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Augmented product information: crafting physical-digital transparency strategies in the materials supply chain

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Abstract

The adoption of digitally enabled manufacturing requires new strategies for managing information about the construction materials beyond the traditional project-driven perspective. This paper contributes an approach to improving transparency and traceability (T&T) of materials using industry 4.0 technologies. The results of an year-long action research in a glass manufacturing company include a guide to identifying requirements for T&T in the materials supply chain and an instantiation of T&T requirements for that sector. Our findings suggest identifying spheres of transparency shaped by enforced and voluntary regulations, and, afterward, creating transparency by design scenarios to complement the physical product with layers of digital information tailored for each stakeholder and product lifecycle phase. Additionally, this research extends the existing body of knowledge in T&T using a combination of technologies that support electronic product labeling. These outcomes are aligned with emerging regulations and calls for disclosure practices to achieve full product information. They are also relevant for materials manufacturers, who can seize the opportunity to boost their brands using technological enablers of industry 4.0, including augmented reality, cloud, and mobile systems.

Keywords: industry 4.0; glass; transparency; traceability; full product information

1. Introduction

Glass has significant importance in the future of construction. First, it enables new designs of physical interfaces that improve the quality of life, as engineers and architects implement larger glass surfaces in their projects with enhanced functionality [1]. Second, the building sector (new buildings, renovations, interiors) uses most of the world's flat glass, including in structural elements. Due to glass's unique properties in handling natural light and heat, there are opportunities for significant energy consumption savings [1, 2]. Therefore, there is a need to find a balance between aesthetics and function to produce glazed surfaces that afford comfort, security, safety, and, above all, sustainable attributes. Addressing these requirements necessitates complete identification of glass products and their properties.

During the lifecycle of glass windows many stakeholders produce and consume diverse information about the product. For example, glass manufacturers need to certify their raw materials for demanding environments (e.g., skyscrapers, bulletproof glass). Plant workers need to guarantee product lots' traceability. Glass information is also essential to guide construction workers in handling and cleaning procedures to avoid damaging the product. End-users may want to confirm that the glass product has, in fact, the expected origin and properties (e.g., in terms of energy efficiency). Additional requirements emerge for recycling the product, putting transparency at the top of the industry's priorities. However, the desired stages of visibility and transparency in industry 4.0 are challenging [3]. Moreover, when the product is literally transparent, as it happens with glass, traceability and information disclosure become a major challenge for supply chains, namely due to the increasing market pressure to reduce all forms of identification (e.g., labels, engravings) in the product for aesthetic reasons.

The vision of digitally-enabled manufacturing presented by [4] suggests "*the emergence of platforms as a new organizational structure to enable longitudinal integration*". Nevertheless, despite the significant advances in mass customization and efficiency gains by the adoption of disruptive technologies such as digital twins and the Internet of Things (IoT), supply chain transparency and traceability still reveal a poor performance in top world retailers (the lowest score amongst 27 criteria of social responsibility) [5]. The lack of transparency in different sectors of the economy (e.g., minerals) "*makes responsible sourcing difficult, for example because downstream companies cannot identify their suppliers*" [6]. Simultaneously it creates challenges in balancing high transparency demands and supply chain performance [7]. According to the recent study presented by [8], this is one of the current paradoxes in the modern supply chain that deserves attention in future research.

This research started at the request of a glass manufacturing company wishing to improve their product traceability and labeling. In the building glass industry, strong network ties, trust, and information sharing can improve organizational performance and make a difference in new markets [9]. Yet, glass lifecycle is complex; for example, (1) there are restrictions in labelling the product – architects usually do not want glass windows excessively marked, (2) multiple lots of glass can be used in a single building, (3) the properties of glass (e.g., safety, comfort) vary according to the manufacturing processes, and (4) it is necessary to enrich product information for construction (e.g., assembly instructions, cleaning procedures, audits) and for deconstruction (e.g., recycling). On the one hand, Industry 4.0 offers an opportunity to develop a digital layer of product information, potentially overcoming the physical limitations, as happens with glass. On the other hand, "*characteristics or ideal working areas of proximity is not currently discussed in the literature and offers potential for further research*" [10]. The company saw an opportunity to strengthen its ties with the business partners and differentiate their brand with a new transparency strategy. Therefore, this paper's overall research objective is to propose an approach to develop explicit transparency strategies using industry 4.0 enabling technologies to share information (internally, externally, voluntary, enforced) in different phases of the product life cycle.

Two complementary research objectives were formulated, namely, (1) *identify requirements of transparency in the building glass lifecycle*; and (2) *implement a technical solution to enable transparency and traceability in construction, respecting the uniqueness of glass requirements*.

The remainder of this paper is organized as follows. The next section presents a review of relevant literature about the fourth industrial revolution, transparency, and traceability. The sequent section explains the research approach, which is the canonical action research described by [11]. Afterward, the glass industry setting is presented, followed by the changes made to improve transparency with digital product information. A discussion of the results ensues, and the paper closes by stating the limitations, opportunities for future research, and key conclusions.

2. Background

2.1. The fourth industrial revolution in the building supply chain

The fourth industrial revolution is blurring the frontiers between the physical and digital realms. This effect is particularly relevant for the building supply chain, with the maturity of building information modeling (BIM). However, the technological opportunities are immense and include the use of cloud, augmented reality (AR), and mobile computing in the construction supply chain [12–14]. Notably, for transparency and traceability, it is possible to use cloud platforms to integrate information from multiple stakeholders and use augmented reality to combine physical objects and their digital representation, taking advantage of regular smartphones as a tool to interact with the construction elements. As [12] stated, "*Industry 4.0 can help construction companies to reduce complexity and uncertainty, to enhance information exchange and communication between project stakeholders and thus to increase productivity and quality*". Construction 4.0 needs to consider its project-driven nature, affecting the "temporary" proximity of supply chain actors and raising product traceability as a priority to managers.

There are social and technical implications in the ongoing transformation of the building supply chains. On the one hand, the technological portfolio associated with industry 4.0 is vast, and the combination of technologies can create synergies. On the other hand, there are implications in the organizations and the skills required for the construction workers' skills [15].

Digital transformation is now influencing construction materials, with important implications for the project level of analysis, namely, in the planning and execution phases, with "*safer and less labour intensive* [functions], *such as to monitor and control automated processes by transferring their know-how to the robotic systems*" [15]. Technologies such as augmented reality and BIM can assist in construction design [16], but the materials supply chain is also adopting automatic tracking (e.g., using RFID, GPS, or GIS) and real-time status [10]. However, despite the enormous changes that the mobile Internet-enabled for the design, execution, and lifecycle data of materials and products after its adoption in buildings [14], there is a lack of studies that address the information flows since the early stages of materials production. This gap must be addressed to ensure real transparency and traceability because the origins of the materials and their original characteristics are baseline requirements to provide trust.

2.2. The critical role of transparency and traceability for the success of industry 4.0

The prospects for industry transformation are vast. However, there is an excessive technological focus, lacking contributions in the social and organizational dimensions [12]. Moreover, it was not possible to find guides to assist industry managers in developing their transparency strategies and in exploring the potential use of virtual information in the product lifecycle. Transparency between clients and the contractors, enabling proper assessment of product quality in the building industry, is determinant for "*improving its market operation, integral processes and societal added value*" [17].

How can firms differentiate using a transparency strategy? On the one hand, technologies such as IoT support real-time information, improving product traceability. On the other hand, cloud, mobile, and system integration technologies facilitate sharing product information with external stakeholders. Other enablers, such as augmented reality, can assist designers and operators with contextualized information [18]. Nevertheless, the fourth industrial revolution is still in its infancy regarding the building supply chains [10], and there is a lack of case studies in traditional sectors. It is now possible to extend recent research in the adoption of augmented reality tools presented by [18] to the supply chain of construction products. In fact, "*despite the given maturity and availability of many technologies, their widespread adoption by construction companies has not taken place until now*" [12].

2.3. Transparency, traceability, and requirements capture in construction

According to [19], it is necessary to consider three types of transparency, namely, (1) history transparency that includes traceability aspects (past), (2) operations transparency, exchanging information with partners and ensuring process coordination (present), and (3) strategy transparency providing critical information for the future. Transparency is also related to the notion of trust, shared understanding, and access to product-related information [20, 21]. Ideally, companies should carefully evaluate management (e.g., ISO 9001 certification), regulatory (e.g., disclosure of information to regulatory and inspection bodies), the consumer (e.g., eco-labels), and public transparency when the information is valuable to the entire society [22].

Several studies addressed transparency in organizational settings, for example, revealing the importance of the social system in small businesses [23], and the guidelines to develop a transparency strategy supported by information technologies [24]. In construction, [25] suggests a process-oriented approach to improve transparency in the planning and control phases using visual tools. However, existing studies do not specifically address glass materials, and few studies show how to put such a strategy into practice using new technologies [26].

A straightforward way to define transparency is the presence or absence of information [27]. Several authors addressed its importance in the industry; for example, "*a greater degree of information transparency improves the* [hybrid manufacturing/remanufacturing] *system performance when uncertainty in the reverse flow is high*" [28]. However, there are different degrees of cooperation within industry supply chains, and the decision to share information with internal and external stakeholders may depend on multiple factors, for example, regulations.

According to [24], there are four main options for transparency strategy, namely, *disclose*, *distort*, *bias*, or *conceal* the information. They state that each option varies according to different informational elements such as the product, price, cost, inventory, or process. For example, the company may *reveal* all product characteristics online, *hide* product costs, and *show only a part* of the inventory data (e.g., show stock availability, but not the number of products available). Another example is to share order status with company partners but not with end customers, to conceal possible delays and manage customers' expectations. The decision to give access to information must be evaluated in each case [24]. Other authors consider transparency without losses or distortions, for example, in the food supply chain [20], considering the interests of the customers and, ultimately, the society (e.g., the environmental impact of the product).

Information technologies are crucial for transparency. For example, implementing traceability systems using RFID or mobile devices [29]. Nevertheless, more case studies about transparency strategies are necessary, as is a deep examination of how the new technologies can be used to implement interactive approaches with business stakeholders [24].

New problems emerge for validation and reliability when the exponential amount of information made public also increases the risk of disinformation [22]. Therefore, ensuring transparency in buildings requires both data access (such as environmental/health product declarations) and data verifiability in product lifecycle management [30]. It is necessary to label each product in a way that confirms its authenticity. Voluntary declarations and certifications are only meaningful if there is an assurance that original products are used. The problem of counterfeit products is particularly relevant to the client when there is an impact on performance, for example, sustainability [31], and the need to allow product recall [32] reinforce the pressure to combine product information with product authenticity, but solutions are lacking.

3. Research approach

According to [33], action research is "*one of the few research approaches that we can legitimately employ to study the effects of specific alterations in systems development methodologies in human organizations.*" It has the dual aim of contributing to science while solving a particular organizational problem [11], making it particularly suited for the glass company context. One of its major strengths is the possibility to promote change in social settings, putting the researcher in the role of an active participant in the setting [34]. However, change must enable the emergence of theory from data, going beyond the project's specific context. Among its multiple forms, the authors have selected the canonical action research (CAR), characterized by five steps [11]:

- *Diagnosing*, identifying, or defining the situation. The participants interpret the phenomenon and formulate a working hypothesis;
- *Action planning*, specifying courses of action to improve the problematic situation;
- *Action taking*, causing change to occur and trying to create improvements;
- *Evaluating* the consequences of the actions, involving a critical analysis of the results;
- *Specifying learning*, documenting, and defining the outcomes that will add to the body of knowledge.

CAR is significantly different from other scientific approaches, such as randomized controlled trials that evolve with different groups and aim to minimize uncertainty in generalization efforts [35]. Action research produces knowledge that emerges from specific contexts [11]: in our case, digitalization and the opportunities for transparency and traceability in supply chains, departing from the construction industry. The work of [36] presents important criteria to guide our form of research, which includes the notion of transferability – "*the extent to which the results could be applied in other contexts*" that we address in section 5.1. To ensure rigor and validity, we assessed the research according to the principles of [37], explicitly proposed for CAR: *Principle of the Researcher–Client Agreement; Principle of the Cyclical Process Model; Principle of Theory; Principle of Change through Action; and Principle of Learning through Reflection*. Rigor is achieved using two main mechanisms, namely: the iteration in a specific sequence of steps that contribute to improvements in a problematic situation; and the continuous diagnosis of the problem to ensure that the activities are relevant to the problem [37]. Rigor and relevance are inseparable in action research, making its outcomes persuasive to both academics and practitioners [34].

We conducted a complete CAR cycle over one year in a building glass company to increase transparency and traceability in their products. Introducing changes in the organization should consider multiple forms of materialities that shape modern industrial products, namely, physical and digital materialities [38]. Complementary, this research adopts the stakeholders theory [39] as an instrumental theory that aims to identify all the interested parties in the business and balance their interests during strategic formulations.

4. Developing an augmented transparency strategy

The next subsection details the case company and the joint diagnosis made by researchers and practitioners. Afterwards, the action phase is presented.

4.1. Case setting and diagnosis

The case company is a European building glass producer, developing its business activity in transforming, commercializing, and applying glass on site. They export to twenty-one countries and use high tech equipment for glass production, including the oven heat-soak test, the cutting machine for laminated glass, machine bilateral edges, cutting table for monolithic beveled glass with automatic loader, complete production line of double glazing and screen-printing machine. Their products are used in wide-ranging buildings, as illustrated in Figure 1.

Fig. 1. *The importance of glass in modern buildings.*

Figure 1 presents two of their recent projects: Shopping Centre in Paris, France, on the left, and a sustainable real estate in Brussels, on the right. The buildings' list is vast, but they all share a common requirement: trustworthy and accurate product information. According to the company manager, "*we want to achieve maximum* *transparency, ensuring that the product history is reliable but also tailored to each actor in the supply chain* [building constructor/contractor, end-user, or assessor]. *Simultaneously, we need to keep our product (physically) as transparent as possible by reducing tags and paper. We are leading this market, and our customers must be certain that they have one of our products installed*". She also highlighted that "*we want to create a digital layer of information that differentiates our company from the competition, providing an example to the construction market.*"

On the one hand, regulatory information must be complete and trustworthy. On the other hand, the physical product must only reveal information when required. When the project started, product information was available on conventional stickers and datasheets, supplied to the building contractor by request, usually via email. The process is lacking because the information is not integrated (1) in the physical product, (2) with the manufacturing execution system, leading to an additional burden for the quality manager, and (3) in a way that addresses the needs of different stakeholders within the product lifecycle.

The correspondence between product lots and customers' orders is essential for historical transparency. Products from the same lot can be shipped to different customers, and, conversely, a single building can include products from different lots. Managing complaints requires a complete trace of the product characteristics in each lot. Moreover, it is essential to ensure that the lot is compliant with customer specifications. Operational transparency has internal and external requirements, depending on the product lifecycle stage. Internally, the employees require distinct information to develop and assemble the glass windows; externally, the inventory information is required by the company partners in each building. When the product is delivered, all the information must be accessible through the product (physically or virtually). Transparency about product characteristics is essential to the intermediaries that incorporate glass products in specific solutions, the company resellers, and the public in general. Although the product brand is vital in multiple sectors of the economy, for example, the fashion industry, it is not (yet) a major concern in glass products. Increasing brand value is another strategic intention in this case.

4.2. Conducting action to improve physical and digital transparency

The frame of reference for the field intervention emerged from a literature review that confirmed the lack of approaches for transparency in the building supply chains, document collection, and observation in the case company, about glass information requirements, and interviews with company managers, energy assessors, and two experts in glass production from a technological institute. The participants were selected by the case company and their technological institute partner. Energy performance is an important aspect to consider in building transparency [40]. Moreover, a recent directive by the National Agency for Energy calls for labels with this information. According to the plan, industry 4.0 scenarios expect an explicit strategy. Figure 2 summarizes to whom it is necessary to ensure transparency.

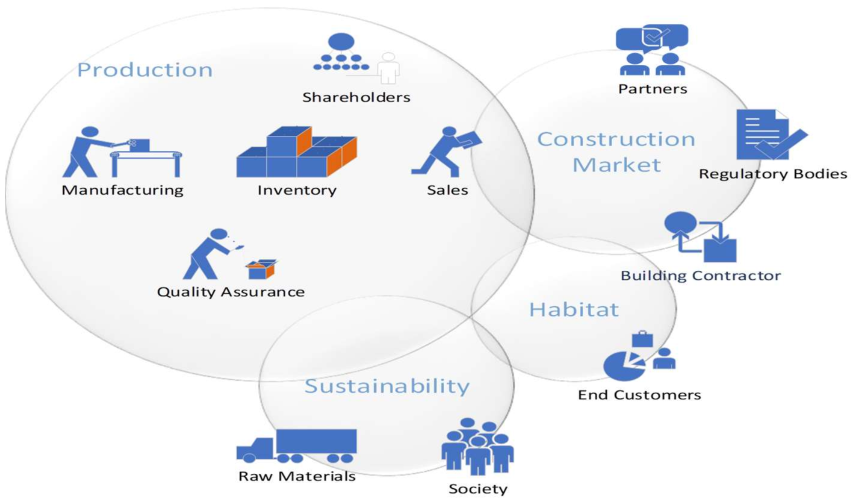

Fig. 2. *The spheres of transparency in building glass.*

Each sphere represents a regulatory context of the organization, enforced (e.g., legal) or voluntary (e.g., policy, standard), each involving a network of stakeholders. First, the production sphere is related to all the product history and the information needed during production. Next, the construction sphere includes the information required for the partners (intermediary) and building contractors implementing the product at its final location. The habitat sphere represents the product in its operation (use) phase, when the end customer may need to verify the authenticity or identify specific information (e.g., energy performance for audits). Finally, the company wants to ensure that deconstruction and recycling information is available to promote safe handling procedures and sustainable practices. This approach takes into account all stakeholders and their particular needs before establishing the requirements of T&T.

The spheres of transparency can be identified at company workshops, as it happened in this case, involving the top manager and experts in production, maintenance, quality, IT, and marketing. Although each participant has a particular perspective about transparency and controversial opinions can emerge in the discussion (e.g., share/not share information with the construction owner during production), there are benefits in a negotiated vision for the transparency system. For example, clarifying the limitations of different company departments in obtaining the required information (e.g., lack of integration in company IT systems) and identifying IT investments to support their problems.

The participants were asked to consider the context of the product lifecycle phase and not just the requirements for their specific functions in the company. It was an opportunity to share different requirements (e.g., regulatory) and joint efforts in defining the information to *disclose.* Although the participants agreed that transparency should be the result of a global action plan, until that moment, it was mostly the result of ad-hoc practices. Interestingly, the existence of information that needs to be private also provides key insights to the organization, exposing risks for their strategy. For example, the product may not be complying with the desired specifications, the information system may not be prepared to provide the required information, or there may be insufficient trust in a segment of the supply chain. However, disclosure may also be a strategic option. The case company decided that part of the product information was only available by requesting or using a specific code for two reasons. On the one hand, part of the product information required manual processing (not integrated in their manufacturing execution system); on the other hand, they wanted to know who was asking for specific parts of the product information (a risk identified in full disclosure practices).

The next phase was the identification of more specific requirements, summarized in Table 1.

Table 1. Requirements of transparency in the building glass.

Sphere	Stakeholder	Type	Informational Element	Purpose
Production	Production employees	Operational	Product, Inventory, Process	Inventory management | Assistance for assembly
	Quality manager	Historical	Product, Process	Product identification | Quality assurance

	Marketing/ Commercial	Operational	Product, Price, Cost, Inventory	Market actions | Negotiation | Shipping management
	Top managers	Strategic	Product, Price, Cost	Strategic alliances
	Assessors	Historical	Product, Inventory, Process	Quality audits | Inspections
Construction	Intermediary	Strategic	Product, Inventory, Price	Technical files (standards requirements) | Orders
	Site employees	Operational	Product, Process	Assembly and cleaning instructions
	Building Constructor	Historical	Product, Price	Technical files | Complaints
	Assessors / Auditors	Historical	Product, Process	Safety inspections | Energy inspections | Building approval
Habitat	End User	Historical	Product	Product Verification | Energy Performance | Sustainability
	Assessor	Historical	Product	Verification
	Maintenance	Operational	Product	Maintenance instructions
Sustainability	Constructor	Operational	Process	Deconstruction instructions | Recycling options

For each sphere of transparency, in column 1, it is requested to identify the stakeholder, the type of transparency [19], the most relevant information elements for the stakeholder, and its purpose. For the sake of simplicity, the purpose of transparency is described while omitting the various data elements to present to each stakeholder (e.g., fields in specific digital interfaces such as web forms and augmented reality apps).

The notions of trust, shared understanding, and access vary in each sphere of the first column. For example, the employees need to know the operational procedures and the complete identification of each product in the production line, but there are no restrictions on the media (e.g., tablet, paper). Conversely, end-customers do not want to see physical identification in the glass product; they want to ensure that the product has the required properties (similar to the purpose of quality assessors). Intermediaries and building constructors may be tempted to omit the information if using a lower-quality glass from a competitor. A transparency strategy that takes advantage of industry 4.0 technologies can contribute to the case company’s transparency goals, ensuring that the information reaches the end-user of the product, mitigating the risk of product substitution by the intermediaries increasing brand value. This phase of the process involves preparation from each participant (e.g., collect standards, identify market necessities) to compile in a common table of requirements. The authors' purpose was to create an artifact useful to different areas of the organization (e.g., IT, to develop their web interfaces, production, train employees, and identify points/technologies to collect traceability data).

Top-quality manufacturers are interested in passing their products' information down the supply chain, avoiding replacements by lower-quality materials. The construction market needs transparency and traceability to integrate the right materials in the building and understand the implications of their decisions for sustainability [22, 41, 42]. End-customers are interested in confirming the provenance of their acquisition and, eventually, increasing the proximity with the suppliers during the use phase for instructions or replacements. Finally, manufacturers can benefit from this proximity by receiving direct feedback about the product and improvement opportunities.

Based on the requirements, we developed and tested a technical solution – second research objective – that (1) minimizes the size of physical labels (market demand) and (2) provides augmented product information. The technologies selected for this scenario were augmented reality, cloud, and mobile. QR codes and linear barcodes are commonly used to ensure traceability, associating a code to a product. Although simple to use in the sphere of production and shipping (the company is already using barcodes in internal operations), there are risks for the spheres of construction, habitat, and sustainability. If the intermediary removes them, it is no longer possible to share information with other supply chain stakeholders. Hundreds of tests were conducted during the process, with physical and virtual tags accessible via QR code, barcode, and symbol for AR, as presented in Figure 3.

Fig. 3. *Adopting augmented reality for T&T.*

The case of the sphere of habitat, i.e., end-users, is illustrated in Figure 4.

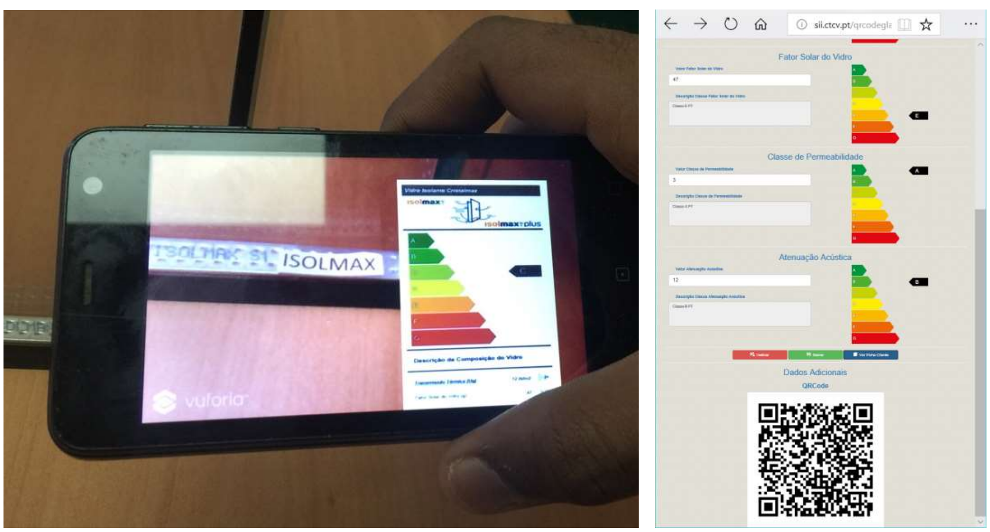

Fig. 4. *Electronic label for the habitat sphere (end user).*

The transparency requirements for the habitat sphere are implemented with a digital label inside the glass (on the left), which ensures product authenticity and no impact on the physical product's transparency, as required by the market. Figure 4 also presents the BackOffice of the developed system (on the right). It generates a digital tag (rightmost image) like the ones used in home appliances (e.g., refrigerator). The integrated identification is unique in the industry and enables transparency for end-users: product verification, energy performance, and sustainability. The interface included a contact form (accessible via the digital tag) to ask for product replacements directly to the glass manufacturer or to validate the information in the digital tag by assessors (e.g., during an audit).

Virtual tags complement their physical counterparts in the production/construction spheres of transparency, and, unlike the latter, which are removed, the former will remain accessible after product installation on-site (e.g., for inspection and deconstruction). In this case, the optimal solution is a combination of QR codes in the physical labels and small symbols embedded in the glass (like the company logo). The symbols have variations according to the product characteristics, ensuring readability by the AR application while minimizing visual impact. We also tested text recognition in specific models (e.g., serigraphy required in the tempered glass as per the standard EN 12150-2). According to interviewed certified experts in energy assessment, the system complies with the recent product information regulations. They suggested that the augmented reality app could provide an interface for product validation during the entire process and not only at the habitat, for example, to include external lab test results (ensuring they pertain to the same lot). That opportunity had already been identified in the production sphere by the quality manager and strengthened by previous research in design variations [18]; nevertheless, it was an opportunity to reinforce the authors' conviction that only with a lifecycle approach it is possible to create a comprehensive T&T strategy.

5. Discussion and lessons learned

The practitioners' interest and the research interest are interrelated in action research and require a permanent reflection. Transparency is a result of design practices and strategic analysis (third research objective). Revealing the spheres of transparency is the first stage. It facilitates the identification of key stakeholders in each sphere and the informational elements needed for each one. Elements can be in the form of product characteristics, price, cost, inventory, or process information. Transparency occurs in specific situations or use cases that must be identified. The sequent phases of the approach represent the implementation using industry 4.0 technologies. In this case, illustrating the end-user stakeholder (the fourth line in Table 1, counting from the bottom).

There are advantages in considering requirements capture for transparency and traceability with a lifecycle perspective. First, it opens new opportunities to include material manufacturers in the transparency efforts, extending existing contributions that mainly address the design and execution [16]. Temporary proximity in building projects can improve transparency in the design and execution phases [10]. However, failing to include both, material manufacturers and end-users will miss the biographies of the materials [43] and the proximity at the extremes of the supply chain. The integration of different stakeholders' concerns in T&T strategy design can have a major influence in the use, renovation, and disposal of the building, overcoming construction projects' temporary nature.

The adoption of industry 4.0 technologies also has implications for the problem of counterfeit materials in construction [31]. In fact, product traceability is pointless if the origin of the product can be easily manipulated or potentially lost at the end of the temporary proximity during the construction work.

Improving trust is not optional for sustainability. Cross-check cases involving different stakeholders are recommended. For example, the digital label of energy performance can include a third-party verification of the glass producer's information. To be “crystal clear,” the data under consideration must have the possibility of being confirmed or infirmed. Moreover, vertical supply chain collaboration in new product introduction, demand replenishment, shared distribution, and the collaborative culture that require effective information exchange [44] can be strengthened with the proposed approach. Visibility is another outcome of the increased integration of information that can be achieved internally and externally to the organization, requiring proper identification of transparency requirements in each sphere.

Transparency requires information protection; therefore, the regulation that affects each sphere can vary. For example, quality tests of specific products may require omitting customer identification to ensure the confidentiality of results (production sphere), while product cost must not be available to the product's end-user. A single informational element, for example, product characteristics, may have different views depending on the product lifecycle phase. In the case company, the digital product information includes extensive technical details for the business partners that are not relevant for the end-user in the habitat sphere; therefore, the digital tag also has a specific lifecycle that must be identified and implemented in practice.

The solution found to enable a single interface to different lifecycle stages was the adoption of a "dynamic output" QR code. In this technical implementation, the QR code remains the same, but the online information it links to changes according to the lifecycle stage. The main difficulty with this approach is the integration of the digital label platform and the manufacturing execution system that identifies product lots. Based on a single field in the database entry representing the lot stage (e.g., 1-under production, 2-at the construction site, 3-in use), the interface opened by the QR code changes to present the required information for that precise moment in the lifecycle. For example, during construction, the output shows technical information to the building contractor, and, during use, a simpler version of the label shows energy efficiency ratings and vendor contacts (e.g., to ask for replacement of the exact same glass in case of damage). The combination of the timestamp (to identify the stage of the product) and location (GPS variable identified when the QR code is scanned) can be used to change the digital AR label of the product dynamically.

The initial task was to identify the *information to obtain* for each sphere of transparency. It may be inside the organization, as it happens in quality control processes, or outside (e.g., raw material traceability from suppliers). Similarly, requirements for the *information to provide* are identified in each sphere. Recognizing potential risks of distortion and bias may also help detect problems in the organization and implement preventive measures to eliminate incorrect information.

Transparency is not a synonym for integral access, and there are also challenges. All efforts can be meaningless if it is not possible to confirm the source and quality of information. In this research, augmented transparency is envisioned as the use of augmented reality and mobile technologies to provide filtered and reliable information in the context of its use, overcoming the limitations of physical objects. It may support backward searches, for example, to trace the product origins and constitution, and forward searches, for example, for assembly planning and evaluation (Wang et al. 2013). In this case, the glass producer can send important information to the end-user that is not visible during the construction stages. There are also risks with the emerging industry 4.0 technologies. The increasing amount of information that can coexist with physical objects requires that each organization develop a transparency strategy. The mere "access" is not enough, and there are problems with the combination of physical and digital layers, as happened in the case of glass. For example, inventory transparency is easier to implement in the production sphere but may be problematic in the construction sphere (exposing delays or quality problems) and is irrelevant in the habitat sphere. Similarly to popular drawing applications, augmented transparency requires adjustments to the "percentage of transparency" required in each case. Establishing a T&T strategy is not restricted to regulatory compliance – it is one of the pillars of industry 4.0 transformation towards horizontal and end-to-end digital integration. Alternatives may be used to hide risks that may hinder supply chain integration and to decide which information to conceal while not compromising T&T requirements.

5.1. Evaluating action research

The evaluation considers five principles specifically designed to ensure rigor and relevance when using canonical action research [37]:

5.1.1. Principle of the researcher–client agreement

The case organization and the researchers agreed that action research was appropriate to develop the project: (1) improve transparency and assist in the transformations required by industry 4.0 in the setting and (2) gathering lessons about the adoption of augmented reality and the opportunities to improve T&T within building glass lifecycle. Data collection included interviews, observation, and document collection, safeguarding confidentiality.

5.1.2. Principle of the cyclical process model

The research project followed the five stages of CAR [11], starting with a diagnosis and a literature review about transparency and the challenges of producing construction glass. Researchers and practitioners developed an action plan and a broad evaluation of the results with a field intervention.

5.1.3. Principle of theory

The theory had a central role in all phases. First, with a comprehensive review on papers that can shed light on transparency and traceability in construction. Second, with frameworks that explore the technological opportunities for traceability [24]. Third, with specific guidelines for canonical action research [37].

5.1.4. Principle of change through action

Three main changes occurred in the glass company. First, adopting practices for transparency by design. Second, identifying synergies in product materialities using augmented reality, namely, creating physical and digital layers of information that support the product lifecycle. The authors comprehensively evaluated the situation of the organization before and after the intervention. Finally, implementing a solution for labeling glass products respecting its uniqueness in construction.

5.1.5. Principle of learning through reflection

Lessons learned were used to create artifacts to assist the project participants. The benefits are (1) to promote awareness about transparency requirements and the responsibility of each stakeholder in the process, (2) to identify risks and obstacles for transparency, inside and outside the organization (e.g. ensure product authenticity information), and (3) to create tailored layers of information according to the product lifecycle phase. This was not achieved by merely replicating traditionally paper-based information on smartphones or smart glasses, but rather by creating a new informational layer that opens an opportunity to merge the physical product and its biography. Materials producers can use industry 4.0 to be active participants in this digital transformation or face the risk of being excluded from the major supply chains. T&T strategies must result from joint design, aiming at concrete business benefits, not merely a compliance effort.

5.2. Transferability of results to other contexts

Canonical action research allows the transferability of the results to a similar class of problems and organizational settings [46]. To that end, we identify the following characteristics to frame the context of result transferability in advanced manufacturing technology:

1. Existence of market pressures (voluntary or imposed) to improve product traceability (e.g., safety, sustainability) and authenticity;
2. Need to incorporate full product information using digital technologies to overcome the physical constraints of the product (e.g., small products) or of the lifecycle (e.g., circular economy);
3. Need for improved communication with the supply chain participants;
4. Need for improved "literacy" about product transformation and use during its lifecycle (e.g., guides for energy consumption, recycling guidelines, assembly procedures).

To illustrate the opportunities described above, we evaluated the possible use of the proposed approach in a small company operating in the technical coating sector (TC company). They are experts in techniques such as High-Velocity Oxygen Fuel (HVOF) coating, electrocoating, or physical vapor deposition. We selected this case study because the researchers had an ongoing industry 4.0 project with the company, and management was particularly interested in the personalization of their product (coatings of metal components), traceability, and compliance with their recent ISO 9001 certification.

According to their CEO, a component (e.g., valve) can receive a specific coating before entering operation and returns several times for maintenance. The production sphere requires identifying the work order information and the requirements for quality control (including the target dimensions and visual appearance of the component), and the resources used during the process. Some components require subcontractors' activity (who need detailed information about their work order, without identifying the end customer). Nevertheless, one of the most interesting applications of augmented information is related to the customer; for example, airlines that need to identify product degradation or track the supplier interventions over time (e.g., for compliance and audit).

Presently, there are severe limitations in marking metal components. It is possible to engrave codes in metal, but the space available for information is limited. According to the CEO of TC company, they have distinct spheres of transparency that require different information over time. Using our proposed approach, we identified a solution that would differentiate the company from the competition by offering a product augmented with information tailored to each phase of the lifecycle. For example, internal coating processes, subcontractor operation, quality control using augmented reality contrast of the desired component and the actual state, and traceability accessible by the end customer. The solution also simplifies work when the component returns for maintenance (by reading a QR code engraved in the product), identifying the latest coating's performance and the product coating log.

This case study is merely illustrative of the potential of transferability, as we did not develop the entire solution for T&T in this case. However, it exemplifies how to implement augmented product information in other contexts to improve transparency and traceability in manufacturing settings.

6. Study Limitations

Action research is important for practice, evolving in a real organizational setting while simultaneously producing new knowledge [11, 35]. Contrasting with approaches that focus representative populations, prediction of events, and the researcher's role as an observer, CAR studies involve field intervention and the interpretation of knowledge to produce guides and artifacts for organizational development [11]. Therefore, action research produces situational knowledge. This type of limitation can be addressed by extrapolating "*to other situations and to identify how the AR project could inform like organisations, similar issues and so on*" [46]. Our research produced an emergent and incremental theory that can be meaningful for others [34], but this is the first CAR cycle in a complex industry setting that requires physical and digital transparency. More cases are needed to refine and validate the approach. Secondly, the fieldwork included a limited set of industry 4.0 technologies (AR, cloud, mobile) but there are other potential scenarios, such as blockchain [47] or the combination of big data and social networks for the cross-check phase. The study presented by [41] is a promising starting point for the latter. Thirdly, it was not possible to fully explore the social changes that occurred, namely, at the phase of glass assembly and use because the system is recent. Fourthly, although the company and the construction assessors provided enthusiastic feedback, socio-technical contexts are complex. There are risks of the Hawthorne effect, which suggests that participants' behavior may be "*related only to the special social situation and social treatment they received*" [48].

7. Avenues for Future Research

There are several organizational and technological opportunities to explore in the future.

The project-driven perspective that has prevailed in recent BIM advances [49] can be complemented with a product-driven approach supported by electronic labels made possible by industry 4.0. Product labeling enables the addition of new digital layers optimized for the end-user, supported by disclosure practices that combine regulatory compliance with end-to-end integration strategies and the opportunity to cross-check information by multiple stakeholders. Additionally, a product-driven approach to T&T could be explored in future revisions of popular standards, such as ISO 9001.

Construction glass manufacturers can take advantage of industry 4.0 to become more relevant in sustainability-driven contexts. Brands are not yet as usual in buildings as they are in other sectors, such as automotive (e.g., where a car buyer looks at tires and expects to find top brands), but "parts manufacturers" that provide augmented product information for sustainable performance within the product lifecycle [42] can benefit from this strategy. We also found that other manufacturing sectors can explore the added value of augmented product information. For example, the metalworking industry can use the selected approach to identify spheres of T&T, extending the physical identification with layers of digital information tailored to the needs of different stakeholders, differentiating their product, and ensuring authenticity. Examples of other sectors that need to explore augmented product information are equipment manufacturers (integrating planned maintenance with equipment manuals and operation procedures), quality departments in manufacturing using augmented reality to assist inspections or marketing experts in developing product brands.

There are also technological alternatives to QR codes that can be used, such as marker-less identification of products, smart glasses, and other traditional traceability technology such as RFID. Future research can compare candidate T&T technologies for each type of product and study the impact in practice, instantiating spheres of transparency tailored for different sectors of the economy. Moreover, it will be interesting to study how the augmented interaction with the products can produce feedback to the supply chain, for example, including the possibility to provide immediate feedback to specific partners of the supply chain, trace product location, and support audit and inspections made by third party entities. For example, public authorities inspecting product provenance, insurance companies evaluating incidents, or certification bodies. The support blockchain can provide for transparency in the augmented product information is another opportunity for future work.

8. Conclusions

The materials industry has a crucial role in the requirements of transparency and traceability. Until now, BIM has been one of the main drivers for transformations in construction and posed new challenges for manufacturers, requiring new forms of representing products in digital media. Although relevant, these changes have been mostly in the early phases of the building supply chain, in reaction to the needs of building design and execution. The materials supply chain should create an agenda to take full advantage of disruptive technologies, increase product value and visibility to the end-users, protect their brand, and implement transparency strategies that adhere to societal challenges.

This paper presented an action research study to create T&T strategies. The results include the requirements and a real case to improve (1) physical and (2) virtual transparency in glass products using industry 4.0 technologies. The lessons learned in this study enabled us to understand the concept of "augmented transparency," sharing information in all phases of the product lifecycle with the strategic intent of transparency. A new form of proximity that promotes trust can be achieved by disclosing the required information and enabling bidirectional and direct communication between end-users and material producers.

The proposed artifacts provide guidelines for the designers of information systems in temporary or permanent supply chains. First, the spheres of transparency are used to reveal the contexts and stakeholders. Next, specific informational elements (e.g., technical characteristics, price) are identified for each stakeholder. The physical and virtual access to the informational elements can be described in the form of use cases, revealing potential industry 4.0 scenarios. To the best of authors' knowledge, this is the first industry 4.0 project that ensures building information with a threefold goal: (1) support all the stakeholders within the building lifecycle, (2) assess the product conformity in the context of use, and (3) validate information in the supply chain.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Not applicable.

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Competing Interests

The authors declare no conflict of interest.

Availability of data and materials

Not applicable.

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