traceability information over the asset life-cycle, lacking information reliability, and unstructured data are still barriers to the wide-spread application of circular principles (ShojaeiKetabi et al., 2021; Hartwell et al., 2021; Giorgi et al., 2022). For instance, Snyder et al. (2018) report how vast data is produced during a building component life-cycle: about 96% of data goes unused, while 13% of the working time is spent searching for information. Although the absence of a common framework for traceability information on building components limits the commitment of companies (Katenbayeva et al., 2016), the increasing sensibility of customers to environmental issues leads to a strongly evolving field.

This paper aims to clarify the enabling role of IoT in fostering CE principles through the management of traceability information in the façade sector. A common theoretical framework is proposed to map façade life-cycle information flows, clarify the relationships with (and among) stakeholders, and investigate the role of IoT technologies in managing traceability information. Specifically, this paper address two main research questions (Rq):

- Rq.1 What information is needed to increase façade traceability from the CE perspective?
- Rq.2 What is the enabling role of IoT in creating, managing, and sharing traceability information?

To answer those questions, a scoping literature review, combined with stakeholders' unstructured interviews, is executed on four key elements: façade life-cycle information, stakeholders, information management tools, and IoT tracking technologies. The interplay among these elements constitutes the main contribution of this study. A broad overview of façade information flows relevant to CE and the investigation of future scenarios in building components traceability are key actions to unify a fragmented literature and lay the basis for the development of an organic and life-cycle oriented information infrastructure. The proposed theoretical framework is to be intended as a tool to guide scholars and façade companies toward the development of innovative circular products.

2. Methodology

To identify the enabling role of traceability data in fostering CE principles, façade life-cycle information is collected into a single theoretical framework. The choice of this stems from the need to find a structure that can include heterogeneous aspects. As shown in Fig. 1, this study workflow is articulated in three main steps: (i) gathering and reprocessing data on the four key elements by screening the literature and unstructured interviews; (ii) organizing them into a common life-cycle framework for CE (Rq.1); (iii) highlighting on this the enabling role of the IoT (Rq.2).

Specifically, during the first research step, four main elements are identified to organize the typical façade life-cycle information flows: information (which data are exchanged?), stakeholders (between whom are they exchanged?), information management tools (in which way?), and the IoT (how can we use it?). For data gathering, a scoping literature review was carried out to screen the main experiences on the topic. The scoping review is generally used "when a body of literature has not yet been comprehensively reviewed or exhibits a large, complex, or heterogeneous nature not amenable to a more precise systematic review" (Peters et al., 2015). Given the research's purpose and gaps that still exists in the scientific literature on building components traceability, data were combined with qualitative information directly from the interviews with a panel of experts (namely "focus group" in the text). Indeed, searching on the Scopus and Web of Science databases the main keywords combination, limited to open access contributions published in the last 10 years, did not yield significant results for information flows mapping (Table 1). To further narrow the results, the research string included the keyword "material passport" as it is a concept that is both strictly related to the traceability issue and useful for collecting relevant information for research purposes.

Table 1
Number of papers from search keywords combination on Web of Science and Scopus: Concept 1 (life-cycle information) "AND" Concept 2 (façade technology).

Search string combination		Scopus + Web of Science	Strictly related
Combination 1	"traceability"AND ("façade" OR "building envelope*" OR "curtain wall*")	–	–
Combination 2	"track*" AND ("façade" OR "building envelope*" OR "curtain wall*")	36	2
Combination 3	"traceability" AND ("building component*" OR "building material*" OR "building system*")	25	3
Combination 4	"track*" AND ("building component*" OR "building material*" OR "building system*")	72	8
Combination 5	"Material Passport*" AND ("building component*" OR "building material*" OR "building system*")	37	12
Filter:	(1) Abstract, title, keyword (2) Open Access (3) 2012–2022 (4) Engineering related journal		

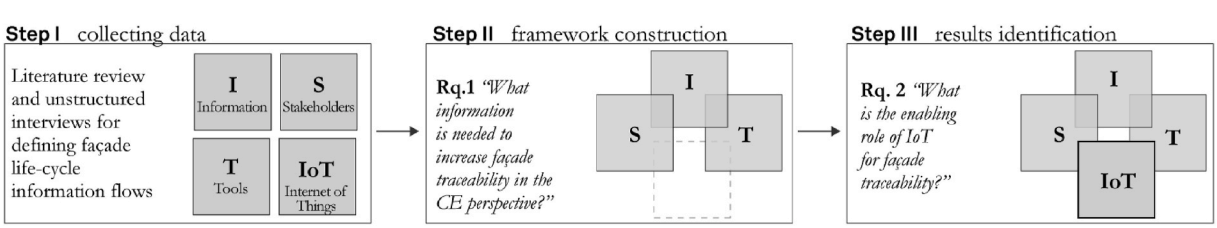

Fig. 1. Research workflow.

After reviewing the literature, a focus group composed of 8 professionals and scholars was set to fill the scientific literature gap and refine information specifically on façade systems. Unstructured one-to-one interviews were carried out virtually. The interview structure was designed to investigate the stakeholders' information needs through open-ended questions. Designers, façade manufacturers, facility managers, and companies in the field of end-of-life were involved to confirm the information gathered in the literature and intercept missing ones. Qualitative data were collected and analyzed according to the main purpose of the research.

3. Key elements for information flows

Collecting and organizing asset life-cycle information flows is not trivial. Four main elements emerge as crucial aspects to investigate asset traceability: the façade life-cycle information typologies, the stakeholders, the information management tools, and, finally, the IoT tracking technology. Although the results from the literature might not be exhaustive, they can be considered useful for this research's purpose.

3.1. Façade life-cycle information

Quantitative and qualitative information on products and processes become a commodity and new commercial viability among stakeholders (Argus et al., 2020). However, defining a systemic information flow about a long-lasting asset in a highly fragmented market is challenging (Santana and Ribeiro, 2022). Indeed, a façade system is generally designed to last more than thirty years and can incorporate a large number of suppliers in its production chain. Currently, several stakeholders are inclined to keep some information private and still a lot of information is not digitized. Two main MP experience for building components are used to intercept the main life-cycle information: the BAMB project's MP (Heinrich and Lang, 2019) (BAMB, 2020), and the Madaster platform (Madaster, 2020). Different approaches are used to organize the information ontology and data gathering process. In BAMB MP, life-cycle information is divided into "physical", "chemical", and "production" data for different detail levels (e.g., systems, products, components, ingredients). The first includes data regarding asset features and performance (e.g. dimension, structural data, thermal, lighting, and fire resistance capacity, lifespan, recyclability rate, etc.). The second one refers mostly to the collection of environmental and product certifications (e.g. LCA, LCC, social assessment, material criticality, etc.). Lastly, the "production" section collects detailed data on supply chain process (e.g. timing, company information, etc.). A slightly different structure is planned for the Madaster platform. In this case, the product's physical dimension and quantities are the main information in the MP. Asset description, geometric features, and materials information are organized in a graphical interface that allows a quick overview of specific circular indicators, such as recyclability and reusability rate for the entire building (Madaster, 2020). In addition to MP experiences, further information was included from the systematic literature review. More precisely, several scholars are focusing on traceability information for improving the effectiveness of activities in-use and end-of-life stages.

From different MP ontologies and BIM-based workflows present in literature, the interest in the asset information extends to multiple fields of application. In the use phase, information on maintenance activities, safety (Atta et al., 2021), contracting (D'Angelo et al., 2022), static behavior (Bertin et al., 2020), and facility companies (Kedir et al., 2021) emerged as crucial to manage the asset by optimizing resources. While as regards the end-of-life stage, information on building components such as reuse and recycling capacities (Iacovidou et al., 2018), chemical composition, and disassembly guide (Honic et al., 2019) are needed to preserve asset value. Finally, from the focus group, new potential information emerged. From façade providers side, data on product certification (e.g. cascading contracts for product testing lab) and environmental assessments (e.g. embodied energy, carbon) represent key information to address regulatory compliance and ensure to the client a valuable asset. On the other hand, from the service providers' point of view, interest is mostly in feedback data during the in-use stage. Data on real asset performance and user interaction is fundamental for service optimization and bridging the knowledge gap between simulated and real performance. According to the wide range of criteria adopted in the literature and to the goal of this study, four types of information can be identified including twelve application domains (Table 2). Data specifications are collected to provide a more comprehensive overview of the subject.

3.2. Façade stakeholders

The market fragmentation, façade companies' size, and the "engineer-to-order" nature of construction projects (Montali et al., 2019) make the mapping of the players involved more challenging. A large number of stakeholders are present in 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 2.

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 designers 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 contractor 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.

Table 2
Overview of the four main façade life-cycle information types and the respective domains, as identified in the analyzed literature and by the unstructured interviews.

Façade life-cycle information			
Type	Domains	Specifications	References and sources
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 instructions	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), Interviews
	Feedback	investment, design, product, and process feedback	Interviews

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 3).

3.3. Information management tools

Tools for managing asset information are many and varied. Nowadays, information is collected in paper documents, standalone databases, virtual models, and multiple spreadsheets according to stakeholders' activities and goals (ChenAdey et al., 2022). Digitalization of the construction sector tends to develop collaborative systems where information management is available to many actors in different phases. In the perspective of supporting multidimensional and multidisciplinary information flows, different research experiences are joined by the intention to develop collaborative platforms (Liu et al., 2015) (ChenAdey et al., 2022). In this context, a significant experience is provided by the "Houseful" European project, where an innovative workflow for the take-off was tested in two case studies in Spain and Austria (Itec et al., 2020). As in the construction industry, information flows in the façade sector are still organized through stakeholder-specific software, according to a "silo" mentality (Teisserenc and Sepasgozar, 2021). To simplify a wide panorama of tools, this paper organizes management information tools into three main families. According to Charef (2022), information management tools should 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

Table 3
List of façade life-cycle stakeholders emerged from the literature and interviews.

Façade stakeholders		
Family	Actors and industry professionals	References and sources
Users	owner, resident tenant, worker tenant, etc.	(Klein, 2013; Azcarate-Aguerre et al., 2018; Hartwell et al., 2021)
Investors and Developers	contractors, private owners, public authorities, real-estate companies, ESCo, financial organizations, banks, etc.	(Klein, 2013; Azcarate-Aguerre et al., 2018)
Designers and Consultants	architects, façade engineers, structural engineers, building physicists, lighting designers, acoustic engineers, façade consultants, urban planners, contractors, research institute etc.	(Klein, 2013; Azcarate-Aguerre et al., 2018; Hartwell et al., 2021)
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.	(Klein, 2013; Azcarate-Aguerre et al., 2018; Hartwell et al., 2021; Sangiorgio, 2022)
Service Providers	facility managers, maintenance providers, cleaning providers, building energy managers, building managers, building data managers, etc.	(Klein, 2013), interviews
End-of-Life Providers	Demolition contractor, disposal companies, recyclers, etc.	Hartwell et al. (2021)
Community	citizens, public authorities, regulatory authorities, certification organizations, etc.	(Klein, 2013; Azcarate-Aguerre et al., 2018)

the façade design phase. Montali et al. (2019) explore the currently available digital tools supporting façade design identifying nine categories of tools. Among those, BIM is considered the most suitable software to collect heterogeneous information when the project LOD (level of detail) is low. This is used to evaluate the spatial and architectural relationship with other building systems as during the design phase drastically reduce errors and delays (Honic et al., 2019).

AIMs include all the software and tools from asset production to the use phase. During the executive design (es. mockup test) and production phases, façade providers generally use software, often developed by the companies themselves, able to handle more detailed information and dialogue, sometimes, with numerically controlled machines such as those for extruding and cutting profiles or their assembly. AIM are key tools for project managers to monitor the status of the order and verify adherence to planned schedules providing considerable cost and time savings (Demiralp et al., 2012). During the production and delivery of the asset to the construction site, (often still) paper checklists are filled in to verify the asset's compliance with project and regulatory requirements. During the in-use phase, facility management software should be used to schedule (and check) maintenance and cleaning activities. Furthermore, the recent trend to integrate dynamic components (e.g. solar shading), photovoltaic panels, or led screens has led to the widespread use of remote computer-based control systems such as BMS (Building Management System).

Lastly, DIMs refer to an emerging set of tools for managing the building end-of-life activities and facilitating circular management of the façade materials. These are intended for two main application domains. The first ones are used specifically to manage the demolition phase activities, separation of materials, and material disposed of delivery. Nowadays, common dismantling practices have not required the use of management applications to support disassembly practices and verify the correct separation of materials (Charef, 2022). The second one refers mainly to online shared platforms that collect data on building components thus enabling the second market of materials (Giorgi et al., 2022). In this way, more knowledge about the amount of available material can guide the decision-making process of stakeholders and facilitate new business models.

3.4. IoT tracking technologies

IoT is defined as an "infrastructure of interconnected entities, people, systems and information resources together with services which processes and reacts to information from the physical world and virtual world" (ISO/IEC, 20214:2021). The lessons learned by other industrial sectors (e.g automotive, manufacturing, etc.) show how integrated, connected, and collaborative cyber-physical systems can generate large amounts of data to optimize resource consumption, rethink usage modes, enable data-driven approach, extend product service life, and create immaterial economies based on sharing services (Bressanelli et al., 2018; Ingemarsdotter et al., 2019). Technology development and cost reduction stimulate a faster deployment in the construction industry and open up interesting scenarios in addressing traceability issues (Minunno et al., 2018). Among the wide panorama of IoT technologies, RFIds are considered the most suitable ones to achieve traceability along complex chains for durable asset service life (Atzori et al., 2010; Costa et al., 2021). Such technologies may contribute in a significant way to the circular shift (RejebSuhaiza et al., 2022) supporting the creation of a digital product passport (Gligoric et al., 2019). In particular, RFId refers to a technology that allows the remote recognition of an object by using radio communication. Benefits in asset identification and geospatial monitoring could rapidly raise traceability data collection and re-elaboration in the building components production chain, thus ensuring a reduction of time and cost. In the current façade market, prefabricated façade panels are generally tagged with paper-based labels. In this regard, there are only limited experiences of using IoT to improve efficiency in site logistics management and production chain monitoring (Permasteelisa Group, 2018). Over the past decade, the interest of several scholars in RFId sensors in construction has introduced new opportunities such as the use of tags for long-term monitoring of the structural health of concrete slabs (Strangfeld et al., 2019). However, the greatest advantages are still highlighted in asset identification and geolocalization. Demiralp et al. (2012) compare a fully-automated supply chain with the traditional one, characterized by paper-based methods. In this case, RFId can lead to a significant reduction of time spent on identification and locating goods (about 93%). Compared to the most used technologies for asset identification such as barcodes and standard 2D codes, RFId systems have several advantages (Gligoric et al., 2019). First, RFId does not require a line of sight to be identified, has a limited cost (from 0,1 to 10$), is less affected by wear and tear than paper-based barcodes, can be writable over time recording information on the use phase, it cannot be duplicated ensuring greater information transparency, and it allows to be connected with other sensors (e.g. temperature, humidity, lighting, etc.). However, it should be mentioned how some technical aspects should be considered such as signal transmission issues where metallic components are present (Iacovidou et al., 2018), and the tag service life, still shorter than the façade one.

4. Traceability for CE in the façade sector

4.1. Circular façade information flows

To address the first Rq of this paper, an overview of façade information flows is proposed (Fig. 2). Information list is defined according to CE principles. Increased traceability can lead to more efficient and circular management of the material and the creation of new values.

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). The relationship between information types and circular strategies is emphasized by the numbering. 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.

With a view to promoting CE in the façade sector, the most significant traceability information can be identified as follows:

1. Asset contract. Having direct access to contractual information on the product façade is essential to establish environmental responsibility and product ownership, especially in service-oriented business models. Tracking and sharing this information can, on the one hand, trigger more responsible asset management through forms of self-controlling and, on the other, enhance the company's circular commitment.
2. Service contract. Similarly, direct access to service information can be decisive in making the exchange of services more transparent and reducing the gap between consumer and service provider. Verification of services performed and access to historical information can be decisive in due diligence processes for asset value assessment. This can guide the different stakeholders in making the most responsible choices.
3. Technical features. Information regarding façade typologies, dimensions, weight, and materials properties such as frame and glazing type is necessary to make many actions easier and faster during the façade life-cycle. Having access to detailed and technical knowledge has direct effects on reducing time, cost, and resources. As-built drawings and technical characteristics of materials are basic data over in-use and end-of-life stages for the service contracts conclusion (e.g. cleaning and maintenance), evaluation of different scenarios, and the faster assessment of asset related activities (e.g. pre-audit for disposal costs).

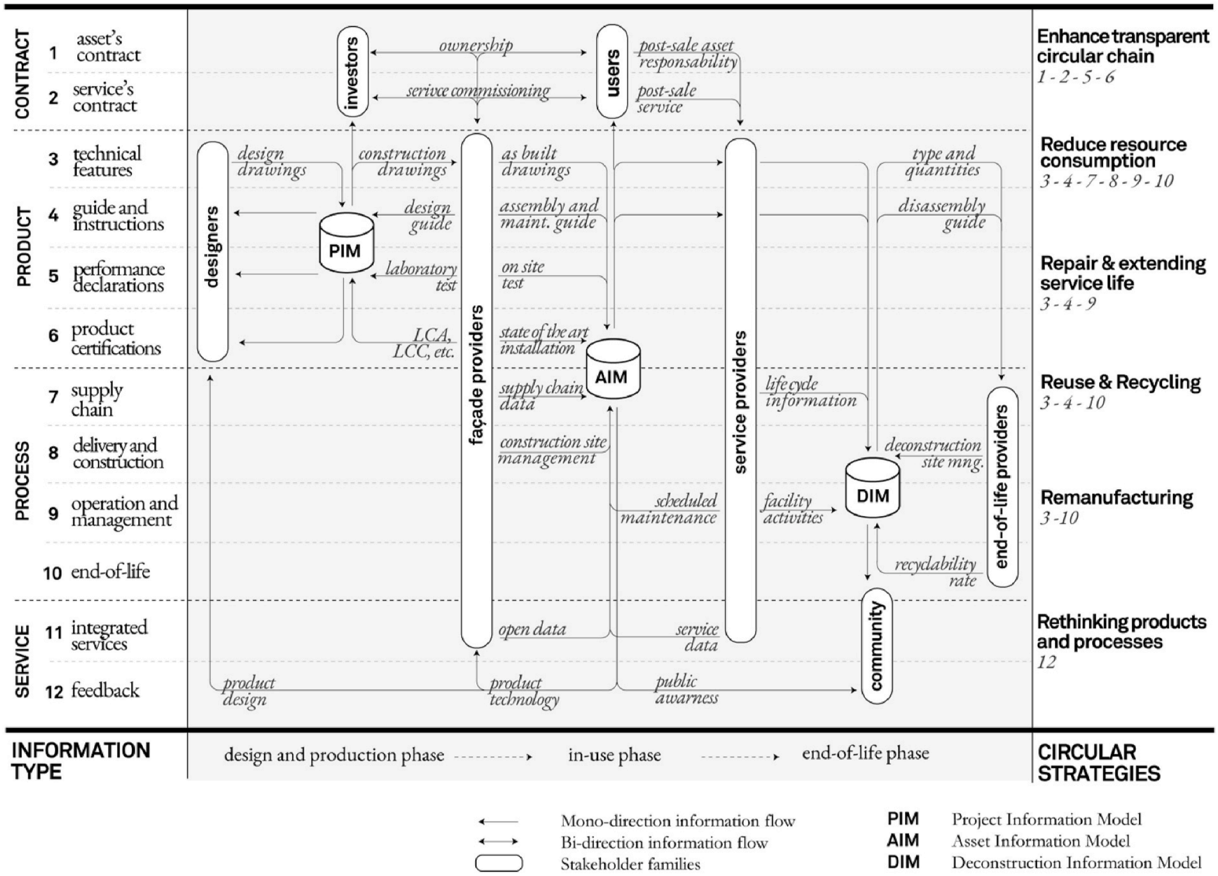

Fig. 2. Façade information flows, organized per information type and stakeholders along the facade life-cycle stages.

4. Guide and instructions. Information on how the material should be installed, maintained, and disposed of is fundamental in reducing time-consuming activities and increasing asset quality. A non-negligible amount of time is spent by maintenance workers to trace the asset information to replace systems and components. Furthermore, the ever-increasing complexity of the façade systems that integrate dynamic and multifunctional systems such as automated blind, opening, and mechanical systems make the maintenance activities more frequent and difficult. Keeping track of the construction, management, and end-of-life instructions and making them available for users, maintenance workers, and disposers would ensure a reduction of wasted time and cost and facilitate the extension of asset service life.
5. Performance declaration. Regulatory compliance and project fulfilments risk overlapping and confusion if they are not brought together within a management and communication system. Tracing and collecting this information in a single and open-access platform would provide an advantage for project and construction managers during the acceptance of material on site construction. Moreover, access to this information becomes essential in performance-based contracting.
6. Certifications. Currently, environmental certifications are mainly used at the design stage. In this case, product and process certifications such as the environmental declaration, recyclability, or recycled content are required for building permits and sustainability assessments. In this context, life-cycle oriented traceability is a central aspect to ensure the veracity of data and update the real impact of the good (e.g. CO_2 emission counting).
7. Supply chain. Information on supply chain traceability can drastically increase asset value. More attention to sustainable chain, product recyclability, recyclable content, embodied energy, and supply chain distance is due to the recent update in national regulatory frameworks and a greater public awareness of environmental issues as shown by the growing demand for voluntary sustainability protocols. A controlled and transparent supply chain becomes a competitive factor for façade manufacturers to show the company's environmental commitment and counter the economic down-selling with global competitors.
8. Logistics and construction. Tracking processes, such as assembly and installation phases, can provide huge savings in time and cost. Façade shipping and construction site management are still the main tasks for façade project managers with a strong impact on project success. In this sense, tracking real-time production line monitoring and site logistics information is essential to meet the project's timelines.
9. Operational and management. Traceability information on operational and facility management activities should be particularly effective in optimizing specific tasks and defining the current value of the façade. Thus, tracking maintenance, cleaning, and building space-time use can ensure the proper performance of contracted services activities. From this, historical data on the facility's activities could be used to estimate the remaining service life of the façade and guide asset manager decision-making. Such information is essential for due diligence (in asset selling or service contract) and investor risk assessments.
10. End-of-life. Information on the companies involved, the disassembly protocols, the selective material separation methods, end-of-life management plans, material transport, and disposal are crucial to address material disposal regulations and verifying the proper closing of a circular process. Towards a fully circular supply chain, more attention will be also imposed by new players in the recovery and reuse components.

11. Integrated services. The introduction of new functionalities for enclosure systems (e.g. comfort monitoring, automation of components, etc.) facilitates the dematerialization of markets and increases the asset value. In this perspective, the traceability of integrated services can provide manufacturers with new data on which to structure their commercial offerings and to customers' new services to manage the asset in a circular way.
12. Feedback. Certified records on products and processes' effectiveness could provide clients, designers, façade providers, and investors data to evaluate their tasks. The collection of a large amount of data is a prerequisite for continuous updating of technology and attracting new investors. Data on product behavior and user interaction can reduce investment risk and support the creation of new performance-oriented contracts.

4.2. The enabling role of IoT for façade traceability

Once the circular façade information flows are defined, the framework is used to identify the potential positioning of IoT over the asset service life. The enabling factor of the IoT is manifested in different ways. From monitoring and controlling to optimization and prediction assessments, data can produce several benefits. On the one hand, IoT technology makes existing activities easier and faster (e.g. tracking façade module over construction stage), on the other hand, it enables new ones through the reprocessing of large volumes of data (e.g. supporting predictive maintenance). The integration of an RFId tag into the façade system is thus conceived with a view to embedding, recording, and sharing asset information. With a view to developing an integrated life-cycle oriented "memory", the framework highlights five potential enabling actions (Fig. 3): (a) the creation of smart contracts for improving safety and circular chain; (b) the process optimization and predictive assessment for reducing resources consumptions; (c) the introduction of a data-driven approach for redesigning products and processes; (d) the support of new business models based on service exchange for market dematerialization; and (e) the development of a digital materials cadastre for improving material reuse and recycling.

More precisely, the circular action enabled by IoT ca be identified as follow:

a) Smart Contract. The truthfulness of information is a key value in promoting CE principles. A greater trust could be unlocked by the use of IoT for tracking activities. Potentially combined with blockchain technologies, IoT could allow the creation of an extremely secure, digital, and controlled data management infrastructure (Li et al., 2020; ShojaeiKetabi et al., 2021). Immutable and safe records can drive "good behavior" and reduce the information gap between customers and façade-service providers. Moreover, the implementation of Smart Contracts means forcing environmental responsibilities to be made explicit and open (Argus et al., 2020). In a highly fragmented market such as the façade sector, the IoT could reduce contract administration tasks and limit wasted time for repetitive activities. An IoT tracking system with blockchain technology could ensure the execution of a job and/or delivery remotely by facilitating worksite tracking, file sharing, and payments between suppliers and customers (Mastos et al., 2021). Secure and automated forms of payment, such as at the delivery of materials or services, would reduce delays and issues related to companies' cash flows. From this perspective, greater transparency in contracting issues would facilitate higher control in the circular management of the asset.
b) Process optimization and predictive assessments. Nowadays, tracking information during the production, construction, and use

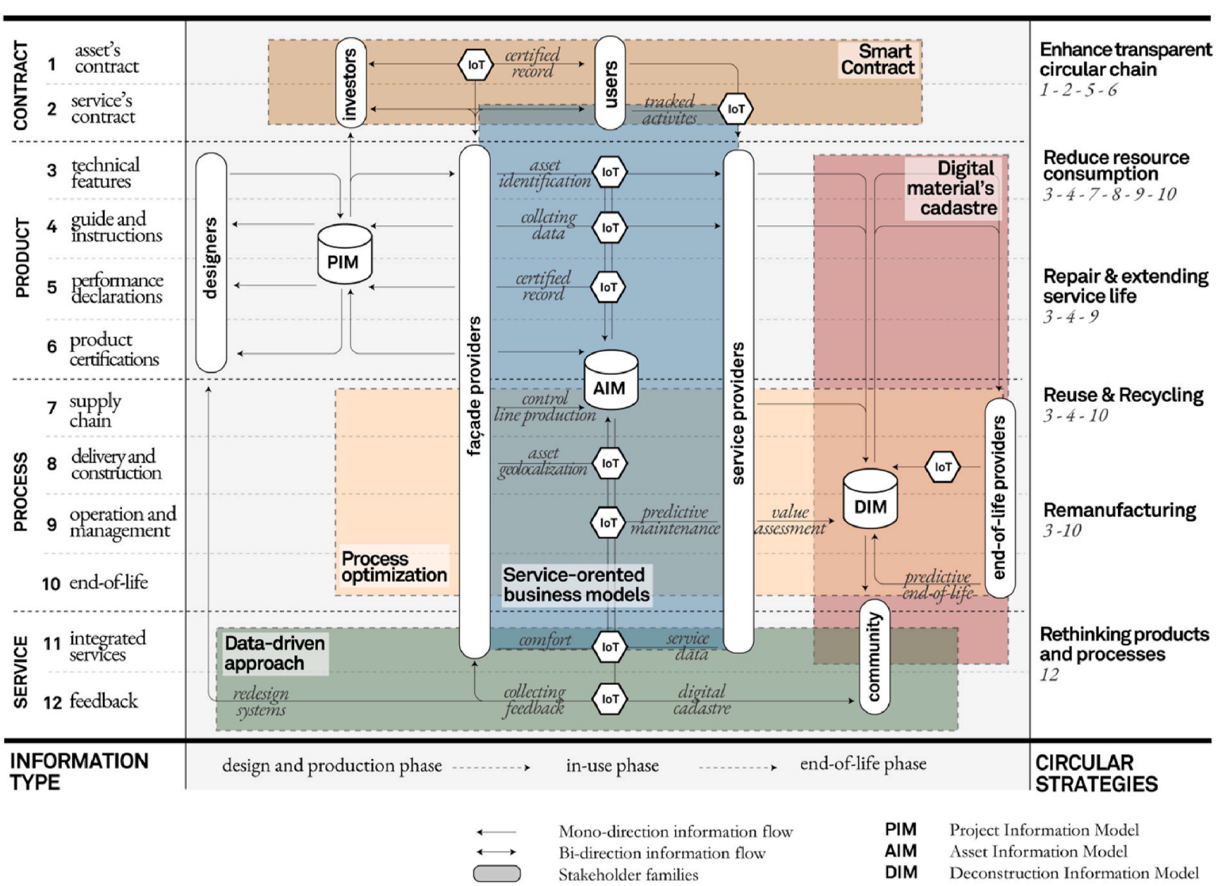

Fig. 3. IoT-enabled framework for circular façade information flows.

phases requires a large amount of time. The automation of product identification and tracking processes along the supply chain could provide significant cost and time savings. Even in the construction site phases, smart tags embedded into the façade systems to trace and geolocalize the asset would enable the optimization of logistic activities, especially on construction sites with limited space for material storage. Some experiences in the field of site management confirm a reduced time and increased safety (Shin et al., 2011). In this context, the most interesting scenarios are in the field of facility management. The production of large datasets over time could introduce predictive and forecasting model approaches to rethink facility activities (Villa et al., 2021). More precisely, predictive maintenance schemes could replace traditional maintenance schedules anticipating the presence of a failure based on different data: the cycle of use monitoring (e.g. openings number, shielding drive, etc.), site-specific weather conditions, static behavior, and others. Thus, this information can be used to feed continuous simulation models to extend the façade service life.

c) Data-driven approach. Huge datasets can guide the design and management choices of designers, product-service providers, investors, and others. The more data we have, the lower the risk and uncertainty that wrong choices will be made. Extending the theme of traceability into the in-use phase of the façade means creating an organized dataset to understand how the asset is used over time. Basically, the recording of data on how it is used, its level of performance, and its state of preservation can trigger a feedback process in the supply chain to rethink product design (designer), optimize service and technology (façade and service provider), and constantly evaluate the effectiveness of the investment (investor and/users). The IoT can be used to evaluate design alternatives for end-of-life products (Joshi and Gupta, 2019). This approach is particularly promising in the customization of product services offered as the flexibility to update contracts, insurance, and services on the actual enjoyment of the asset could be a highly competitive factor for service providers. Furthermore, the widespread use of IoT is essential to monitor environmental and envelope-use parameters to optimize the value of the product in use (PoliMainini et al., 2020).

d) Service-oriented Business Models. IoT can drive new business models based on service exchange and usage-centric business models (Bressanelli et al., 2018; Rosa et al., 2019; Langley, 2022). A large amount of data can be produced by tracking digital technologies. IoT enables new digital services to be included in the products and new ways of managing assets. Indeed, business models such as leasing, pay-per-use, or sharing require the service provider to manage its resources more wisely. Through the creation of an IoT infrastructure, the providers of the service good would obtain vast amounts of data to manage the good more rationally. Access to such information is a central prerequisite for making the most of the value of the commodity. In this perspective, the Façade As a Service business model proposed by Azcarate-Aguerre et al. (2022) explicitly requires the labeling of physical assets to increase the second market value of components and the tracking of physical components to schedule maintenance and increase the efficiency of facility management. Moving towards the circular shift, the creation of digital economies dramatically increases the value of tangible goods.

e) Digital matters' cadastre. The digitization of the building sector tends towards the creation of digital twins, from the building components to the urban scale, where information flows converge for better asset management. Simulation tools and virtual models are used to assess and predict the functioning of the component/building/city system. In this context, the use of IoT technologies for façade material traceability, on the one hand, facilitates the creation of an end-of-life market for materials and components and, on the other hand, they fed the accuracy of predictive models for matter management. Greater knowledge of materials and components embedded in the built environment can serve governing bodies to develop more sustainable regulations. Bonuses and incentives for building refurbishment could be therefore designed based on real economic and material availability.

5. Discussion

Organizing asset life-cycle information in a single framework allows a comprehensive view of the subject. Transdisciplinary dimensions of circular transition make information mapping extremely challenging. The state-of-the-art analysis of the key elements for information flows and their interplaying over the façade life-cycle is the main contribution of this research. To fill the literature gap and improve cross-cutting knowledge for company engagement in traceability (Katenbayeva et al., 2016), a theoretical framework has been developed. Compared to other similar experiences in the proposal of circular frameworks (Ingemarsdotter et al., 2019; Charef, 2022), this one focuses on specific building subsystems. The off-site production process and technical modularity of façade systems enable a higher level of traceability compared to other building components. Among the plethora of façade life-cycle information, defining which strictly affects circular principles is a primary action for a full understanding of traceability benefits. From the circular façade information flows (Fig. 2) overview, 12 information typologies are identified as crucial for CE. Traceability information on building assets can drastically lead to a transparency and more efficient supply chain, reduce resources consumption in daily task activities, improve asset management for extending service life, and support the reuse and recycling of façade materials and components. As confirmed by many authors (Hartwell et al., 2021; Santana and Ribeiro, 2022), this latter aspect, crucial to enhance circular value and achieve the "closing the loop" goal, is a priority action to foster CE. The proposed framework aims to propose an accessible information management infrastructure able to overcome the "silo" mentality (Teisserenc and Sepasgozar, 2021), which underlies the current information flows between stakeholders with different goals. In this perspective, the pivotal role of façade manufacturing companies emerges in sharing information. By having the most data sharing relationships and being able to fully exploit the value of these to optimize complex processes and rethink the efficiency of their product, façade providers play a key role in the circular transition.

To address the second Rq, the IoT-enabled framework (Fig. 3) is proposed. The close interaction between information technology and CE is highlighted through five main actions: the creation of smart contracts for improving safety and circular chain, the process optimization and predictive assessment for reducing resources consumptions, the introduction of a data-driven approach for redesigning products and processes, the support of new business models based on service exchange for market dematerialization, and the development of a digital materials cadastre for improving material reuse and recycling. Tracking asset life-cycle information and reprocessing it by diagnostic, prescriptive, and predictive analysis can fully exploit data value. Specifically, the IoT-enabled strategies proposed promise significant growth margins for the in-use and end-of-life stage, as pointed out by the literature (Ingemarsdotter et al., 2019). Indeed, as proposed in the framework (Fig. 3), the integration of an RFId sensor to trace and manage asset information is understood in the perspective of achieving an organic and life-cycle oriented informative infrastructure. Compared to some experiences found in the literature (Strangfeld et al., 2019; Naranje and Swarnalatha, 2019), the proposal of digital-physical integration goes beyond solving specific problems. From this perspective, the value of information technology for traceability is influenced by the ability to collaborate with information management tools (RejebSuhaiza et al., 2022). The development of an IoT-oriented collaborative infrastructure is necessary to achieve life-cycle traceability. Product and process innovations aimed at increasing the traceability of building components can today represent unique opportunities for façade companies to increase revenues and achieve circular goals.

6. Research implications

On the basis of the research results and discussions, further aspects need to be considered. More specifically, theoretical, technical, and managerial issues must be addressed to promote a fully and accessible traceability of building components.

6.1. Theoretical aspects

With a view to exploiting the pervasiveness of IoT technologies for the circular transition, some theoretical aspects still need to be addressed. As reported by RejebSuhaiza et al. (2022), to understand the innovative dimension of information technologies, the use of IoT must be considered not as a simple "problem solver" but rather as an organic, integrated, and multi-scalar infrastructure. In this regard, studies using this approach are still scarce and limited to specific areas. For instance, more research experience in the field of traceability for maintenance and end-of-life of assets would allow to verify the benefits in the long term. Nowadays, the lack of data on environmental and economic benefits represents one of the most important barriers for the development of a life-cycle oriented information infrastructure for building components. This approach also implies further research on the issue of data quality, reliability and privacy, which are central aspects in the IoT-EC debate. Finally, the long-term dimension of circularity and sustainability requires a cultural paradigm shift in the relationship between producer and consumer. Greater attention to the environmental performance of the façade system must be stimulated in users through greater awareness of the issue. In this perspective, IoT technologies can reduce the information gap and thus trigger user engagement in the circular management of the asset.

6.2. Technical aspects

In the proposed physical-digital integration, technical aspects are central. In addition to the issues associated with the physical integration of the IoT (e.g. location, power supply, visibility, maintainability, signal shielding, etc.) (Iacovidou et al., 2018), it is necessary for the façade IoT-oriented to be embedded in a digital infrastructure (the building) and a smart supply chain. Indeed, to make data accessible to multiple actors and generate valuable information, all identified stakeholders must be "connected". Further technical implications such as sensors service life and maintainability must be investigated. Indeed, on the one hand, the shorter service life of the sensor compared to the technological system is still a major obstacle for manufacturers and operators because it requires continuous maintenance over time. On the other hand, the rapid progress in the field of sensor and IoT technologies raises some concerns in the rapid obsolescence of these technologies. Finally, future research will have to focus on the consumption of resources and energy produced by a widespread IoT network and the management of large amounts of data. To achieve a full circularity of the system, further investigations on reuse strategies for digital components need to be carried out to limit their environmental impact.

6.3. Managerial aspects

The proposed framework is intended as a tool for companies to consider the opportunities provided by technology and direct future investments in the development of circular innovations. An overview of life-cycle oriented traceability implies several aspects, including overcoming the "silo" mentality in information management. This means promoting a collaborative supply chain between suppliers and producers in which (at least hypothetically) the interests of the different parties are not in conflict. In this perspective, the biggest barriers are dictated by the limited environmental responsibility of the producer and the inability to predict the residual value of the material to be disposed of. To extend the interest in circular asset management and increase its value, new performance-oriented business models that preserve the assert value are necessary. In this perspective, further research on development in after-sales services in the façade sector is needed to trigger more interest in the IoT technology and traceability topic. This framework can therefore be used as a starting point for the implementation of circular strategies. For companies, investing today in the development of innovative traceability strategies means increasing market competitiveness by anticipating regulatory actions and future market demands. Finally, from a managerial point of view, it is evident that one of the problems to be solved is the industry's lack of knowledge of IT. In order to understand the opportunities offered by IoT technologies, new professionals (e.g. computer scientists and data managers) need to be trained and integrated into the corporate workforce.

7. Conclusion and future developments

To address the lack of traceability information on building components, a framework for façade systems enabled by IoT technologies was developed. Specifically, the goal of this work was twofold: first, to provide a framework for façade information flows to identify which data needs to be tracked and maintained over time, and second, to define the enabling role of IoT in fostering circular actions. Regarding the first objective, 12 information types identify the main specifications needed to enable circular activities. The proposed framework highlights the importance of storing information in a common, life-cycle oriented framework accessible to multiple actors. Overcoming the "silo" mentality that characterizes industry players and often hinders access to information must be driven by product and process innovations that facilitate such processes. From this perspective, façade manufacturers, being the central players in the system have the task of driving this transition. With regard to the second research objective, five main actions enabled by the IoT were identified: the adoption of smart contracts, process optimization, the triggering of a data-driven design approach, the support of service-oriented business models, and, finally, the introduction of a digital cadastre of material components. The collection of information in a physical and digital memory as an integrated component in the building product (e.g. an integrated passport) would solve the problem of findability, accessibility, and loss of a still large amount of information over time. Furthermore, the scalability of data could be instrumental in driving the transition in the entire construction sector. Greater and more detailed knowledge of the materials in use could facilitate the creation of circular systems and the definition of government guidelines and incentives tailored to the real demand of the existing building stock. Advances in IoT and lessons learned from other industries in the use of RFId technologies to manage large data sets with limited cost and time allow us to imagine future scenarios. In conclusion, the close relationship between traceability data and CE in the façade industry can be strongly enabled by IoT technologies. Product and process innovations, supported by new business models, to preserve the value of the material for as long as possible and to create new intangible values are crucial actions for the development of the sector. The IoT, based on the value of the data it produces, can provide the impetus toward a circular transition.

CRediT authorship contribution statement

Matteo Giovanardi: Conceptualization, data collection and framework definition, Writing – original draft, Writing – review & editing, All authors have read and agreed to the published version of the manuscript. **Thaleia Konstantinou:** Conceptualization, data collection and framework definition, Writing – review & editing, All authors have read and agreed to the published version of the manuscript. **Riccardo Pollo:** coordination, Writing – review & editing, All authors have read and agreed to the published version of the manuscript. **Tillmann Klein:** coordination, Writing – review & editing, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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