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Carbon Dashboard for Real-Time Embodied Emissions Tracking

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Abstract: A large proportion of the worldwide emissions caused by greenhouse gases is attributed to the construction sector and the manufacturing industry, with much of it related to embodied carbon or emissions associated with the extraction of materials, their production, transportation, and assembly. This paper involves the conceptualization and validation of a real-time carbon dashboard meant to monitor embodied emissions in supply chains and project stages. The dashboard is designed to provide dynamic monitoring, predictive analysis, and forecasting of emissions, integrating technologies from the Internet of Things (IoT) and Life Cycle Assessment (LCA), and presenting the results in visual forms. An on-site pilot test at a commercial construction project demonstrated that the system conducted time-stamped emission logging and alerted to high-impact building materials, and can transform procurement and operational practices. The article describes the architecture of the dashboard, the methods of data acquisition, the validation process, and the practical implications, as well as its opportunities to facilitate sustainable decision-making and stakeholder engagement. The barriers to cost implementation, data quality, and system integration will be discussed, as well as future challenges such as integrating machine learning and blockchain. Carbon tracking, specifically real-time embodied carbon tracking, has been identified as a crucial tool for achieving net-zero targets, ensuring compliance, and facilitating ESG reporting. Not only does the dashboard enhance the visibility of emissions, but it also serves as a strategic lever to advocate for building towards carbon-mindful action, which is applicable across the built environment.

Keywords: *Embodied Carbon, Real-Time Emissions Tracking, Carbon Dashboard, IoT in Sustainability, Life*

Cycle Assessment (LCA)

INTRODUCTION

Carbon reduction has become a significant issue in both politics and business as events like climate change take center stage. However, existing endeavors have prioritized operational carbon emissions, which are generated through heating, cooling, and electrical usage. There is growing interest in embodied carbon, the amount of greenhouse gases associated with mining raw materials, processing components, shipping them overseas, and assembling the result. Embodied emissions have the potential to account for as much as half of a building's lifetime carbon footprint, according to the World Green Building Council, particularly in new constructions. Construction, manufacturing, and logistics industries, in particular, are under growing pressure to measure and, where possible, mitigate these hidden effects far earlier in the lifecycle of a facility or product, even before it reaches the customer.

Traditional lifecycle assessments (LCAs) and end-of-life carbon reporting have their place, but they are too late to consider daily. Design teams have already made final decisions about material choices, supply routes, and construction methods, usually months before the numbers have been added up. Real-time dynamic tracking changes. A carbon dashboard that integrates live IoT sensors, RFID, material passports, and cloud-based enterprise systems can reveal the embodied carbon status of a project at the point when steel is ordered, a truck leaves the factory gate, or a prefabricated module is installed on site. Real-time responses enable project managers to transition to less impactful materials, streamline logistics, or adjust tasks if the carbon curve begins trending counterproductively. In addition to enhancing environmental stewardship, flexibility also provides a competitive boost to businesses, improving the value of ESG credentials, increasing the speed of green-building certifications, and positioning companies to make gains rather than simply paying for clean-up under new carbon-pricing regimes.

This article presents a feasible structure for creating a Carbon Dashboard. It describes why real-time information can be harvested at multiple points in a product or project life cycle, translated into metrics that provide meaning and serve stakeholders through an easy-to-understand interface. Through a presentation of mandatory technologies, analytical engines, and visualization methods, accompanied by an investigation within a pilot deployment in practice, the discussion reveals the dimension of continuous tracking to not only enhance carbon accountability but also support teams in instilling a low-carbon approach to day-to-day practice.

2. Literature Review

2.1 Embodied Carbon: Definition and Relevance

Embodied carbon is what carbon dioxide emissions are associated with: the extraction, processing of the materials, manufacture, transportation, and installation aspects of the materials (1). This contrasts with operational carbon, which covers emissions created by the use of a building or product, such as energy used for lighting, heating, or machinery. Although some operational emissions can be minimized through energy efficiency and renewable energy, embodied emissions are set in stone at the moment of construction or production, so they must be tracked and reduced in an early stage.

Embodied carbon in the building sector can be identified in various structural components, including concrete, steel, glass, and insulation. For example, direct gross emissions of concrete alone have been estimated to contribute approximately 8 percent of global carbon dioxide emissions, primarily due to the production of cement. Embodied emissions can be associated with raw materials, such as plastics, metals, and textiles, which are used in the manufacturing of products. These materials demand carbon-intensive industrial processes. Production costs in the transport sector, such as the production of cars, including batteries for electric vehicles, also possess a high embodied carbon cost. Embodied carbon is receiving increased attention as a target for intervention, particularly in industries where the use of materials is unavoidable, as countries adopt net-zero emission targets.

This growing concern is visually summarized in Figure 1, which illustrates the stages at which embodied carbon accumulates throughout the material life cycle.

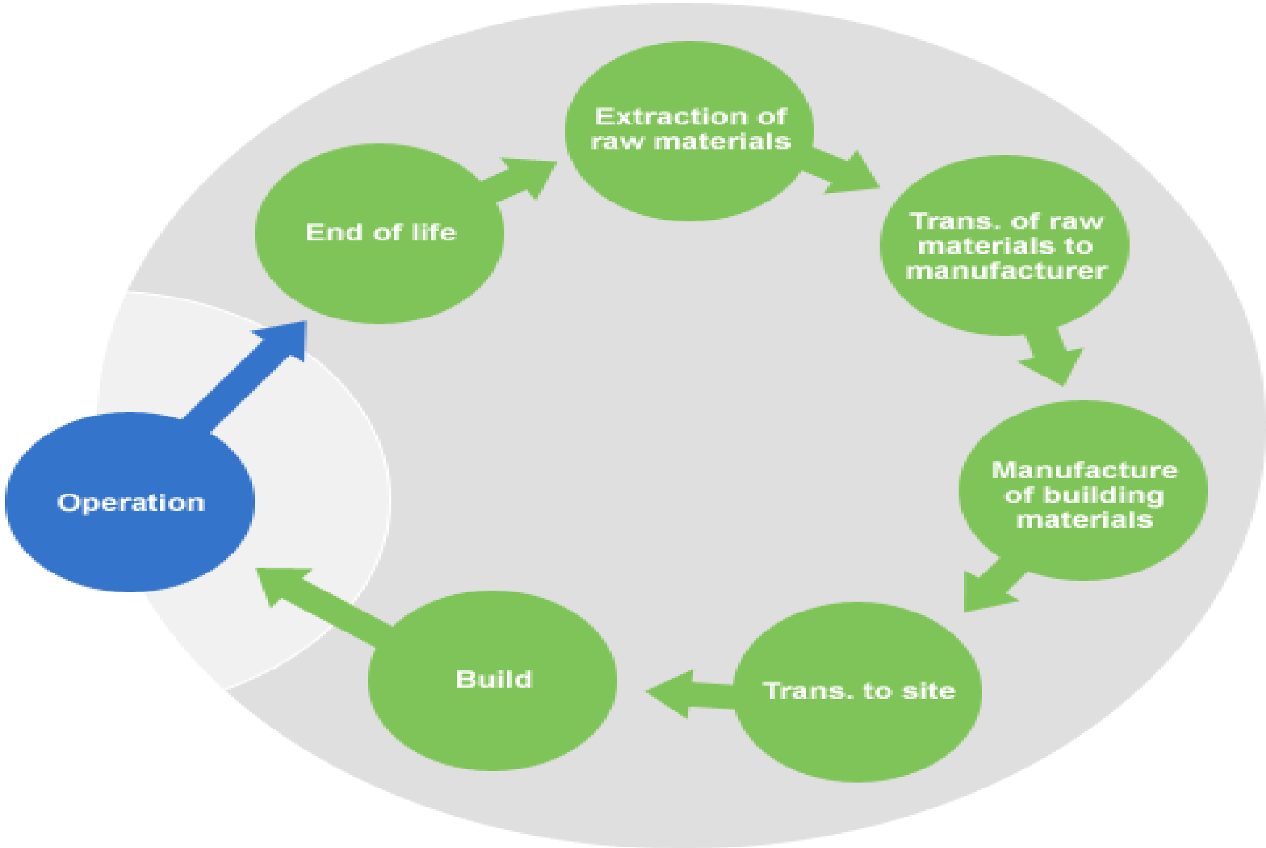

Figure 1: embodied carbon

2.2 Current Tracking Systems and Platforms

Several tools have been developed to estimate and report embodied emissions, and some have gained significant popularity in the construction sector (22). Among the best-known tools is OneClick LCA, a platform that assists architects, engineers, and contractors in conducting life cycle assessments by referencing a comprehensive repository of Environmental Product Declarations (EPDs). OneClick LCA enables users to calculate the embodied carbon mass of various materials and building stages, as well as compare alternative material sourcing strategies. This aligns with the growing industry shift toward data-driven, dual sourcing approaches that improve environmental transparency and reduce supply chain vulnerabilities (15). The second standard tool is the Embodied Carbon in Construction Calculator, also known as EC3. As a free, cloud-based tool, EC3 was developed in the United States and allows users to determine the carbon footprint of building materials before purchasing them. It is based on expanding the EPDs database accepted by a third party. It is beneficial when making procurement decisions aimed at selecting products with lower embodied carbon values.

Although these are practical tools often used, they mainly offer a static assessment. It requires manual work for inputting data, and updated information is not typically automated. Consequently, they may be suitable for use in the design phase and post-construction reporting, but not during live operations. They are also requiring the use of EPDs, which are regionally and supplier-specific in terms of accessibility and quality. These shortcomings leave an opportunity for instruments that can provide real-time, automated information about embodied emissions as they occur.

As illustrated in Table 1, several tools have emerged to help estimate embodied carbon across construction and manufacturing projects. OneClick LCA, a commercial software solution, enables users to conduct life cycle assessments by leveraging a robust Environmental Product Declaration (EPD) database.

Table 1: Comparison of Existing Embodied Carbon Tracking Tools

Tool	Type	Functionality	Strengths	Limitations
OneClick LCA	Commercial Software	Conducts life cycle assessments using EPDs database	Comprehensive material analysis; supports full building lifecycle	Requires manual data input; lacks real-time updates; EPD-dependent
EC3 (Embodied Carbon in Construction Calculator)	Free, Cloud-Based Tool	Estimates embodied carbon of materials before purchase using EPDs	Supports procurement decisions; third-party verified data	Static tool; not integrated into live operations; region/supplier-specific EPDs

2.3 Data Dashboards (Sustainability)

Real-time dashboards are not new to other fields of sustainability, and evidently, the most notable infusion has been in the field of energy and water use (31). For example, building energy management systems often include dashboards that display electricity and HVAC usage in real-time. These dashboards enable facility managers to identify any rise in usage, as well as track any equipment faults and then take swift remedial action. Likewise, intelligent water meters provide real-time information to dashboards that monitor consumption characteristics and leakages, promoting conservation methods. Real-time feedback based on dashboards has been found to influence behavior, thereby enhancing sustainability performance. Real-time dashboards of energy in commercial buildings were associated with energy reductions of up to 15 percent, as they enable users to respond promptly to inefficiencies. Systems of this kind demonstrate the effectiveness of combining sensors, cloud computing, and data visualization in environmental monitoring.

The carbon tracking directly applies to these lessons. Although energy and water dashboards are commonly used to monitor operational impacts, the same framework can be extended to track embodied emissions by leveraging emissions data from construction activities, material deliveries, and digital twins. Carbon tracking is an active but still-developing field within the broader category of real-time dashboard solutions. However, the success of similar real-time data systems in domains such as big data management and performance monitoring—particularly those using scalable NoSQL architectures like MongoDB—demonstrates the feasibility and reliability of this approach (12, 13). By reflecting on these established practices and adapting them to the specific challenges of embodied carbon, tools can be developed that not only visualize emissions but also drive efficiency in material procurement and construction timelines.

3. Theoretical Framework

3.1 Life Cycle Assessment (LCA) Methodology

Life Cycle Assessment (LCA) is a technique used to categorize the environmental impact of a product, procedure, or system throughout its entire life cycle. LCA also provides an organized framework for calculating the level of emissions associated with the production, transportation, installation, maintenance, and disposal of materials in the context of embodied carbon. This is accomplished through the following four steps: goal and scope determination, inventory study, impact determination, and interpretation.

Phase one involves the clear separation of system boundaries and the functional unit (5). As an illustration, aiming to measure the embodied carbon of a residential property over a 50-year perspective, with the scope limited to construction materials and activities. The second stage is the life cycle inventory, which involves gathering information on all inputs and outputs, including the volumes of raw materials used, the amount of fuel consumed, distances covered, and the amount of energy utilized. The third stage is the transformation of this data into environmental impacts (carbon dioxide emissions) using emission factors taken from databases, such as Eco Invent or Inventory of Carbon and Energy (ICE). Lastly, the interpretation phase involves analyzing results and making decisions or recommendations.

LCA depends on material flows and chains of processes. Every process throughout the supply chain also contributes to emissions, including the mining of raw materials, manufacturing, shipping, and use. Even minor modifications of one component of the chain, such as using a vendor located near each other or cultivating recycled steel instead of virgin steel, may have profound implications for the embodied emissions at the end. An effective measurement of such flows through LCA lays the basis for measuring and lowering the effect of carbon in a quantifiable manner.

As illustrated in Figure 2, the LCA process is structured into four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

Figure 2: Life Cycle Assessment Stages

3.2 Integration of IoT and Sensors

The use of Internet of Things (IoT) technologies in carbon tracking enables the transformation of traditional monitoring into real-time, data-driven processes (25). IoT devices are capable of gathering physical data—such as material movement, fuel consumption, and equipment use—and conveying it to centralized systems without human involvement. During embodied emissions tracking, various IoT-based tools are deployed, including RFID tags for material identification, GPS modules for tracking transport distances, and smart meters for logging energy use. This automated data flow mirrors principles used in secure and intelligent systems integration in other sectors, where real-time input is essential for system responsiveness and reliability (19, 27). By adapting these practices, carbon dashboards can provide continuous feedback loops to inform sustainable decisions across the construction lifecycle.

The RFID (Radio Frequency Identification) tags are frequently embedded in construction materials or shipping containers. They can be tracked automatically using these tags as goods move through the supply chain. To illustrate, when a batch of cement leaves the manufacturer, the RFID tag records the shipment details, and the system updates when it reaches the site. GPS modules provide additional information related to location, and transport routes can be tracked. The emissions from logistics operations can be categorized by distance, type of fuel, and vehicle efficiency. Smart meters, which are typically used in factories or construction sites, enable the real-time measurement of power consumption, contributing to the evaluation of carbon emissions from onsite machinery and equipment. All these information sources are integrated by secure networks, commonly with cloud systems, which combine the data towards centralized data storage. This source-to-dashboard data flow consists of at least three layers: first, sensor data must be gathered and pre-processed; then, it is transferred to a storage facility; and subsequently, the emission factor algorithms are applied to the data and visualized on the dashboard. This tiered solution will ensure that information is timely, accurate, and readily available to decision-makers.

3.3 Human-Computer Interaction and Data Visualization

The carbon dashboard may be effective in presenting information, as well as in the accuracy of the data used. Indeed, data visualization is a crucial element in converting intricate data sets into comprehensible and usable information. There are guidelines for good dashboard design, including clarity, simplicity, and relevance. The common elements used include charts, graphs, color-coded indicators, and real-time alerts, which are used to display the user's status of embodied emissions.

The human-computer interaction (HCI) theory suggests that human interaction with dashboards influences the decisions individuals make and the actions they take (14). For example, when a project manager receives a real-time alert indicating that the amount of carbon emitted from a given material shipment exceeds the budgeted amount, they are more likely to ask questions and initiate immediate corrective actions. Behavioral science studies indicate that they boost awareness and prompt more sustainable decisions when feedbacks are presented promptly. A comparison-based dashboard, such as one comparing emissions to those of previous projects or an industry average, can spur improvement.

The combination of the LCA framework, IoT data tracking, and user-focused dashboard design creates a solid theoretical basis for developing real-time embodied carbon monitoring tools. These components collaborate to ensure that carbon information is both technically and practically viable while also providing helpful information to inform improved decisions in design, procurement, and operational activities.

4. System Architecture and Components

4.1 Architecture Overview

The system architecture for a carbon dashboard to track embodied emissions in real time involves data collection, data processing, data storage, and data analysis within a visualization window, all working together through connections between the different components. All these elements combined would ensure that emissions data could be tracked and viewed in an easy-to-read format, allowing for real-time use. A system can be deployed with either cloud-based or on-premises architecture in two main options. A cloud system is built on remote servers and can be used to access and manage information stored on those servers over the Internet. It is scalable, remotely accessible, and can be integrated with third-party services, such as environmental databases or external analysis tools. This model is suitable for mass projects involving multiple stakeholders located in various locations. It is also capable of providing automatic updates and centralized control over datasets and configurations. All large cloud providers, such as Amazon Web Services (AWS), Microsoft Azure, and Google Cloud, provide the infrastructure on which these systems can be hosted (6). In contrast, an on-premise architecture would entail installing the system within the local infrastructure of a firm or construction site. This type of model is favored in environments where data privacy and security are a concern or where connectivity is poor. On-premise systems allow all data and system configurations to be under the organization's control. Yet, these types of setups tend to be more costly to invest in initially and require continual maintenance by IT staff members.

The system architecture typically consists of several interconnected layers, regardless of the specific deployment model used. These include a data acquisition layer, a processing and analytics engine, a database layer, and a front-end visualization interface. Data streams originate from physical IoT sensors or software programs and are ingested into the system, where they are processed into actionable insights and rendered on interactive dashboards. This modular and layered design mirrors the principles of fault-tolerant, event-driven architectures, which ensure continuity and resilience even under high data loads (7). Moreover, the clear separation of responsibilities within the architecture aligns with best practices in microservices development, where context boundaries are deliberately established to enhance scalability, maintainability, and system evolution (8).

As illustrated in Figure 3, the system is designed to offer seamless data flow—from acquisition to end-user interface—ensuring that emissions can be monitored and interpreted as they occur.

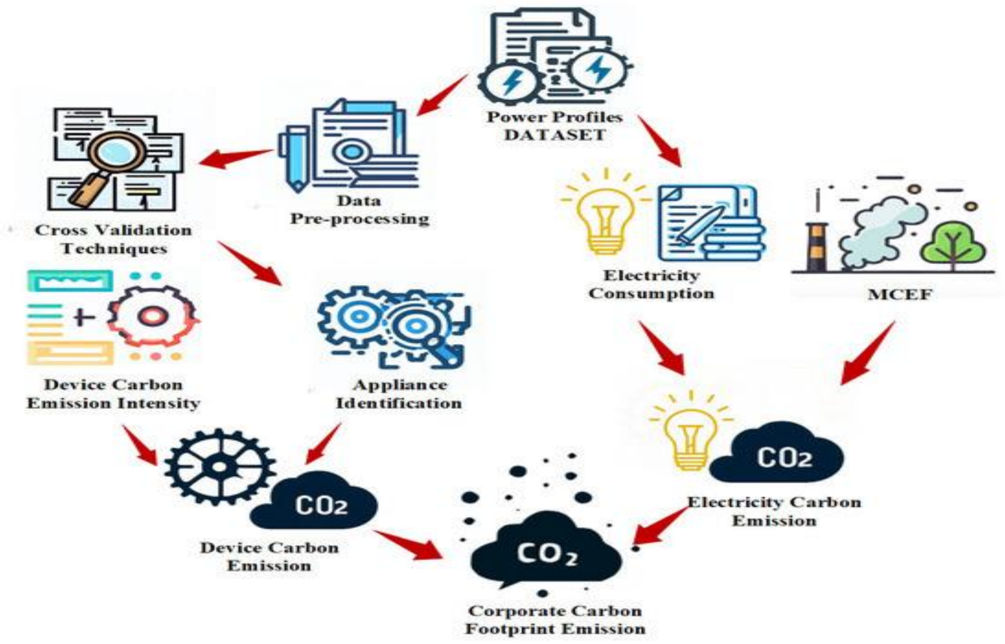

Figure 3: Approach of the real-time ICF calculation.

4.2 Essential Elements

The data acquisition layer forms the base of the system. The latter defined this layer, which is responsible for collecting real-time information about a range of sources that participate in the life cycle of construction materials or a versatile industrial process. Movement, energy consumption, and equipment use are captured through RFID scanners, GPS trackers, and smart meters, which are hardware devices installed. Application programming interfaces (APIs) used to extract data within Building Information Modeling (BIM) systems, digital material passports, procurement logs, and transport management software are all based on software. These inputs are updated continuously to reflect the type of materials, quantity, source, and flow required for computing embodied emissions.

After the data-capturing process is complete, it is relayed to the engine used to calculate emissions. The emission factors of each input are determined using life cycle assessment (LCA) databases, such as Eco invent, GaBi, or the Inventory of Carbon and Energy (ICE), in this engine. To illustrate a similar example, when recording the delivery of one ton of steel, the engine accesses the database information regarding the emissions of that ton, which is then multiplied by the quantity received. Sophisticated systems also utilize artificial intelligence (AI)-based estimators that can fill in missing pieces of unmeasured data, estimate emissions based on historical trends, and correct calculations in real-time when anomalous sensor data is detected or when a material is substituted with another. The last inner structure is the dashboard interface that converts processed information into visual formats for users. This interface is primarily web-based and readable on both desktops and mobile devices. It displays emissions information using graphs, time-series charts, maps, and heat meters. Users can view emissions at varying levels of detail, including shipment-wise, material-wise, by project stage, or over time. Filtering and custom views enable reviewing stakeholders to make informed decisions about specific indicators, compare alternative design scenarios, or identify emissions exceeding limits.

It also features an interactive component on the dashboard, including alerts, reports, and integration capabilities (2). Project managers can even be informed through real-time notifications when emissions surpass specific set requirements. Automated reporting capabilities produce downloadable summaries that can be used to comply with reporting requirements or sustainability reporting standards. Integration capabilities ensure that the dashboard can communicate with other systems within the enterprise, such as procurement platforms, carbon offset registries, or construction management tools. Overview: The system architecture of a real-time carbon dashboard relies on a powerful list of technologies to gather, compute, and display embodied carbon data. Sensor-based inputs, coupled with computation through LCA and its effective visualization, become possible, enabling the dynamic monitoring and proactive mitigation of carbon impact throughout a project's lifecycle.

As shown in Table 2, the Data Acquisition Layer serves as the foundation, collecting live information from various physical and digital sources throughout the material life cycle.

Table 2: Core Components of a Real-Time Carbon Dashboard System

Component	Function	Technologies Used	Key Features
Data Acquisition Layer	Collects real-time data from physical and digital sources across the material life cycle	RFID scanners, GPS trackers, smart meters, APIs (from BIM, procurement logs, digital passports, TMS)	Tracks material type, quantity, source, energy use, and transport activity
Emissions Calculation Engine	Computes embodied emissions based on input data and emission factors	LCA databases (Ecoinvent, GaBi, ICE), AI-based estimators	Real-time calculation, fills missing data, corrects anomalies, handles material substitutions
Dashboard Interface	Visualizes emissions data for users, supports analysis and reporting	Web-based UI, graphs, time-series charts, heatmaps, maps	Interactive views (material-wise, shipment-wise, stage-wise), filtering tools, emissions alerts
Reporting & Integration Module	Enables communication, alerts, and data sharing with other enterprise systems	Automated reports, API integrations, notification systems	Real-time alerts, downloadable summaries, integration with procurement, carbon registries, CM tools

5. METHODOLOGY

5.1 Research Design

The methodology employed in developing the carbon dashboard novelty construct is an exploratory and analytical study approach. This approach is suitable for constructing a new system with little precedence, and the goal is to develop and demonstrate a working prototype. The exploratory component involves identifying user requirements, technical issues, and system needs through a literature search, available tools, and existing industry practices. The analytical part entails planning the dashboard architecture and implementing the solution, followed by testing it in a real-world setting to determine its functionality and performance. This integration helps innovation, as well as practical verification of the dashboard in real-time embodied carbon monitoring.

The process began with gathering requirements through interviews with construction engineers, sustainability consultants, and developers of digital tools. The insights and experiences of these stakeholders were instrumental in shaping the structure of the dashboard and identifying the essential features to incorporate. Once the system architecture was established, the visioning phase focused on designing all tiers of the dashboard—from data acquisition to real-time visualization. The solution was then tested under both simulated and actual construction environments to evaluate its capacity for emissions reduction. This stakeholder-driven and iterative design process aligns with practices in predictive analytics and intelligent system development, where input from domain experts and phased validation are central to creating reliable and impactful tools (26, 20).

5.2 Data sources and acquisition

A real-time carbon tracking system requires reliable and diverse data sources for its success. The research utilized both static and dynamic data to provide a comprehensive coverage of emissions. The most important sources of static data were Environmental Product Declarations (EPDs), material passports, and Building Information Modeling (BIM) outputs in digital form. EPDs produced uniform carbon factors for specific materials, including cement, steel, timber, and insulation. The BIM models provided more precise quantities of materials, dimensions, and dates of material procurement, which helped estimate the baseline emissions of each building component.

Seamless data collection was achieved through the real-time feeds of construction equipment, transport systems, and supply chain platforms. The devices on delivery trucks, which are GPS-enabled, provide distance and route information, enabling the proper calculation of transport emissions. The energy consumption of the equipment and tentative erections was accounted for by smart meters positioned on the construction sites. Procurement systems will present real-time information on material deliveries, contributing to the confirmation of the schedule compliance and the emission loads. Researchers developed APIs to automatically retrieve and update such data, which helps eliminate the need for manual input and lessons.

As illustrated in Figure 4, which aligns with net-zero planning stages, the system integrates both planned carbon targets and live operational data to facilitate continual alignment and course correction.

Figure 4: -net-zero-plan-stage

5.3 Development Model and Utilities

Created with the help of open-source and cloud-connected development tools, the dashboard was designed to be flexible, with compatibility with IoT systems. Node-RED, a visual programming system of choice for real-time, real-time transactions, was used to manage the data flow and logic. It facilitated the speedy prototyping of labor processes that interconnected sensors, APIs, and processing motors. Monitoring time-series data, as well as the visual analytics of the dashboard, were created using G, which is widely used for tracking time-series databases, surveillance, and real-time notifications (3). Grafana also offered customization of dashboards, allowing for the display of data on emissions at various granularities. PostgreSQL database was used as backend storage, and its robustness, scalability, and spatial data capabilities enabled location-based emissions analysis. Python was used for data processing and integration activities, where access to a host of libraries enabled the calculation of emissions, as well as libraries that aid in LCA modeling and conversion activities. To support compatibility with IoT infrastructure, the system was connected to platforms such as Azure IoT Hub and AWS Green grass, allowing for a seamless connection between sensors, cloud storage, and the dashboard environment.

5.4 Testing and Validation

The validation was conducted in two stages to assess the precision and practicality of the carbon dashboard. The initial stage involved benchmarking the system output against the results produced by established life cycle assessment (LCA) tools, such as OneClick LCA and Tally. To ensure accurate comparisons of emission values across selected materials and construction activities, consistent methodologies were applied. Additionally, the observed differences were analyzed to refine emission factors and improve the precision of the underlying algorithm. This validation approach reflects practices in other data-intensive fields—such as telematics in fleet management—where tracking accuracy, system calibration, and real-world testing are crucial for improving operational efficiency and decision-making (23).

The second stage represented a pilot construction project. An existing commercial mid-rise building, currently under construction, was chosen for the project. RFID tags were attached to primary materials, such as rebar and precast concrete, and smart meters monitored energy consumption by machinery. The dashboard was observed over a four-week period. The test demonstrated that the dashboard would be able to monitor material-related emissions in real time and issue an alert when they exceeded preset limits. According to project managers, the tool helped them make more informed decisions, initially during the procurement process and in managing materials on-site. Using this systematic process, the dashboard was able to improve the perception and control of embodied emissions in live construction projects.

As summarized in Table 3, the first stage involved benchmarking the dashboard's emission outputs against conventional life cycle assessment (LCA) tools such as OneClick LCA and Tally

Table 3: Dashboard Testing and Validation Summary

Validation Stage	Description	Tools/Methods Used	Key Outcomes
Stage 1: Benchmarking	Compared dashboard emission outputs with results from conventional LCA tools	OneClick LCA, Tally, consistent emission factor methodology	Identified minor discrepancies; refined emission factors and improved calculation accuracy
Stage 2: Pilot Project	Real-time testing on an active mid-rise construction project	RFID-tagged materials, smart meters on machinery, 4-week trial	Enabled real-time monitoring and alerts; improved procurement and material handling decisions

6. Dashboard Features and Functionalities

6.1 Real-Time Emission Monitoring

Monitoring real-time embodied emissions is a key attribute of the carbon dashboard. This capability is enabled through the continuous collection and analysis of data sourced from construction sites, transportation systems, and procurement channels. Each item used in a project is assigned a unique RFID or barcode identifier, allowing it to be tracked through every phase—from material production to on-site installation. As materials arrive and are used, the associated emissions are automatically recorded and timestamped in the system. This process creates a detailed, product-specific carbon footprint history, categorized by product, location, and activity. Similar to the application of generative models in complex 3D environments, this granular tracking framework allows for high-resolution mapping of real-world systems and supports improved decision-making in dynamic project environments (28). It is also possible to generate timestamped carbon logs within the system, indicating the exact time, quantity, and value of emissions for each material transaction. These logs are crucial in producing accurate records that can be utilized in reporting, auditing, or certification. These logs are capable of providing a stable basis on which emissions performance can be measured with time in large projects.

The dashboard also features a real-time alert solution, which can be used to show emission hotspots to support decision-making throughout project execution. The alerts will be activated when high embodied carbon value materials are delivered or when activities exceed a specified limit, such as those that are energy-intensive. These warnings are displayed on the dashboard and can be reported via email or text messages. The feature enables project managers to take corrective action, such as reviewing procurement decisions, modifying the construction series, or seeking alternatives that utilize low-carbon footprint materials.

6.2 Editable Views and Filters

Due to the complexity of typical construction and manufacturing projects, the dashboard provides flexible filtering and visualization tools. The user can view the data on emissions in a manner of their choice, depending on the project requirements. The system features numerous project profiles, enabling users to switch between sites, phases, or product lines. Projects can be set up with their carbon budgets, targets, and reporting forms. Time steps, such as hourly, daily, and monthly totals, can also filter the emitted information. Such temporal filtering enables users to identify both temporary and long-term trends, making it easy to spot instances of operational inefficiencies or excessive emissions. An example is an increase in emissions in a particular week, which can suggest either a high-carbon delivery site for a material or a high-energy-demanding construction activity that warrants further investigation.

It is also possible to filter by the type of materials in the dashboard (33). Users can segregate emissions associated with concrete, steel, insulation, or other critical materials to determine which products have the most significant environmental impact. A construction company can also examine emissions by phase, such as foundation work, structural framing, or finishing. This type of breakdown helps identify high-impact phases and supports staged sustainability planning. The scalability of such opinions means that they would not only be accessible but also consumable in teams enacting various roles and disciplines.

6.3 Carbon Budget and Forecast

The dashboard incorporates carbon budgeting and forecasting tools that enable users to set and manage emissions targets throughout a project's lifecycle. These features allow users to define carbon budgets for entire projects or specific project segments—such as a building floor or a section of headquarters—based on internal sustainability goals or external environmental benchmarks. The system continuously monitors these budgets in real time, offering intuitive visual cues such as progress bars and dynamic color-coding to signal when predefined carbon thresholds are being approached or exceeded. Much like comparative systems used in fields such as image captioning, where visual and performance indicators guide system evaluation and adjustments, these dashboard features help stakeholders quickly interpret trends and make timely, informed decisions (32).

The system integrates predictive analytics to facilitate progressive planning. The dashboard will be able to project future emissions on the current activities by using past and current trends in the materials used. Forecasted models will consider sequential deliveries, planned stages of construction, and likely options for materials. This helps project teams make informed decisions that prevent carbon overruns before they occur. Comparison tools also enable users to benchmark their performance in emissions against industry norms or past projects. The benchmarks help set expectations and identify areas that need improvement. This dashboard facilitates the continuity of performance-enhancing carbon management by ensuring accountability through the provision of clear and understandable information. In combination, these features can make the carbon dashboard a high-potential real-time control and a powerful planning tool to help teams minimize embodied emissions in a transparent and data-driven manner.

As demonstrated in Figure 5, which outlines strategic navigation through carbon budgets, the dashboard incorporates budgeting and forecasting capabilities to support forward-looking carbon management in construction and manufacturing projects.

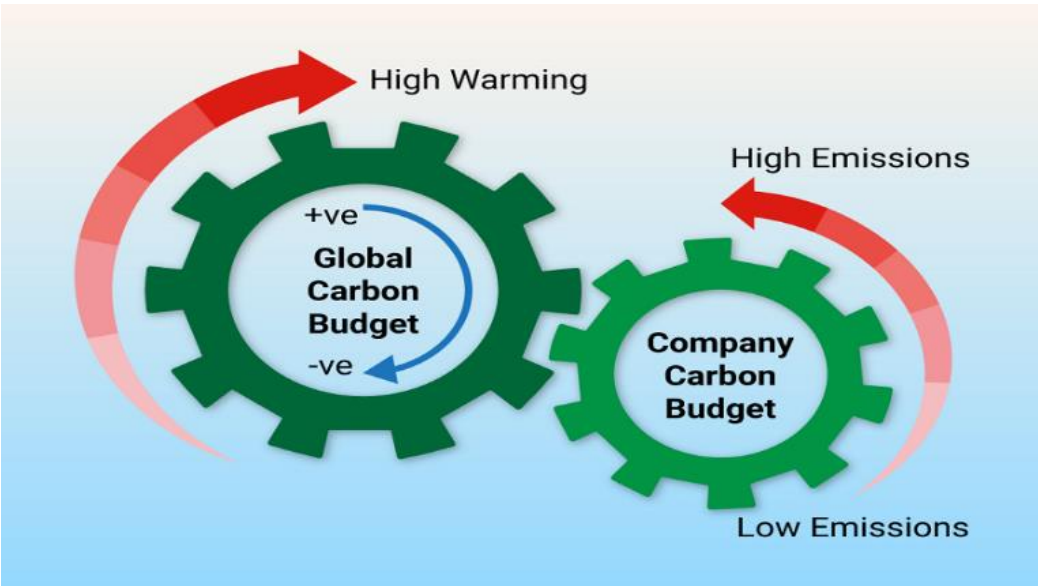

Figure 5: pulse/navigating-carbon-budget-guide-companies-climate

7. Case Study: Pilot Implementation

7.1 Site or Industry Description

To assess the applicability of the carbon dashboard in practice, its pilot implementation was conducted in a mid-sized commercial construction project located on the outskirts of Nairobi, Kenya. The building was a five-story office constructed from traditional building materials, including steel, concrete, glass, and insulation panels. It was chosen due to its active work schedule, varied material consumption, and the presence of multiple contractors, which provided an excellent opportunity to test the dashboard's real-time capabilities. The scope of implementation was limited to the complete structural phase of the project, beginning with groundworks and extending through the completion of the superstructure. The objective was to monitor embodied emissions linked to material deliveries, on-site machinery operations, and installation procedures. Particular emphasis was placed on high-impact construction materials—such as cement, rebar, and steel beams—due to their substantial contribution to the overall carbon footprint. This targeted approach reflects the importance of prioritizing critical emission sources in complex systems, much like ethical frameworks guide AI deployment in sensitive domains such as healthcare and surveillance (29). It also highlights the importance of equipping professionals with the necessary tools and knowledge to effectively manage sustainability goals in an evolving technological landscape (17).

7.2 Process of Implementation

The implementation process was initiated by deploying the required hardware and software on-site. The material shipments also had embedded RFID tags, allowing the material to be automatically identified and tracked once it was delivered to the supplier level. Site supervisors were employed to check incoming materials using handheld scanners. Conversely, a smart meter mechanism was also installed on major construction equipment at the sites, including concrete mixers and cranes, to record real-time energy consumption. On the software front, the carbon dashboard platform would be hosted on a cloud server, making it remotely available and integrating real-time information. The APIs were also linked to the procurement system on the site to accept delivery schedules, and the processing engine on the dashboard had been customized to utilize the emission factors within the ICE database and the locally available Environmental Product Declarations. The interface between the physical devices, cloud storage, and the visualization interface in Grafana was enabled by data pipelines created using Node-RED.

Site managers, procurement officers, and equipment operators underwent training sessions (16). Those sessions focused on the topics of scanning tagged materials, interpreting dashboard metrics, and understanding how to respond to real-time alerts. The training materials were made more straightforward and incorporated into the toolbox meetings daily to help reinforce knowledge. A significant amount of attention was devoted to stakeholder engagement. This was achieved through weekly meetings with project consultants and sustainability auditors to review and gather feedback on improving system performance.

As illustrated in the Figure below, the highest focus (25%) was placed on hardware installation, including RFID tagging and smart meter deployment on construction machinery. This was followed closely by training sessions for site staff (20%) and software integration efforts (20%), which encompassed setting up cloud-hosted dashboards and linking APIs with procurement systems.

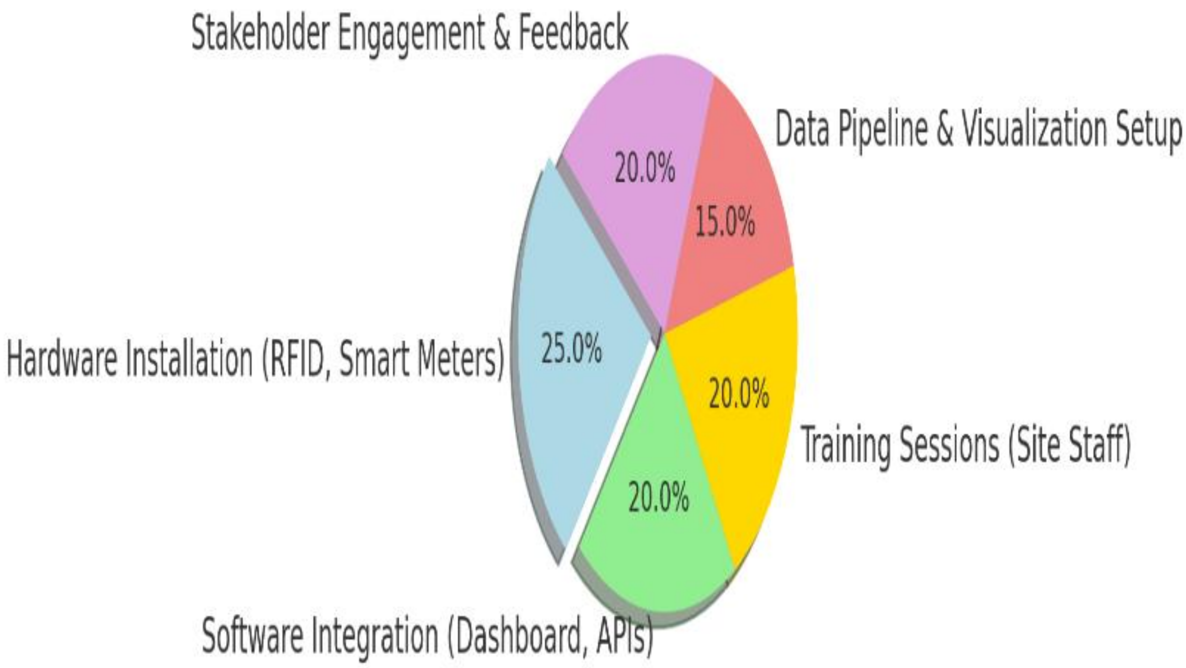

Figure 6: Key Components in the Implementation Process of the Carbon Dashboard

7.3 Results and Observations

The dashboard started to give a good insight into the embodied emissions of the site after two weeks of its implementation. The logs, conducted in real-time, contributed to the percentage of emissions that the project was expected to produce during its duration. An unusual and sharp increase was observed at the time of pouring the foundation slab when the use of readymade concrete and non-stop operation of the machines were considerable. The alert system was one of the most convenient characteristics that were found during the pilot. For example, an entry from a supplier located more than 400 kilometers away was received, indicating a batch of steel rebar despite the existence of a supplier closer to the location. Consequently, the dashboard raised an alert concerning excessive transport emissions. This prompted the procurement team to adjust their buying strategy, resulting in reduced emissions from future deliveries.

The second notable finding was the change in behavior among the site personnel (9). This increases awareness of material choices and the amount of fuel used, as all emissions are visible and tracked weekly in reviews. Operators of machinery, for example, began to reduce idle time after noticing spikes in energy and emissions on their dashboards. Within four weeks, smart meter records demonstrated that the emission rate of equipment-related emissions was 12 percent lower than the base. In brief, the pilot case demonstrated that the carbon dashboard was capable of displaying real-time embodied emissions and aiding decision-making during the active construction process. The quality of the system, in terms of accuracy, ease, and ability to identify inefficiencies, proved very useful to project managers and sustainability personnel. The experiences and lessons learned during the pilot inform the enhancement of the dashboard and the intention to extend it to other construction projects and material-intensive industries.

The figure below illustrates the weekly trend in embodied emissions over the four-week pilot period. Notably, a peak was recorded in Week 1 during the pouring of the foundation slab. The subsequent decline demonstrates the behavioral and strategic adjustments prompted by the dashboard alerts, particularly in terms of fuel consumption and procurement practices.

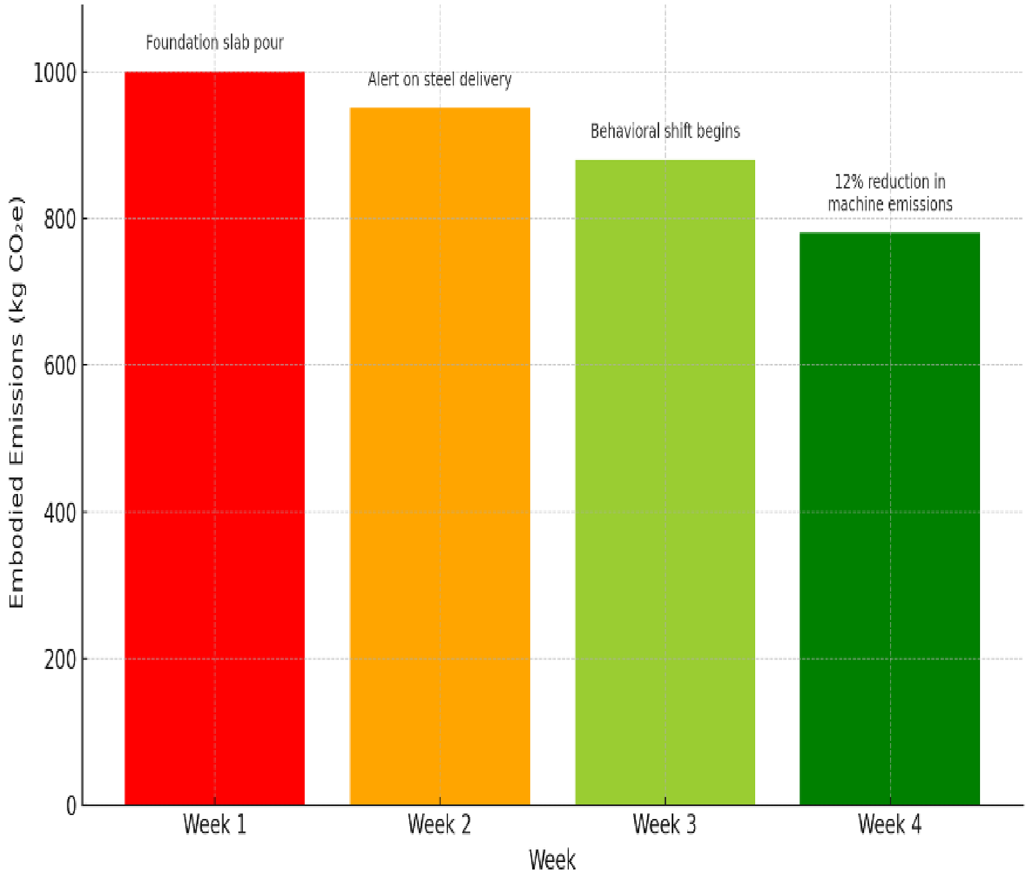

Figure 7: weekly trend in embodied emissions over the four-week pilot period

8. Challenges and Limitations

8.1 Data Quality and Completeness

The quality and completeness of the emission data are also critical challenges in carrying out a real-time carbon dashboard. Embodied carbon calculation relies significantly on accurate, well-defined input data, including the material type, its source, manufacturing cycle, and transportation mode. However, on numerous occasions, the required data can be incomplete, outdated, or lacking coherence. The information summarized in Environmental Product Declarations (EPDs) is helpful, but not all materials and manufacturers have them. The quality of EPDs may also vary, even when they exist, depending on the method and assumptions used to collect them, as well as the degree of validation.

The other concern has been the reliability of the real-time data that sensors are expected to gather (10). Calibration of the sensors is also crucial in accurately recording equipment usage, fuel consumption, and delivery time. Failure to maintain or calibrate the sensors regularly can lead to error-ridden emissions calculations based on data gathered by the sensors. To illustrate, consider a smart meter that misinterprets the energy consumption of a generator, potentially underreporting the site's emissions by a significant amount, which may give an incorrect impression of the site's performance. Additionally, information gaps can arise due to network connections, power interruptions, or device failures, particularly at distant construction sites. Unless rectified by redundancy or data recovery methods, these disturbances can compromise the integrity of the emissions logs and reduce certainty in the dashboard results.

8.2 Connection to the Legacy Systems

There is yet another significant limitation stemming from the fact that numerous problems arise from connecting the dashboard with other tools involved in the enterprise. The combination of multiple software systems in place to procure, manage projects, utilize building information modeling (BIM), or report is already part of many organizations. They are frequently independent systems constructed based on other data structures and formats. This presents some obstacles to the free flow of data, requiring custom integration or the use of middleware to bridge the gaps.

Data silos can hinder the full benefits of real-time carbon tracking. To illustrate, when the procurement system is unable to transmit real-time delivery records to the dashboard, emissions cannot be automatically recorded upon receipt of the material. Similarly, when the project scheduling software and the emission engine cannot communicate with each other, it is necessary to establish a connection for emissions. The action between them developed with sustainability integration in mind. The creation of standardized data formats and API compatibility can be costly and likely requires the assistance of numerous vendors to accomplish. Such integration difficulties can impede implementation and possibly restrict or constrain the capability or scope of the carbon dashboard during its initial implementation.

As depicted in Figure 8, which outlines major IoT application domains, carbon dashboards must operate across a complex technological ecosystem that includes procurement tools, project management software, Building Information Modeling (BIM) systems, enterprise resource planning (ERP) platforms, and various reporting frameworks.

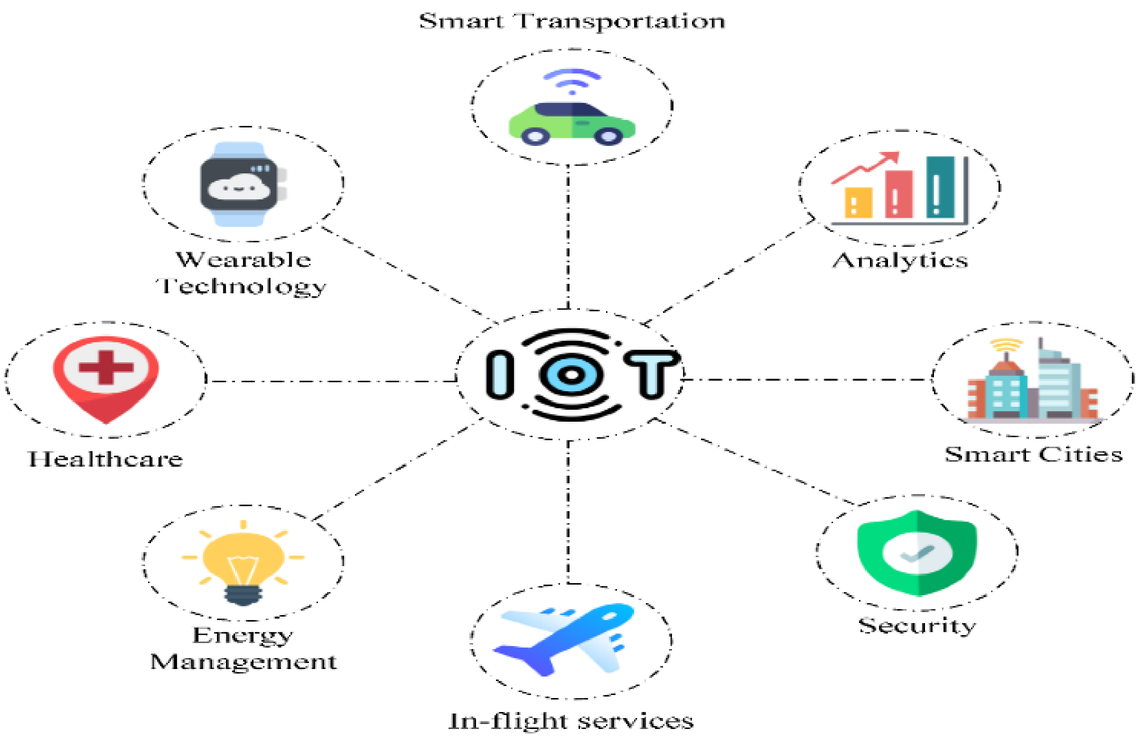

Figure 8: Important IoT application domains.

8.3 Scalability and Cost

Scalability is another area of concern, particularly in the increasing use of dashboards across multiple projects or sectors ([18](#)). Although cloud application types offer flexibility to support extensive amounts of information and large user numbers in their applications, the very implementation of sensors, meters, and scanning devices is nonetheless strenuous and resource-demanding. The price of acquiring, installing, tallying, and maintaining them can prove to be a stumbling block towards their mass use. The problem is particularly topical for small and medium-sized enterprises (SMEs), which may lack the funds and technological expertise to maintain a high-level IoT infrastructure. Many small to medium-sized companies use spreadsheets or manual solutions to track materials, and an upgrade to a data-driven, real-time system may be considered too complicated or costly. The return on investment (RoI) of carbon dashboards is likely to be long-term, with payback depending on avoided carbon prices, certification benefits, or a better market image. These opportunities may not be evident to small-time actors.

The cost of subscriptions to cloud services, dashboard analytics services, and access to trusted carbon databases can also contribute to operational expenses. Smaller companies may not be able to afford implementation without funding or incentives, as well as without the presence of open-source alternatives. Although real-time carbon dashboards may be beneficial, they are also limited in several ways. These issues include data accuracy and availability, integration challenges with existing systems, and financial and technical barriers that can limit scalability. It will be crucial to address these issues, as carbon-tracking technologies should gain more widespread adoption and continue to bring success to those industries in the long term.

9. Benefits and Impacts

9.1 Enhanced Decision-Making

Among the most significant advantages of a real-time carbon dashboard is that it facilitates in-depth decision-making at various stages of a project. Historical forms of embodied carbon measurement would often come with slow lessons well after materials were procured or the foundation stone was laid. Conversely, real-time dashboards provide near real-time data on emissions, allowing mitigation strategies to be instituted promptly to minimize any carbon impact before it is embedded in a project. Project managers, designers, or procurement teams can view the current carbon footprint related to a particular material, process, or supplier. Such visibility encourages more sustainable choices, including the use of lower-carbon options, more efficient material utilization, and planning high-emission work around other high-carbon processes to minimize overlap. By incorporating the emission data into procurement processes, it will be possible to identify high-emission materials early and replace them with more sustainable ones. Design processes enable materials and structures to be iteratively evaluated for their carbon impacts (in advance of construction), facilitating optimization. The consequences are a more effective and knowledgeable decision-making arena, with sustainability issues incorporated into routine operational conditions rather than being relegated to post-hoc reporting obligations (11).

As represented in Figure 9, which illustrates a general decision-making process, the availability of live emissions data allows sustainability to be embedded directly into each step, from design and procurement to scheduling and execution.

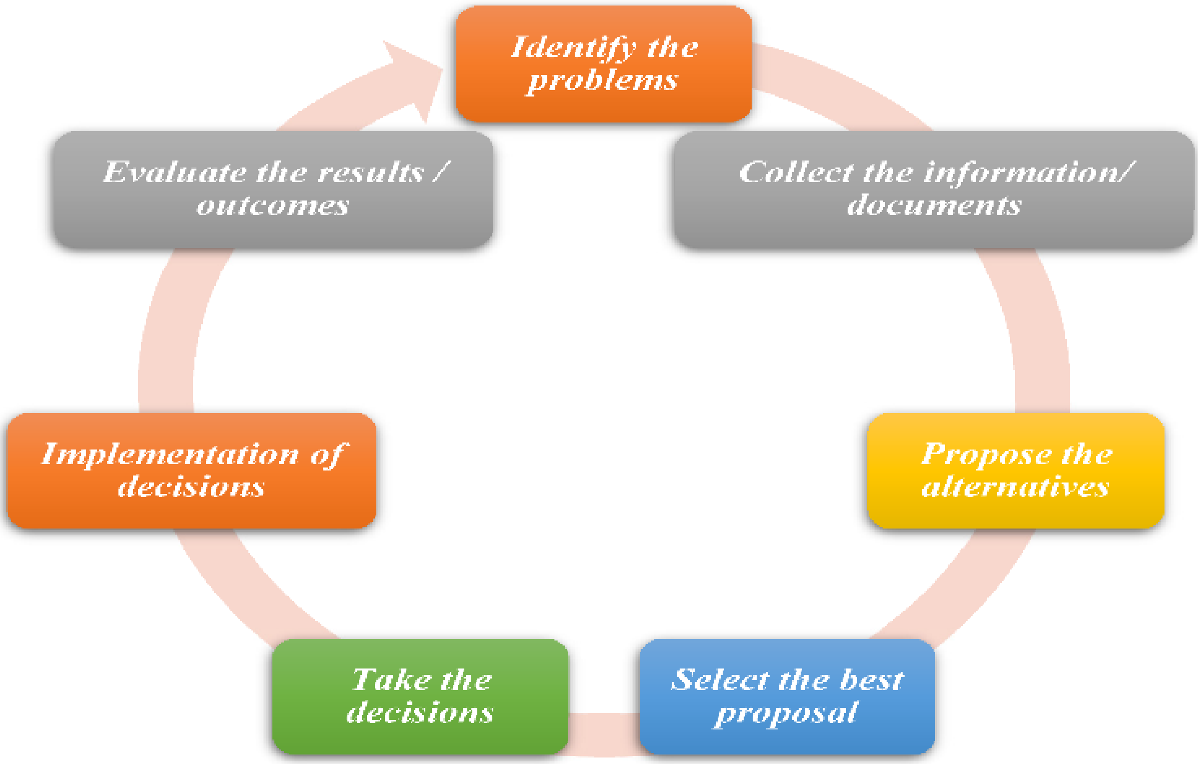

Figure 9: General decision-making process.

9.2 Transparency and Stakeholder Engagement

The use of a carbon dashboard also increases interaction with material stakeholders, such as clients, regulators, investors, and the general public. Enhanced carbon reporting transparency is becoming increasingly required in the current regulatory and market conditions. Real-time dashboards offer a transparent and evidence-based platform for exchanging sustainability performance data. Clients can have real-time visibility into the environmental developments of their projects, which establishes trust and alignment with their corporate sustainability objectives (4). Auditors and regulators also find it helpful to have timestamped sets of data logs to demonstrate whether either the environmental standards or building codes are met. Lenders and investors primarily interested in the ecological, social, and governance (ESG) standards can review the emissions records to assess the sustainability of projects included in their portfolios.

Additionally, dashboards facilitate the documentation required for green building certifications, such as LEED, BREEAM, and EDGE. Such certifications frequently require precise monitoring of emissions, transparent material procedures, and ongoing improvement reports. The dashboard streamlines a lot of this work and minimizes administrative workload, effectively enforcing compliance. When employed, public-facing dashboards are also capable of fostering greater accountability and community trust, especially in infrastructure or publicly known sector projects. Periodically or live reporting of embodied carbon performance can project the image of environmental responsibility and enhance reputational status.

9.3 Net-Zero Contribution

Embodied emissions real-time tracking is an integral part of the bigger trend towards net-zero carbon. As emissions created during the operations of the energy owner decrease due to renewable energy and efficiency gains, the embodied emissions become a bigger percentage of the total lifecycle emissions. They now take up more than 50 percent of the overall footprint in some buildings. This renders embodied carbon one of the major concerns of any genuine endeavor of carbon neutrality. By allowing for the real-time measurement of embodied carbon, project teams can align their emissions trajectory with science-based targets. For example, an increasing number of companies will now pursue targets through the Science Based Targets initiative (SBTi), which requires the monitoring and minimization of both direct and indirect emissions. A carbon dashboard helps convert these top-level objectives into lower-level initiatives that are measurable and quantifiable during the construction or production process.

ESG reporting is also available on the dashboard, enabling consistent and auditable carbon data. This is especially relevant to companies that need to report on carbon performance as part of the Task Force on Climate-related Financial Disclosures (TCFD) or other national environmental regulations. Real-time emissions data enhances the quality of reporting, making it more timely, accurate, and meaningful. Overall, the carbon dashboard offers a range of value-added benefits in terms of decision-making, transparency, compliance, and sustainability strategy. It helps organizations make better decisions by transforming carbon data into actionable intelligence, enabling them to engage stakeholders with confidence and make a valuable contribution toward global decarbonization.

As outlined in Table 4, one of the most significant shifts in recent years is the changing emissions profile of buildings and infrastructure projects. With operational emissions steadily decreasing due to efficiency improvements and clean energy adoption, embodied carbon now accounts for more than 50% of total lifecycle emissions in many new developments

Table 4: Contribution of Real-Time Embodied Carbon Dashboards to Net-Zero Goals

Aspect	Description	Impact
Shift in Emissions Profile	As operational emissions decrease, embodied emissions now account for over 50% of total lifecycle emissions	Elevates the importance of managing embodied carbon for true carbon neutrality
Alignment with Science-Based Targets	Real-time tracking allows alignment with the Science-Based Targets initiative (SBTi) requirements	Enables measurable, real-time control of direct and indirect emissions during construction
Support for ESG and Regulatory Reporting	Dashboard provides consistent, auditable data for frameworks like TCFD and national regulations	Enhances quality and timeliness of sustainability disclosures and improves regulatory compliance
Strategic Value Addition	Transforms carbon data into actionable insights that support smarter decisions and stakeholder engagement	Strengthens sustainability strategies, transparency, and contribution to global decarbonization

10. Future Work and Enhancements

10.1 Machine Learning Integration

The use of machine learning is one of the most promising areas for improving the carbon dashboard in the future (24). Predictive modeling can significantly enhance the dashboard's capacity to anticipate embodied carbon delivery by leveraging past precedents, current information, and project variables. These models are capable of learning the material selections, the distances covered due to transportation, the weather, conditions, and registration schedules to predict future patterns of emissions. For example, if a project frequently purchases steel from a distant source, the system could yield greater transportation emissions and propose nearby options or optimal delivery paths.

Machine learning can be used to detect anomalies together with forecasting. The pattern of emissions is well understood in certain phases of construction or manufacturing. Any electricity operations that involve an abrupt jump or sudden increase in carbon production may be indicative of inaccurate resource tracking, equipment failure, or data manipulation. Such anomalies can be identified with the help of machine learning and marked for subsequent analysis, thereby enhancing data integrity and alerting managers to other operational deficiencies or data quality issues during administration.

As those algorithms develop, they can also supply optimization engines that automatically suggest lower-carbon pathways in procurement, sequencing, or logistics applications, making the dashboard a decision support system rather than a tool for reporting.

10.2 Data Integrity Blockchain

The technology of blockchain can also be beneficial in another field, specifically in ensuring the integrity and traceability of emissions data. Embodied carbon reporting is often questioned, particularly when such reports are used in the context of regulating a company, such as through carbon credits or green finance. Blockchain could provide emissions supplies with a decentralized, immutable way of tracking them, offering a tamper-proof record of data. This ensures that the material supply can be traced to the delivery location and the installation point. The system works by recording every piece of data entered into it, such as the delivery of materials, energy usage, or the purchase of carbon offsets, on a blockchain ledger, ensuring that it is collectively modified retrospectively. This enhances trust among stakeholders and is easily verifiable independently. The application is particularly relevant in carbon offset and credit systems, where transparency and verification play a crucial role in maintaining the credibility of these systems. Moreover, to facilitate the exchange and verification of carbon credits, the use of blockchain within a dashboard setting is to be discussed. An example of this would be a project that has overcommitted its emissions reduction level; the surplus credits may be safely tokenized and either traded or held against future emission journeys. This lends financial and strategic significance to the monitoring of emissions, contributing to increased involvement in the sustainability market.

10.3 Spreading to the Operational Emissions

Although the dashboard is designed to cover embodied carbon, additional modules will be added later to track operational emissions as well. These include electricity emissions, water usage, the heating and cooling system, and the transfer of materials throughout the building's life cycle. Incorporating operational measurements would enable the dashboard to become a comprehensive carbon-monitoring tool that embraces the whole life cycle of a compound or building. Through connections to innovative building systems, energy meters, and transportation management tools, the dashboard can provide a consolidated carbon footprint that encompasses both embodied and operational aspects. This combined method would give a more comprehensive overview of the overall environmental impact and facilitate the implementation of more detailed sustainability plans. It would also be consistent with global systems, such as whole-life carbon assessments, which are hemorrhaging in Europe and elsewhere (30). This growth would enable organizations to track their decisions throughout the design and construction phases as they relate to long-term sustainability performance, thereby bridging the gap between design intent and impact.

As visualized in Figure 10, which sketches a building designed with life-cycle sustainability in mind, this integrated approach captures emissions not only at the construction and procurement stages but also during the building's long-term operation.

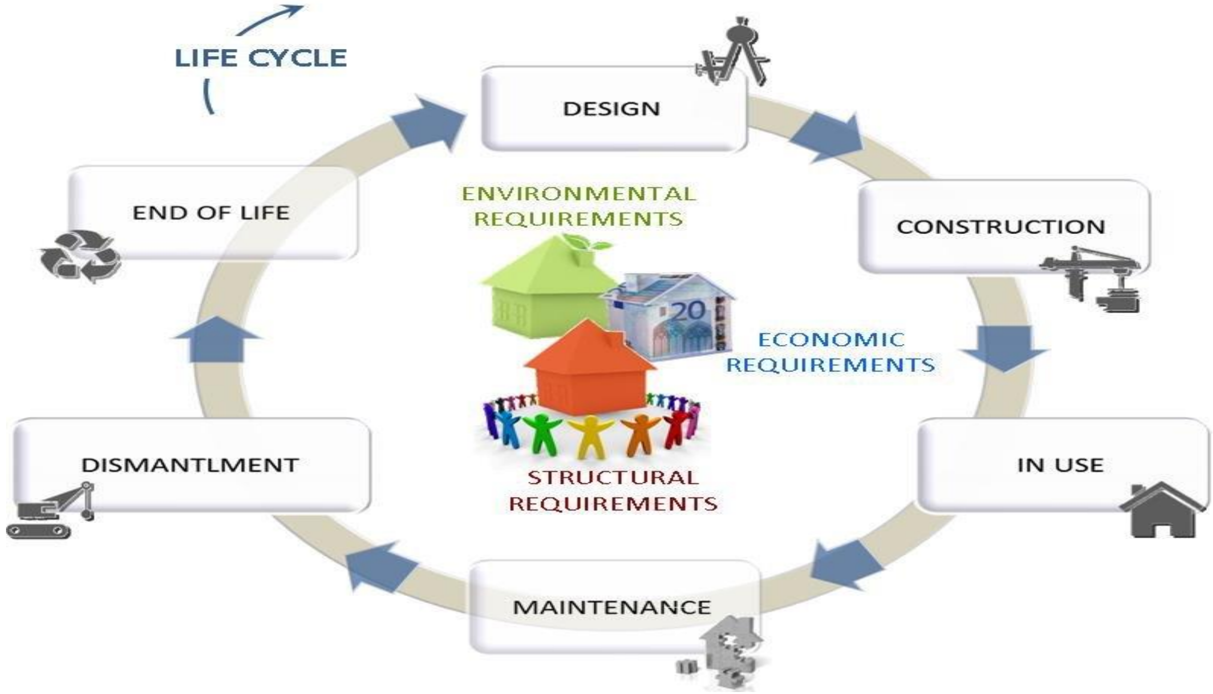

Figure 10: Sketch of building design for life cycle towards an integrated sustainable

11. Recommendations

To maximize the potential of real-time carbon dashboards and encourage their widespread application across various industries, several strategic recommendations can be provided. Such recommendations encompass technological advancements, industry adoption, regulatory considerations, and capacity building. First, there is a need to make additional investments in open-access and standardized emissions databases (34). The accuracy of embodied emissions has a significant impact on the reliability of any real-time carbon tracking system. The government and industry organizations should be involved in funding and standardizing Environmental Product Declarations (EPDs), digital material passports, and life cycle inventory datasets to maintain consistency and interoperability across initiatives, software, and jurisdictions. Second, one should pay more attention to ensuring the interoperability of dashboard developers with available industry software. Compatibility with procurement systems, Building Information Modeling (BIM) models, construction project timelines, and enterprise resource planning (ERP) software will be seamlessly integrated into the carbon dashboard software, enhancing its utilization and usability. Future development should focus on open APIs, as well as modular design and data connectors that can be used on a plug-and-play basis.

Third, policymakers should consider real-time carbon dashboards as tools for transparency and low-carbon innovation. The regulatory framework and policies towards public procurement may be revised to introduce digital emissions tracking as a requirement or an incentive parameter. For example, real-time carbon reporting projects may be prioritized in approval processes, as well as access to green finance or tax credits. Fourth, the carbon dashboard technology should be made more accessible to small and medium-sized enterprises (SMEs). The high cost of initial setup and technical complexities still excludes many. Scalable pricing strategies, shared platforms, and government-funded pilot programs can promote inclusion and accelerate the diffusion of this technology throughout the greater value chain. Fifth, awareness campaigns and training should be undertaken to develop internal capacity among construction professionals, procurement officers, sustainability managers, and data analysts. The best dashboard cannot be effective without users connected to knowledge, enabling them to make informed decisions based on the presented information. Curricula and short courses on real-time carbon management tools should be developed in industry associations, universities, and certification bodies.

Synergy among the private sector, academic institutions, and governmental agencies plays a crucial role in ongoing improvement (21). Collaborative research initiatives, pilot projects, and information-sharing sessions can set the pace of innovation and ensure that real-time carbon dashboards adapt to real-life demands and emerging environmental objectives. Overall, although the technical basis for real-time embodied carbon tracking already exists, there is still much to be done in terms of strategic action regarding policy, technology, finance, and education to realize its full potential. When aligned, carbon dashboards will be essential to mainstreaming carbon accountability and realizing global sustainability goals.

12. CONCLUSION

The carbon dashboard featured in this article represents a significant step forward in sustainability tracking, as it enables real-time monitoring of embodied emissions. This dashboard is different because it offers a dynamic and responsive, data-intensive platform compared to conventional approaches involving static reports and unresponsive feedback. This system provides resilient support for industries such as construction and manufacturing by integrating technologies from the Internet of Things (IoT), Life Cycle Assessment (LCA), and advanced data visualization, offering users a comprehensive solution for measuring embodied carbon.

The dashboard features include timestamped emission logging, automated notifications, custom dashboards, and the ability to build predictive analytics, all of which provide users with the tools they need to react to carbon information throughout the lifecycle of a project. The pilot implementation not only demonstrated the system's technical feasibility but also its practical usefulness. It identified quantifiable changes in emissions awareness, purchase planning, and overall carbon performance, which support the dashboard's potential to influence low-carbon project delivery.

The carbon dashboard has a powerful material application in the specialty areas of policy, industry, and investment, whereas it is not as applicable in technical contributions. It provides policymakers with the transparency and integrity of data they need to sustain regulatory compliance and track performance against emissions caps, serving as the basis for programs such as carbon pricing and trading schemes. It empowers science-based enforcement of policy and performance-related incentives by supporting verifiable real-time reporting modality.

The dashboard enables companies in industrial environments to achieve sustainability standards, mitigate risks, and enhance competitiveness. It offers practical information that can be used to guide material selection, logistics planning, and partnership among contractors, designers, and clients. Due to the growing importance of environmental responsibility as a core component in client expectations and contractual relationships, having a system that promotes the visibility and traceability of carbon information is a strategic benefit. In the context of ESG investors and financial institutions, the dashboard enhances due diligence activities. It provides a reliable source of their emissions data, enabling them to continually evaluate their performance and inform investment decisions in green businesses. Real-time carbon dashboards are not merely a technological advancement; they are a catalyst for change within the system. These tools enhance sustainability beyond a compliance practice by incorporating environmental decision criteria into day-to-day business operations. They enable project teams to act wisely, be more transparent with stakeholders, and play a significant role in achieving joint climate goals. In the future, the direction of embodied carbon management will be closely tied to the launch of more accessible, timely, and actionable data. As technologies continue to be further developed, positive policy frameworks and close stakeholder partnerships are expanded, making the real-time carbon dashboard a common practice in carbon-intensive industries, bringing objectively measurable improvements in the direction of a more sustainable and resilient built environment.

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