An Integrated Carbon Footprint Calculation System Model for Net Zero Emission in the Manufacturing Industry Based on GHG Protocol and DEFRA

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***Abstract*—Manufacturing industries play a critical role in achieving Net Zero emission targets due to their significant contribution to greenhouse gas emissions. However, existing carbon footprint calculation practices often apply the GHG Protocol and emission factor standards independently, resulting in fragmented methodologies and limited decision-support capabilities. This study develops a carbon footprint calculation system model that integrates GHG Protocol emission scope classification with DEFRA emission conversion factors, supported by a decision-support framework for Net Zero emission planning. Using a Design Science Research (DSR) approach, the study produces a conceptual system model that structures activity data, emission scope classification, and standardized carbon calculation logic into a unified framework. The proposed model enables transparent aggregation of emissions across Scope 1, Scope 2, and Scope 3, while the decision-support framework translates calculation results into decision variables, scenario-based analysis, and Net Zero roadmap formulation. The system functions as a decision-support system that assists manufacturing organizations in interpreting carbon footprint results and supports Net Zero emission planning. The findings demonstrate that integrating standardized carbon accounting methodologies within a system-oriented design enhances methodological coherence, traceability, and strategic relevance for sustainability decision-making in the manufacturing sector.**

***Keywords*—Carbon footprint; net zero emission; GHG protocol; DEFRA; decision support system**

I. Introduction

The global commitment to achieving Net Zero emissions has placed carbon footprint management at the core of sustainability initiatives, particularly in the manufacturing industry. Manufacturing activities are widely recognized as major contributors to greenhouse gas (GHG) emissions due to their energy-intensive processes, complex production systems, and extensive supply chain interactions. As regulatory requirements and stakeholder expectations continue to increase [1], manufacturing organizations are under growing pressure to systematically quantify, manage, and reduce their carbon emissions in alignment with long-term Net Zero pathways.

Carbon footprint calculation plays a fundamental role in sustainability management by providing quantitative information on emission levels and sources. In the manufacturing context, carbon footprint data are commonly used to identify emission hotspots, evaluate environmental performance, and support sustainability reporting.

However, prior studies indicate that carbon footprint calculation practices in manufacturing systems often face challenges related to methodological inconsistency [2], fragmented data sources, and limited transparency in calculation logic, which reduce the strategic value of emission data.

To address these challenges, internationally recognized standards have been developed to support carbon accounting. The GHG Protocol has emerged as one of the most widely adopted frameworks for greenhouse gas accounting, providing standardized principles for emission classification and reporting across Scope 1, Scope 2, and Scope 3 emissions. Its widespread adoption has contributed to improved comparability and accountability in organizational emission reporting. Nevertheless, the GHG Protocol does not prescribe specific emission factors or detailed calculation mechanisms [3], leaving organizations to rely on external sources for quantitative emission estimation.

In contrast, the UK Department for Environment, Food and Rural Affairs (DEFRA) provides detailed and regularly updated emission factors that are widely used for carbon footprint calculation across various operational activities, including energy consumption, transportation, materials, and waste. DEFRA-based emission factors are valued for their transparency and standardization, making them suitable for operational-level carbon calculation [4]. However, DEFRA guidelines primarily focus on emission factor provision and do not explicitly address emission scope classification or the strategic use of carbon footprint results for sustainability decision-making.

Despite their complementary roles, existing studies and practical implementations frequently apply the GHG Protocol and DEFRA in isolation rather than within an integrated system model. This separation results in fragmented carbon footprint calculation processes that lack methodological coherence and traceability. Moreover, many carbon footprint information systems developed for the manufacturing sector function primarily as monitoring or reporting tools, offering limited support for translating emission data into actionable strategies. Prior research in sustainability-oriented information systems [5] highlights that such systems often emphasize data visualization while providing insufficient decision-support capabilities for long-term sustainability planning.

Based on the reviewed literature, a clear research gap exists at the intersection of standardized carbon footprint calculation and sustainability-oriented decision support.

There is a lack of integrated system models that combine GHG Protocol-based emission classification with DEFRA-based calculation logic within a transparent and traceable framework. Furthermore, few studies extend carbon footprint calculation beyond monitoring to support scenario-based analysis and strategic Net Zero planning in the manufacturing industry. Addressing this gap requires an integrated approach that bridges standardized carbon accounting with decision-support mechanisms, enabling carbon footprint data to be effectively utilized in the formulation of Net Zero emission strategies.

The novelty of this study lies in the integration of GHG Protocol emission scope classification with DEFRA emission factors within a single, system-oriented carbon footprint calculation model. Unlike existing approaches that apply scope classification and emission factor calculation as separate or sequential activities, this research embeds both elements into a unified system logic that ensures methodological coherence, traceability, and decision readiness. Conceptual validation is conducted using Design Science Research (DSR) principles, emphasizing logical consistency among system components, traceability from activity data to emission outcomes, and alignment with Net Zero emission decision variables.

Although various carbon accounting tools, life cycle assessment (LCA)-based systems, and sustainability information systems have been reported in prior literature, most existing approaches primarily emphasize emission quantification, product-level environmental assessment, or compliance-oriented reporting. LCA-based models typically focus on detailed life cycle impact analysis and require extensive data collection, which limits their suitability for continuous operational monitoring and strategic decision making in manufacturing environments. Similarly, many carbon footprint calculators operate as standalone tools with limited transparency, traceability, and integration with organizational decision-support processes. In contrast, the proposed system model advances existing approaches by embedding GHG Protocol–based emission scope classification, standardized DEFRA-based calculation logic, and decision-support mechanisms within a unified system-oriented framework. This integration enables methodological coherence, traceable data flow from activities to emission outcomes, and structured decision readiness, thereby supporting both operational carbon monitoring and strategic Net Zero planning in manufacturing organizations.

In response to this gap, this study proposes the development of an integrated carbon footprint calculation system model combined with a decision-support framework for Net Zero emission strategies in the manufacturing industry. The proposed approach integrates the GHG Protocol for emission classification and reporting with DEFRA-based emission factors for standardized carbon calculation. By extending carbon footprint calculation toward scenario-based analysis and Net Zero roadmap formulation, this study aims to enhance the strategic relevance of carbon footprint systems and contribute to the advancement of sustainability-oriented information systems in the manufacturing context.

II. Literature Review

A. Carbon Footprint Accounting in Manufacturing

Carbon footprint accounting has become a central focus in sustainability research due to the significant contribution of the manufacturing sector to global greenhouse gas emissions [6]. Manufacturing activities involve energy-intensive processes, diverse material inputs, and complex supply chains, which generate emissions across multiple operational stages. Previous studies [7] emphasize that accurate carbon footprint calculation is essential for identifying emission hotspots, supporting environmental disclosure, and informing emission reduction initiatives in industrial contexts.

Despite its importance, carbon footprint accounting in manufacturing remains methodologically challenging. Many manufacturing organizations adopt heterogeneous calculation approaches that rely on fragmented data sources and inconsistent assumptions [2], Prior research reports that carbon accounting practices often prioritize reporting compliance over methodological rigor and strategic integration. As a result, carbon footprint data are frequently treated as static indicators rather than dynamic inputs for sustainability decision-making.

B. Emission Accounting Standards (GHG Protocol and DEFRA)

International emission accounting standards play a critical role in structuring carbon footprint calculation practices. The GHG Protocol is widely recognized as a global framework for greenhouse gas accounting, providing standardized principles for categorizing emissions into Scope 1, Scope 2, and Scope 3 [8]. This classification framework enhances comparability and transparency in organizational carbon reporting and has been extensively adopted across manufacturing industries.

However, the GHG Protocol primarily focuses on emission classification and reporting principles and does not prescribe detailed emission factors or quantitative calculation methods [4]. To address this limitation, organizations often rely on external emission factor databases. Among these, the UK Government GHG Conversion Factors for Company Reporting, developed by DEFRA, are widely used for operational-level carbon footprint calculation. DEFRA provides standardized and transparent emission factors for various activity categories, including energy consumption, transportation, materials, and waste [4]. Nevertheless, DEFRA guidelines [9] emphasize emission factor provision and methodological assumptions rather than emission scope classification or the strategic application of carbon footprint results.

C. Sustainability Oriented Information Systems

The role of information systems in supporting sustainability initiatives has received increasing attention in recent years. Sustainability-oriented information systems are designed to facilitate the collection, processing, and dissemination of environmental performance data across organizational functions. In manufacturing contexts [10], such systems are often implemented to support emission monitoring, regulatory reporting, and performance tracking.

Recent studies suggest that sustainability-oriented information systems have primarily evolved as operational tools rather than strategic systems. Many implementations focus on data aggregation and visualization through dashboards and reporting interfaces, with limited emphasis on analytical integration or cross-functional decision support [5]. This operational orientation limits the ability of information systems to support long-term sustainability transformation, particularly in complex industrial environments where emission sources span multiple scopes and organizational boundaries.

D. Decision Support Gap in Carbon Footprint Management

Decision support is increasingly recognized as a critical requirement for effective sustainability management [11]. While carbon footprint data provide valuable insights into emission levels and sources, prior research indicates that such data are rarely embedded within structured decision-support frameworks. Instead, carbon footprint systems often stop at the level of monitoring and reporting, offering limited guidance for evaluating mitigation options or prioritizing emission reduction initiatives.

This gap is particularly evident in manufacturing contexts, where emission reduction decisions involve trade-offs between cost, operational feasibility, and environmental impact. Studies on sustainability decision-support systems highlight the need for analytical frameworks that integrate environmental data with scenario analysis and strategic planning [12]. Without such integration, carbon footprint initiatives risk remaining compliance-driven activities that fail to support meaningful emission reduction outcomes.

E. Net Zero Emission Strategies and System Oriented Approaches

Net Zero emission has emerged as a central objective in global climate mitigation strategies, with manufacturing industries identified as key contributors to achieving long-term decarbonization targets [13], [14]. Net Zero strategies emphasize not only the measurement of emissions but also the systematic reduction and balancing of residual emissions through coordinated technological, operational, and organizational interventions [1], [15]. These integrated approaches highlight the need for structured frameworks that support informed decision-making and long-term sustainability planning within manufacturing organizations.

Recent research underscores that achieving Net Zero emissions requires system-oriented approaches that integrate standardized emission calculation, performance evaluation, and decision-making within a unified framework [15]. However, existing studies in manufacturing contexts have largely emphasized emission quantification and reporting compliance, often addressing GHG scope classification and strategic decision support in isolation [2]. As a result, carbon footprint initiatives tend to remain fragmented and operationally focused, limiting their strategic impact and traceability across organizational boundaries [5]. This gap highlights the need for system models that explicitly connect standardized carbon footprint calculation, scope-based emission classification, and decision-support mechanisms to support Net Zero planning in manufacturing contexts.

III. Research Methodology

This study adopts a Design Science Research (DSR) methodology to develop a conceptual carbon footprint calculation system model that supports Net Zero emission strategies in the manufacturing industry. DSR is particularly suitable for this study because it focuses on the design and development of problem-solving artefacts, such as conceptual models and system frameworks, rather than hypothesis testing. In sustainability-oriented information systems research [16] DSR has been widely used to translate fragmented standards and practices into structured system artefacts that can guide organizational decision-making.

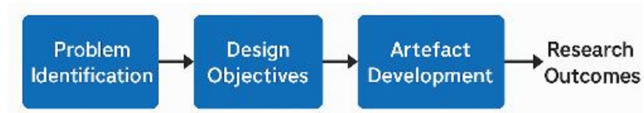

Fig. 1. Design science research stage.

To operationalize the DSR approach, this study follows a structured and sequential research framework as illustrated in Fig. 1. The framework consists of five interconnected stages: problem identification, design objectives formulation, artefact development, conceptual validation, and research outcomes. This structure is consistent with contemporary DSR practices, where the research contribution is embodied in a validated artefact rather than a fully implemented software system [17]. The use of a staged DSR framework ensures methodological rigor, traceability, and alignment between the research problem and the proposed system model.

A. Research Design (Problem Identification and Design Objectives)

The research design corresponds to the problem identification and design objectives formulation stages of the DSR framework. At this stage, the study examines existing challenges in carbon footprint calculation practices within the manufacturing industry, particularly the fragmented use of emission accounting standards and the limited integration of carbon data into sustainability-oriented decision support. These challenges are identified through a focused review of recent literature and international reporting practices.

Based on the identified problems, the design objectives are formulated to guide the development of a conceptual system model that integrates emission scope classification and standardized carbon calculation mechanisms. Consistent with DSR principles, the design objectives define what the proposed artefact should achieve rather than prescribing how it should be technically implemented.

B. Data Sources and Methodological Standards (Input to Artefact Design)

This subsection supports the artefact development preparation stage of the DSR process by defining the methodological foundations used in the system model. Emission classification in the proposed model is structured according to the GHG Protocol, which categorizes greenhouse gas emissions into Scope 1, Scope 2, and Scope 3. This classification framework provides a standardized basis for organizing emission sources and is widely recognized in manufacturing sustainability practices.

For quantitative emission estimation, the study adopts emission factors derived from the UK Government GHG Conversion Factors for Company Reporting [4]. The DEFRA methodology is selected because it offers transparent, regularly updated, and activity-based emission factors that are suitable for operational-level carbon footprint calculation. Within the DSR framework, these standards function as design knowledge inputs, ensuring that the developed artefact is grounded in authoritative and reproducible methodologies.

C. System Modeling Approach (Artefact Development)

The artefact development stage of the DSR framework is realized through a conceptual system modeling approach. The proposed artefact is a carbon footprint calculation system model that represents the logical structure and functional relationships among key system components, including activity data inputs, emission scope classification, emission factor mapping, carbon footprint calculation, and decision-support outputs.

Conceptual system modeling is widely used in DSR to represent complex systems at an abstract level, enabling clarity of logic and facilitating future implementation. In this study, activity data are systematically mapped to emission scopes defined by the GHG Protocol and linked to DEFRA-based emission factors. This integration constitutes the core design contribution of the artefact and reflects the artefact development stage depicted in Fig. 1.

The appropriateness of developing a conceptual system model as the primary DSR artefact is supported by [17], which demonstrates that DSR artefacts may take the form of conceptual- or prototype-level systems when the research objective is methodological integration rather than full software deployment.

D. Research Procedure and Conceptual Validation

This subsection corresponds to the conceptual validation stage of the DSR framework. After the artefact is developed, the proposed system model undergoes analytical and conceptual validation to assess its logical consistency, methodological soundness, and alignment with the selected emission accounting standards. The validation process focuses on evaluating whether the integration of emission scope classification and standardized emission factors is coherent, traceable, and capable of supporting sustainability-oriented decision-making.

IV. Results and Discussion

The overall structure of the proposed carbon footprint calculation system model and its integration with the decision-support framework are illustrated in Fig. 2, which provides an overview of the system logic and information flow across activity data, emission calculation, and decision-support components.

This section presents the results of the Design Science Research in the form of a conceptual carbon footprint calculation system model and a supporting decision-support framework for Net Zero emission strategies in the manufacturing industry. The proposed artefacts are derived from the integration of the GHG Protocol and DEFRA standards and are discussed to highlight their methodological contributions, transparency, and relevance for sustainability-oriented decision-making.

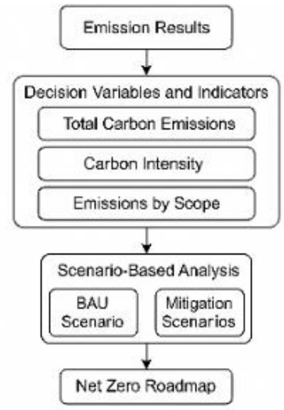

Fig. 2. Decision support framework diagram.

A. Carbon Footprint Calculation System Model

This subsection presents the primary result of the study in the form of a conceptual carbon footprint calculation system model for the manufacturing industry. The proposed model represents the main artefact produced through the Design Science Research process and serves as a structured framework for integrating standardized emission classification and calculation mechanisms. Rather than focusing on technical implementation, the model emphasizes methodological coherence and transparency to support Net Zero emission strategies.

The conceptual system model follows a logical input–process–output structure. The input component consists of activity data representing key manufacturing operations, including energy consumption, transportation, material usage, and waste generation. These data form the basis for carbon footprint calculation and are assumed to be obtained from organizational operational records.

The process component comprises three interrelated functions. First, activity data are classified into emission scopes (Scope 1, Scope 2, and Scope 3) in accordance with the GHG Protocol. Second, each classified activity is linked to the appropriate emission factor derived from the DEFRA conversion factors. Third, carbon emissions are calculated by applying standardized calculation logic to the activity data and emission factors. This structured process ensures consistency and traceability throughout the calculation workflow.

The output component generates structured carbon footprint results, including total emissions, emissions by scope, and emissions by activity category. From a results perspective, the model demonstrates how standardized emission accounting practices can be systematically embedded within a unified system framework. From a discussion perspective, the proposed model addresses a key limitation in existing practices by explicitly linking emission scope classification with quantitative emission calculation, thereby enhancing transparency and decision readiness in manufacturing carbon management.

B. GHG Scope Classification Logic

This subsection presents the emission scope classification logic embedded in the proposed carbon footprint calculation system model. The classification logic represents an important result of the study, as it operationalizes the GHG Protocol framework within a structured system workflow rather than treating scope classification as a separate reporting activity.

Within the proposed model, manufacturing activities are systematically mapped into Scope 1, Scope 2, and Scope 3 emissions based on emission sources and organizational boundaries. This mapping is performed prior to quantitative calculation to ensure that emission boundaries are explicitly defined and consistently applied. From a results perspective, embedding scope classification at an early stage of the system workflow reduces ambiguity and supports structured aggregation of emission results. From a discussion perspective, this approach enhances transparency and traceability by clearly linking operational activities to their respective emission scopes.

To illustrate how the scope classification logic is applied within the system model, Table I summarizes the conceptual mapping between typical manufacturing activities and GHG emission scopes.

TABLE I. MAPPING OF MANUFACTURING ACTIVITIES TO GHG EMISSION SCOPES

Activity Category	GHG Emission Scope		
	Example Activity	*GHG Scope*	*Description*
Fuel combustion	Diesel usage in boilers or generators	Scope 1	Direct emissions from on-site fuel combustion
Company-owned transportation	Internal logistics vehicles	Scope 1	Direct emissions from company-controlled vehicles
Electricity	Electricity consumption for production	Scope 2	Indirect emissions from purchased energy
Steam/cooling	External energy supply for processes	Scope 2	Indirect emissions from off-site energy generation
Raw material procurement	Purchased materials from suppliers	Scope 3	Upstream emissions in the supply chain
Third-party transportation	Outsourced logistics services	Scope 3	Indirect emissions from external transport providers
Waste treatment	Disposal or recycling by third parties	Scope 3	Downstream emissions from waste management

[a] Sample of a Table GHG Emission Scope

C. Carbon Calculation Logic

This subsection presents the carbon footprint calculation logic embedded in the proposed system model. The calculation logic constitutes a key quantitative result of the study, as it operationalizes standardized activity data and emission factors into measurable carbon footprint outcomes. By integrating emission factors derived from DEFRA within a structured calculation workflow, the proposed logic ensures consistency, reproducibility, and methodological transparency.

In the proposed model, carbon emissions for each manufacturing activity are calculated using standardized activity data and corresponding emission factors. This calculation approach follows the fundamental principle defined in the UK Government GHG Conversion Factors for Company Reporting, in which greenhouse gas emissions are estimated by multiplying activity data by the relevant emission conversion factors. The basic calculation logic is expressed as follows:

$$CFi = ADi \times EFi \quad (1)$$

where, CFi denotes the carbon footprint of activity i (kg CO_2e), ADi represents the quantified activity data associated with activity i, and EFi refers to the emission factor obtained from the DEFRA conversion factors.

To derive the total carbon footprint across manufacturing operations, emissions are aggregated across all activities and emission scopes:

$$CFtotal = \sum_{s=1}^{3} \sum_{i \in s} (ADi \times EFi) \quad (2)$$

From a results perspective, this calculation logic enables the system to generate both activity-level and scope-level emission results in a structured and traceable manner. From a discussion perspective, the explicit aggregation across emission scopes extends the basic DEFRA calculation approach by aligning it with the GHG Protocol's scope-based reporting structure, thereby supporting more comprehensive carbon footprint analysis and Net Zero emission planning.

D. Handling Supplier Heterogeneity and Scope 3 Emission Uncertainty

Scope 3 emissions are inherently subject to supplier heterogeneity, data uncertainty, and estimation errors due to variations in supplier practices, data availability, and emission reporting quality. In the proposed system model, supplier heterogeneity is conceptually addressed through activity categorization and emission factor mapping, allowing emissions from different supplier types and logistics providers to be represented using differentiated activity data and DEFRA emission factors.

Data uncertainty arises primarily from estimated activity data and the use of secondary emission factors. To address this issue, the system model supports tiered data quality levels, ranging from primary supplier data to industry-average estimates. Estimation errors are acknowledged as an inherent limitation of Scope 3 accounting and are managed through transparent documentation of assumptions and calculation logic. Although dynamic supplier-specific emission factors are not implemented in this study, the proposed system model is designed to accommodate future updates as supplier data maturity improves.

E. Uncertainty Quantification and Mitigation Strategies

Uncertainty in carbon footprint calculation primarily arises from variability in activity data and assumptions associated with Scope 3 emissions, rather than from the static representation of emission factors. In the proposed model, updates to emission factors are managed through system-level configuration to accommodate evolving standards, while uncertainty is conceptually addressed through data quality classification and scenario-based analysis. These mechanisms enable the identification of data sources with higher estimation risk and support the evaluation of alternative assumptions within a consistent system structure.

Mitigation strategies embedded in the model include the use of conservative emission factors, explicit documentation of assumptions, periodic data validation, and sensitivity analysis across alternative scenarios. These design-level measures aim to reduce the potential impact of data uncertainty on carbon footprint results and enhance the transparency of emission estimates. Although quantitative uncertainty modeling is beyond the scope of this study, the proposed system architecture allows such methods to be incorporated in future extensions to further improve the robustness and reliability of decision-support outputs.

F. Decision Support Framework for Net Zero Emission

This subsection presents the proposed decision-support framework as the second core result of the study. Building upon the carbon footprint calculation system model, the framework translates quantified emission results into actionable insights for Net Zero emission planning in the manufacturing industry. Rather than introducing complex optimization algorithms, the framework emphasizes a logical and transparent flow that links emission data to strategic decision-making.

Unlike conventional carbon footprint systems that primarily provide descriptive dashboards or static emission reports, the proposed decision-support framework enables structured scenario-based evaluation and strategic planning. By organizing emission results into scope-based indicators, carbon intensity metrics, and alternative mitigation scenarios, the framework supports systematic trade-off analysis between emission reduction potential, operational feasibility, and strategic targets. Furthermore, the explicit formulation of baseline, target, and reduction pathways enables transparent Net Zero roadmap development, allowing decision-makers to compare alternative emission trajectories within a consistent and traceable framework. This integration extends carbon footprint systems beyond monitoring and reporting toward analytical and strategic sustainability decision support.

The framework operates by structuring emission results into decision-relevant indicators, evaluating alternative scenarios, and supporting the formulation of a Net Zero roadmap. By embedding these elements within a unified framework, the proposed approach extends the role of carbon footprint systems from monitoring and reporting toward strategic sustainability support.

1) Decision variables and indicators: The framework employs a limited set of core decision variables derived from the carbon footprint calculation results. These variables include total carbon emissions, carbon intensity, and emissions by scope (Scope 1–Scope 3). Total emissions provide a baseline overview of organizational carbon performance, while carbon intensity supports efficiency assessment independent of production scale. Scope-based indicators enable the identification of dominant emission sources and support targeted mitigation planning.

2) Scenario-Based analysis framework: The framework incorporates scenario-based analysis to evaluate alternative emission trajectories. Two primary scenarios are considered: business-as-usual (BAU) and mitigation scenarios. The BAU scenario represents current operational practices, whereas mitigation scenarios reflect potential emission reduction strategies. Scenario comparison is conducted using consistent calculation logic, enabling transparent assessment of the potential impact of mitigation actions.

3) Net zero roadmap formulation: Based on the scenario analysis results, the framework supports the formulation of a Net Zero roadmap comprising three elements: baseline, target, and reduction pathway. The baseline is defined using BAU emission results, the target reflects the intended Net Zero objective, and the reduction pathway outlines a structured transition informed by mitigation scenarios. This approach provides strategic guidance without prescribing specific technologies or implementation timelines.

Compared to conventional carbon footprint calculators that primarily focus on emission quantification or reporting compliance, as discussed in prior carbon accounting studies [2], the proposed model integrates emission scope classification, standardized calculation, and decision-support logic within a single framework. Previous studies on manufacturing sustainability systems [5] have highlighted limitations related to traceability and strategic decision support, which are explicitly addressed through the integrated design of the proposed model.

G. Illustrative Manufacturing Case Scenario

Although this study does not include a full-scale system implementation, an illustrative manufacturing case scenario is developed based on observations conducted in a real manufacturing environment. The scenario is informed by operational practices observed at textile manufacturing company, and represents a mid-sized manufacturing facility for abstraction and confidentiality purposes.

The scenario incorporates representative operational data related to energy consumption, internal logistics, raw material procurement, and waste treatment, which are commonly observed in textile and manufacturing industries. Using representative activity data and DEFRA emission factors, the proposed system model generates scope-based emission results that illustrate the aggregation logic and decision-support outputs.

While this observation-based scenario does not constitute a full empirical case study or quantitative system evaluation, it demonstrates the practical applicability and feasibility of the proposed model in a real-world manufacturing context. The results illustrate how carbon footprint calculations can support scope-based emission analysis and inform Net Zero emission planning at the organizational level.

H. System Architecture Overview

This subsection presents a high-level overview of the system architecture that supports the proposed carbon footprint calculation system model and decision-support framework. The architecture is intended to demonstrate the feasibility and logical organization of the system components, rather than to provide implementation level details.

1) High-level system architecture: Fig. 3 illustrates the high-level system architecture designed to support carbon footprint calculation and Net Zero decision support in the manufacturing industry. The architecture positions the carbon calculation engine as the central component, reflecting the core focus of this study on standardized emission calculation and analytical integration.

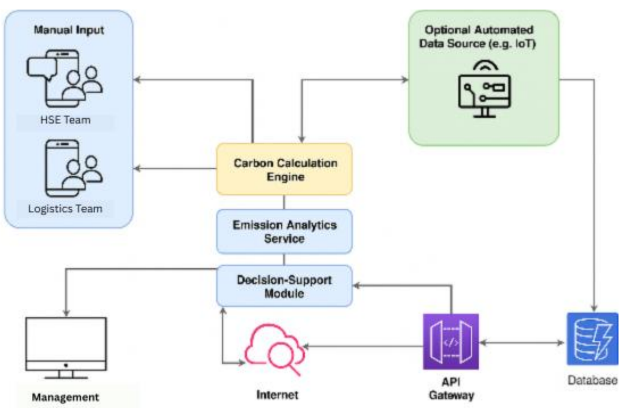

Fig. 3. System architecture with carbon engine.

As shown in Fig. 3, the system receives activity data from two primary sources: manual input and optional automated data sources. Manual input is provided by organizational units such as the HSE and logistics teams, representing common data collection practices in manufacturing environments. In addition, automated data acquisition technologies, such as IoT platforms, may be integrated as optional data sources to enhance data availability. These automated sources are treated as complementary inputs and do not constitute the core contribution of the proposed system.

2) Main functional modules: The proposed architecture consists of two main functional modules. The carbon calculation engine is responsible for processing activity data, classifying emissions by scope, applying DEFRA emission factors, and aggregating emission results. This module operationalizes the integration of GHG Protocol and DEFRA standards within a unified calculation workflow.

The decision-support module utilizes the calculated emission outputs to generate decision-relevant indicators, support scenario-based analysis, and inform Net Zero roadmap formulation. By separating calculation and decision-support functionalities, the system ensures that analytical logic and strategic interpretation remain clearly distinguished, enhancing transparency and maintainability.

I. Limitations of the Study

This study has several limitations. First, the proposed system model is conceptual and has not been implemented as a software prototype or validated using real operational data. Second, the treatment of Scope 3 emissions relies on generalized emission factors and does not fully capture supplier-specific variability or dynamic process changes. Third, uncertainty quantification is addressed conceptually rather than through statistical modeling. These limitations reflect the study's focus on methodological integration rather than empirical system deployment.

V. Conclusion

This study presents a conceptual carbon footprint calculation system model for the manufacturing industry that integrates GHG Protocol–based emission scope classification with standardized emission factors from DEFRA within a unified system structure. Adopting a Design Science Research approach, the study delivers two primary artefacts: a structured system model that formalizes scope-based carbon footprint calculation and a decision-support framework designed to support Net Zero emission planning.

The proposed model demonstrates how standardized carbon accounting can be systematically embedded to enable transparent emission calculation, consistent scope-based aggregation, and the generation of decision-relevant indicators. By integrating scenario-based analysis and structured roadmap formulation, the decision-support framework extends the role of carbon footprint systems beyond compliance-oriented reporting toward strategic evaluation of Net Zero pathways in manufacturing contexts.

Future research will focus on the development of an integrated carbon footprint monitoring system to support the optimization of Green Industry practices toward Zero Emission in the manufacturing sector. This includes translating the proposed conceptual model into a detailed system design capable of continuous monitoring across production, logistics, and supply chain activities. While updates to emission factors can be managed through system-level configuration to accommodate evolving standards, further work may incorporate uncertainty modeling techniques to assess the impact of variability and estimation errors in activity data and Scope 3 assumptions on carbon footprint results. In addition, the integration of supplier-specific emission data, dynamic operational data sources, and advanced decision-support methods—such as optimization and multi-criteria decision analysis—may further enhance the evaluation of alternative Green Industry and Net Zero strategies.

In the broader context of Net Zero transitions in the manufacturing sector, this study contributes a system-oriented approach that enhances decision quality, methodological transparency, and strategic alignment in carbon footprint management. By integrating standardized emission classification, calculation logic, and decision-support mechanisms within a unified system model, the proposed approach improves comparability, traceability, and the practical usability of carbon footprint data. This contribution is particularly relevant for manufacturing organizations seeking to move beyond compliance-driven reporting toward proactive, data-informed, and strategically guided Net Zero transformation.

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