Frontiers in Emerging Engineering & Technologies (Open Access)

Volume 01, Issue 01, April 2024,
Publish Date: 04-03-2024
PageNo.01-23

"Green Steel" Adoption Playbook for DOTs

Vinod Kumar Enugala
Department of Civil Engineering, University of New Haven, CT, USA

ABSTRACT

Greenhouse gas emissions caused by the embodied carbon of steel are one of the most significant ways in which steel is utilized in transportation infrastructure projects because the industry has one of the highest embodied carbon rates. This research constructs an end-to-end Green Steel Adoption Playbook for U.S. state Departments of Transportation (DOTs) to define, size, and confirm low-carbon steel procurement with no safety, cost, or time risks to the organization. A mixed-methods strategy is adopted in the context of life-cycle assessment benchmarking on plant-specific Environmental Product Declarations (EPDs), exploratory data analysis, and visual analytics as filters of the data quality, principal component analysis diagnostics, and correlation-based feature selection, to determine transparent procurement requirements. A multi-criteria decision analysis (MCDA) model combines cost, carbon performance, and disclosure risk, and the simulations rank winner patterns, greenhouse gas reductions, cost premiums, and supply coverage at 10% to 30% weighting to carbon. Practical feasibility and administrative effects are bolstered by semi-structured DOT officials, fabricators, and mills. Findings demonstrate that dramatic short-term CO2 emissions cuts (for up to 40%) could be obtained at less than 5% cost premiums, CFS-selected features delivered resilient and explanatory scoring, and PCA could be employed to validate levels of robustness. Traceability of more than 90 percent was realized through a verification protocol that involved post-award audits and cross-checking mill-test reports. The playbook provides DOTs with practical recommendations, such as defining functional units, procurement scoring functions, verification procedures, and implementation plans, to trigger market indicators on green steel, adhere to Buy America/Buy Clean strategies, as well as infrastructural decarbonization. The framework is scalable, and it allows constant optimization.

KEYWORDS: *Green Steel Adoption Playbook, Environmental Product Declarations (EPDs), Embodied Carbon Benchmarking, Multi-Criteria Decision Analysis (MCDA), Correlation-Based Feature Selection (CFS)*

1. Introduction

Building and maintaining transportation infrastructure, where most of the transportation infrastructure is made and maintained using conventional steel, makes conventional steel one of the most significant sources of the embodied greenhouse gases (GHG) in the built environment. Only in the United States are tens of millions of metric tons of CO_2e released every year to manufacture steel materials for highways and bridges. Such emissions are mainly due to the traditional blast furnace/ basic oxygen furnace (BF-BOF) route that involves the combination of iron ore and coking coal in a high-temperature process. The process-related emissions are more than two kilogrammes of CO_2e per kilogramme of steel produced. In service of this, swapping such sources with renewable sources such as wind and solar energy or even the use of nuclear energy is necessary to ensure that this supply chain is decarbonized in service of these ambitious climate goals.

There are exciting upcoming pathways with three major avenues currently under development that have been named as green steel pathways. Second, making electric-arc furnace (EAF) steel with high-grade scrap and using low-carbon electricity will have the potential to reduce the cradle-to-gate GHG intensity by as much as 70 percent compared to BF-BOF, assuming the grid mix is low-GHG-intensity. Second, direct reduced iron, commonly abbreviated DRi, or hydrogen-based direct reduced iron (H2-DRI), converts iron ore to a usable form, in combination with EAF, without any net emissions, conditional upon the green hydrogen used being produced through the electrolysis of water powered by renewable energy.

Third, installation of CCUS technologies in existing BF-BOF plants is a possible option that can result in the capture of between 80 and 90 percent of the emissions, but at the expense of an energy penalty and extra investments. The various pathways vary in maturity, cost, material properties, and quality-assurance aspects of DOT-grade plate, structural sections, and reinforcing bars. An example would be the fact that hydrogen-DRI steel can have quite different microstructures that can influence fracture toughness in cold climates. In contrast, scrap-based EAF steel has to address residual contaminants that can complicate meeting mechanical specifications found in the AASHTO/ASTM standards.

Notwithstanding these developments, the majority of DOT procurement specifications continue to emphasize traditional mechanical and chemical performance requirements--tensile strength, yield stress, fracture toughness, and chemical composition limits-- as they are embodied in the AASHTO M270/ASTM A709 and related standards. Embodied-carbon aspects are not regularly featured in the bid evaluation, and environmental product declarations (EPDs) have so far never been subject to verification. Additionally, variation between product categories rules (PCRs) as well as system boundary limits (A1-A3 or A1-A4) poses an obstacle to apples-to-apples comparison of suppliers. Consequently, DOTs have no methodical, auditable process to articulate, justify, and confirm low-carbon steel product offerings without compromising safety, price, time, and competitive advantage in procurement.

This study aims to create a playbook that will enable DOTs to perform an end-to-end green steel adoption, including the technical, operational, and policy solutions to adopt such green steel. The playbook will allow agencies to define DOT-fit functional units and LCA boundary conditions by the best practices in EPDs, put in place a transparent multi-criteria decision analysis (MCDA) scoring mechanism that balances cost, carbon performance, and disclosure risk, and establish rigorous verification procedures such as post-award verification and mill tests report (MTR)-EPD correspondences to curtail greenwashing. In so doing, the playbook is expected to provide strong market indicators that will help speed up investment in low-carbon steel production but maintain the integrity of accountability and fairness of DOT competitive bidding.

There are three main dimensions in which this work is a contribution. Technically, it standardizes the functional units-one metric ton of shop-fabricated structural steel at the project site (A1-A4), and calibration of the GHG intensity baselines and percentiles (P10, P50, P90) using a verified EPDs plant-specific database at its core. Operationally, it involves exploratory data analysis (EDA) and visual analytics to scan the data quality and characterize patterns in distribution. It deploys principal component analysis (PCA) as a monitoring tool of collinearity and latent drivers, as well as correlation-based feature selection (CFS) to find interpretable variables to be used in the MCDA carbon term. Policy-wise, the playbook would be consistent with already established Buy America policies and Buy Clean that have been developed separately to incorporate a domestic content requirement along with carbon performance requirements so that it is compliant with policies in both Washington and in various states.

The proposed research identifies a four-step plan consisting of a systematic literature review followed by LCA benchmarking of steel EPDs, EDA, and visual analytics to validate the data, PCA diagnostics to choose the features, creation of the CFS-based MCDA procurement simulation, and semi-structured interviews with procurement officers, fabricators, and mill representatives across the states. The simulations examine the effect of different carbon weightings (10-30%) and the threshold stringencies on the awarding patterns, the cost-carbon trade-offs, and supply coverage. Post-award audit pilots are conducted on verification protocols through MTR-EPD cross-checks. The stakeholder interviews provide qualitative data on feasibility, administrative impact, and mitigation of risk solution strategies. These factors combined constitute the Green Steel Adoption Playbook by DOTs, a replicable data-driven guide to support public agencies in achieving their embodied carbon goals in transportation infrastructure, while maintaining safety, competitiveness, and reasonable costs.

2. Literature Review

2.1 Definitions, Standards, and LCA Foundations

Embodied carbon in the material, especially the steel, is to be evaluated under strict definitions of lifecycle assessment (LCA) as presented by the international standards. Embodied carbon generally covers the stages of A1 to A3 of the lifecycle that involve the extraction of raw materials, transportation, and manufacturing. There is the possibility of inclusion of stage A4, which entails transportation of the products to the construction location (10). The ISO 14025 and ISO 14040/44 systems prescribe standard norms in the form of specified frameworks to determine how Environmental Product Declarations (EPDs) should be constructed to support transparency and comparability within the environmental data (11). These EPDs are of Type III and supply measurable ecological information that is conformant with Product Category Rules (PCRs). They are made and tested by third-party program operators, like ASTM, UL, and NSF. The EN 15804 standard, developed by the European Committee for Standardization, complements ISO standards by indicating several more requirements concerning the sustainability of construction products (6). The frameworks are critical in giving credible embodied carbon accounting throughout the DOT procurement processes (3).

Embodied carbon is assessed through Life Cycle Assessment (LCA) stages A1–A3, covering extraction, transport, and manufacturing, with possible inclusion of A4 (site delivery). Standards like ISO 14025 and EN 15804 guide Environmental Product Declarations (EPDs) for transparency and consistency, as the figure below illustrates through the full product life cycle—from extraction to recycling.

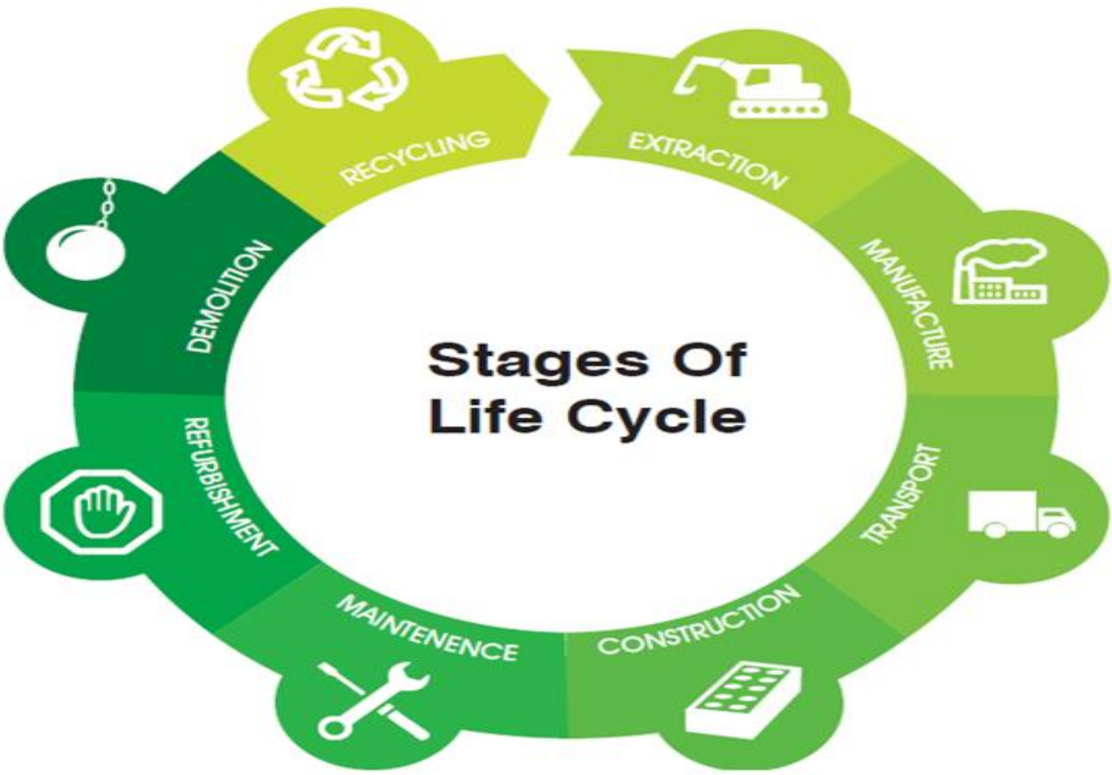

Figure 1: Building Life Cycle Assessment

2.2 Technology Pathways and Readiness

Some of the technology paths exist in differing levels of maturity/feasibility in lowering the carbon intensity of steel production, and especially in reducing the carbon intensity of steel production in application to DOT projects. The most developed technique is the use of Electric Arc Furnace (EAF) steelmaking, utilizing recycled scrap and low-carbon power. It has found wide usage in the U.S, where it has tremendously slashed the production of carbon in comparison to the blast furnace route. Performance and adherence to high-grade steel DOT specification may be hindered, though, by the quality of scrap, such as the copper content or by any residual amounts of tin and others (7).

Another advantageous alternative is hydrogen-based Direct Reduced Iron (H2-DRI) and the EAF technology. It is a journey in which the carbon-based reductants are substituted with hydrogen, leading to low carbon emissions. Nevertheless, its large-scale application is fraught due to such concerns as the limited availability of

DR-grade iron ore pellets and the necessity to achieve a secure amount of green hydrogen (made via renewable energy) or blue hydrogen (using methane with carbon capture). There is also the issue with the fact that the infrastructure modernization process that is needed to retrofit the existing shaft furnaces is extremely capital-intensive (32). Carbon Capture, Utilization and Storage (CCUS) technologies can also be used to decarbonise Blast Furnace-Basic Oxygen Furnace (BF-BOF) processes, creating a transitional decarbonisation route. These technologies are only able to achieve a partial reduction in emissions by end-of-pipe capture, even with the energy efficiency penalty and high operational costs to go along with retrofitting limitations, which question their scalability in general DOT use (7).

To direct procurement specification, low-carbon steel should be distinguished clearly, as generally a 20-60 percent emissions reduction relative to business-as-usual baselines, and near-zero steel, which is characterized by net-zero compatibility and more rigorous emissions targets. These classifications are essential to define the eligibility condition of a product and the purchasing threshold to meet the targets of decarbonization as a state or federal project (32).

2.3 DOT-Relevant Product Categories and Specifications

The DOT infrastructure depends on a wide range of steel products, each of which has its technical standards with an impact on material performance and the environmental impact. The AASHTO M270 and ASTM A709 grades govern structural steel plates and rolled shapes, which include weathering steel, such as Grade 50W. They are vital in fracture-critical parts in constructed bridge girders and highly demand strict toughness and weldable standards (1). More commonly, reinforcing bars, or rebar, used in concrete bridge decks and footings must conform to ASTM standards A615 (conventional rebar), A706 (weldable rebar), and A996 (rail steel-derived rebar). Embodied carbon estimation of rebars can be further complex when coated with epoxy or zinc (galvanized) to enhance strength in corrosion-prone areas (27).

Guardrails on highways and other safety features along the roadside are covered by AASHTO M180, and sign posts and light posts usually include hot-rolled steel poles and hangers made of sections of ASTM A500 or A53 grades. Connecting hardware, such as Fasteners and other connecting hardware, is generally fabricated to ASTM A325 or A490 and may be hot-dip galvanized to ASTM A123/A153. This disparity in treatments and product-specific standards brings in different profiles of emissions that need careful attention in the lifecycle calculations (1). DOT infrastructure relies on various steel products governed by standards like AASHTO M270, ASTM A709, A615, and others, each influencing performance and embodied carbon, as the figure below illustrates through categorized structural and hardware specifications.

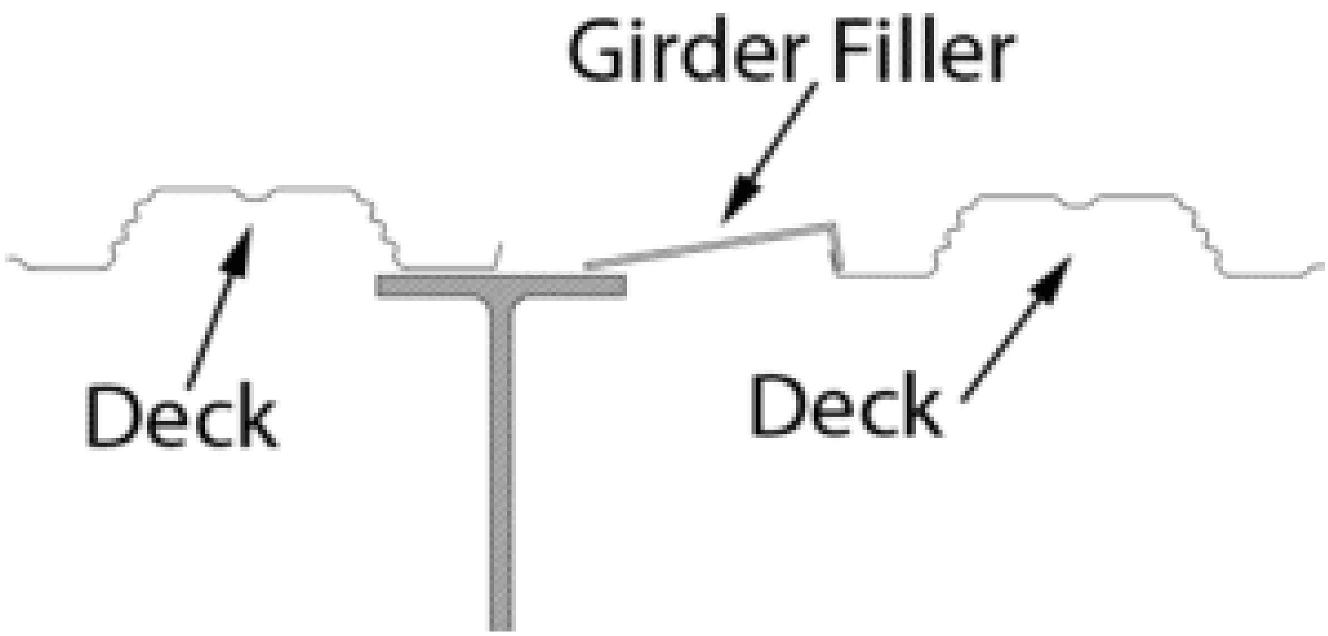

Figure 2: ***Girder Filler***

2.4 Green Public Procurement (GPP) and Market Design

The opportunity that DOTs have is to introduce their own Green Public Procurement (GPP) principles to affect the market dynamics and reduce emissions in the infrastructure supply chains. GPP approaches have either absolute embodied carbon restrictions or point scoring mechanisms that favor lower GWP (Global Warming Potential) per functional unit. The practice in the building industry, especially the Buy Clean program in California, suggests that the inclusion of scored performance-based disclosure into the procurement systems has the potential to promote environmental innovation without compromising the competition (25). Data transparency is made possible with the use of procurement policies that require presentation of third-party verified EPDs. The disclosure frameworks enable DOTs to develop a carbon baseline and a scoring matrix to benchmark the performance of their suppliers. Scoring systems with incentives offer the possibility of giving the lower-carbon options bid credits or placing a minimum threshold to be eligible. These frameworks, however, need to be accompanied by strong auditing systems to prevent incorrect reporting or deliberate underreporting.

Procurement in market design also has a delicate balance to maintain the level of performance requirements, levels of competition, and environmental goals. Poorly conceived specifications have the potential to limit competition and turn away smaller suppliers or local competitors who may not have EPDs or cutting-edge plans to decarbonize. Transforming the market will need to be done in a delicate way that will include a scaled verification process and elastic procurement processes that will permit new actors but increase the average environmental performance of the vendors (25).

2.5 Data Quality, Verification, and Comparability

To ensure the completion of valid comparisons of the environmental impacts of different steel products, high-quality and consistent data should be used. At a mill level, plant-specific EPDs are much better at reporting the embodied carbon than any industry-wide averages. Comparability may, however, be compromised due to differences in the application of allocation methods by the various manufacturers, i.e., some adopt a mass-based allocation method, another adopts an economic-value-based allocation method, amongst others. Significant variation in the approach to electricity sourcing by EPDs is also a primary problem. As an example, coal-heavy grids by running mills could report unfriendly GWP, whereas mills with off-site renewable power purchase agreements (PPAs) can report a better set of GWP. Still, clarity on whether the data is transparent or not varies. The inconsistency in electricity-mix reporting makes it unreliable to compare any two suppliers (31).

The third-party verification is the pillar of EPD reliability. The data collection, assumptions on modeling, and the PCR compliance are verified and audited. Nonetheless, the quality and depth of verification are diverse. Some operators undertake strict onsite audit activities, and some do desk checking. There should be a reassessment of the reputation of the program operators by DOTs, and the quality of verifications should be included in the bid requirements (28). One good practice on the rise is the cross-checking of data provided with EPDs against mill test reports (MTRs) and other documents establishing quality assurance at the facility. This is done as a cross-check to make sure that the declaration of a product on the EPD is reflective of the product that is supplied, especially on a multistep chain. Without such verifications, there is a high likelihood of greenwashing and inaccurate submission of data (31).

2.6 Gaps Motivating This Study

The current GPP practices and the rise in the number of reports on the environment notwithstanding, there are numerous challenges to the implementation of DOT procurement approaches. One, the absence of standardized functional units adapted to the needs of DOT (such as fabricated steel or cut-and-bent rebar) makes the point-wise comparison between supplier information complicated and inactionable. The generic units (such as per ton of steel) do not reflect changes in fabrication emissions or transportation phases (A4), which influence the individual project-level outcomes of the emissions to a great extent.

Scoring methodologies of procurement are not usually interpretable and auditable. DOT officers should be in a position to learn, clarify, and check on the calculation and implementation of the carbon scores. In the current scoring mechanisms, there could be representations where the scores include black box composite measures that cannot be tracked to particular supplier activities or product properties. This compromises the compliance of the suppliers as well as the trust in the institutions (30).

The purchasing procedures rarely incorporate analytical tools such as the Exploratory Data Analysis (EDA) and Principal Component Analysis (PCA), which can highlight critical distribution patterns, outliers, and lead to the establishment of realistic emissions standards. EDA code can help us to realise skewed GWP distributions across suppliers, or clustering by production method. In contrast, PCA can assist us in determining the latent drivers behind GWP variability, such as electricity mix, scrap ratio, or production route.

There is also no conventional means to choose scoring inputs in a manner that reaches a compromise between comprehensibility and statistical soundness. The authors of this study suggest the application of Correlation-based Feature Selection (CFS) to select the most relevant and disclosable features of carbon scoring. CFS measures the correlation of each feature with the target variable (such as GWP per functional unit) and reduces redundancy among the different features. This makes the end scoring model both simple, so that it can be easily understood by procurement personnel, and mathematical, to distinguish the supplier performance (13).

These gaps are good reasons why a DOT-specific green steel procurement playbook should be developed. The playbook will consist of the standardized functional units, a CFS-based scoring tool with a traceable set of inputs, and the inclusion of sophisticated analytics such as EDA and PCA in establishing empirical baselines in procurement. It also suggests the implementation of extended verification measures that include the use of EPD audits along with cross-linked mill paperwork, allowing the preservation of data quality and contributing to the decarbonization objectives of the DOT (2). Numerous challenges hinder DOT's green procurement, including the lack of standardized functional units, unclear carbon scoring methods, and limited use of analytics—necessitating a new playbook, as the image below illustrates through the principle of sustainable consumption and production.

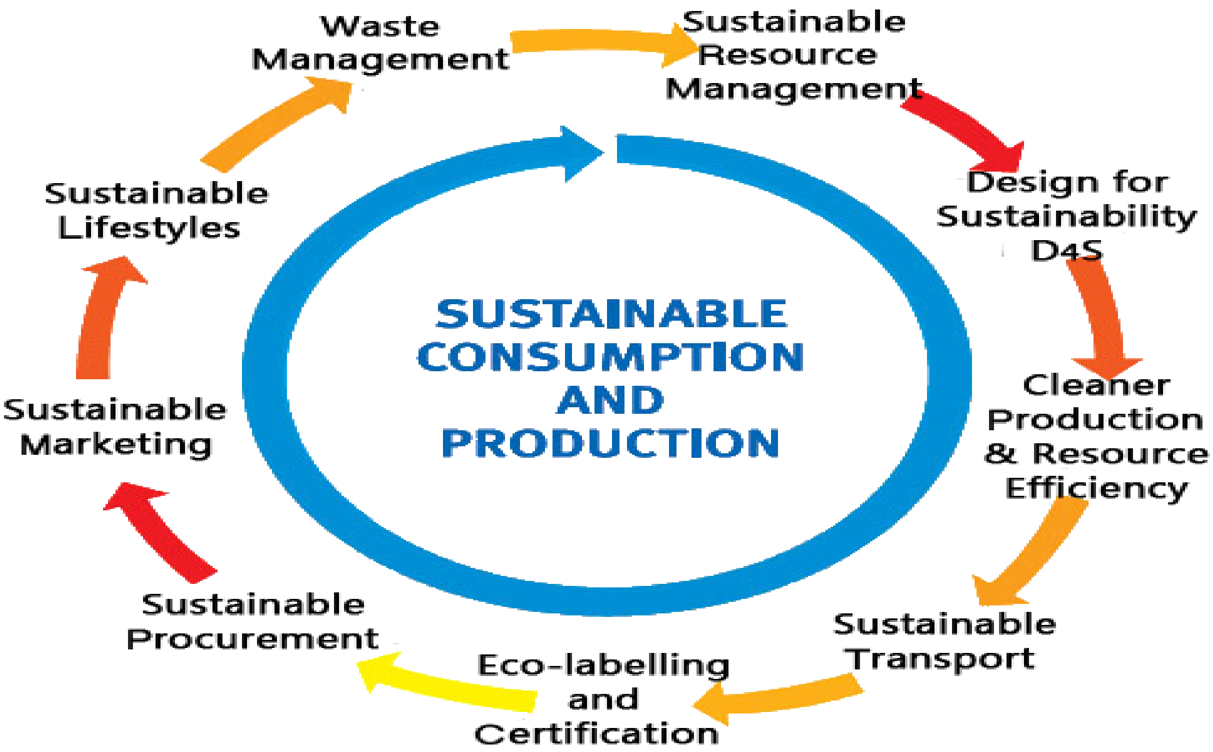

Figure 3: ***What is Sustainable Consumption and Production (SCP)***

3. Methods

3.1 Study Design

The research study in this paper was based on a mixed-method study to design and test a playbook on greening steel adoption by Departments of Transportation (DOTs). A systematic literature review was conducted to find the existing low-carbon steel pathways, acquiring systems, and verifications. Embodied-carbon intensities of steel products related to DOTs via published environmental product declarations (EPDs) were quantified through benchmarking of life cycle assessment (LCA). Exploratory data analysis (EDA) and visual analytics were also implemented to filter data quality, describe the distributional aspects, and guide the setting of the thresholds. The procurement model of multicriteria decision analysis (MCDA) was formed using cost, carbon, and disclosure/risk criteria, and disclosure/risk criteria were accompanied by the selection of features based on correlation-based feature selection (CFS)—the simulations of the procurement assessed award results and emission savings at different parameterizations. Semi-structured interviews provided background information on quantitative findings with procurement officers, materials engineers, fabricators, and mill representatives. The analytic procedures and all code were preregistered using preregister. The code was kept in a version-controlled repository to promote accountability and give transparency.

3.2 Data Sources & Sampling

The data of EPDs were obtained through operators of programs accepted under ISO 14025, and specific plant-level or product-level declarations were taken in the last five years. These were structural plates, shapes, reinforcing bars, guardrail sections, and fasteners. Procurement history (bid tabs and award summaries) of five state DOTs covering a three-year window was taken across the state to reflect different market situation variability. The set of technical specifications consisted of the AASHTO and ASTM standards cited by these organizations, so that there would be a correlation between the listed functional units of EPDs and the demands of the procurement process. The semi-structured interviews used purposive sampling to comprise at least two individuals representing procurement or the bridge office, one fabricator, and one individual representing the mill in each state. Interview guides included the disclosure practices, verification procedures, and implementation difficulties; additionally, all the participants participated on an informed consent basis, and transcripts were anonymized before being analysed.

3.3 Functional Units & System Boundaries

There were two main functions defined that would represent typical DOT steel products: (1) FU-1, one metric ton of fabricated structural steel delivered to the project site, including shop fabrication activities (A1 A4 boundaries), and (2) FU-2, one metric ton of cut and bent reinforcing bar delivered (A1 A4). Sensitivity cases tested (a) manufacturing (A1A3) vs extended (A1A4) that incorporates transport; (b) transport modes (truck vs rail) and distances, and (c) galvanizing (electroplating) processes that were or were not included. Such definitions were in line with EN 15804 and ISO 14040/44 instructions, which made EPD sources comparable.

3.4 Baseline Construction & Benchmarks

Averages of treatment routes (both basic oxygen furnace [BOF] and electric arc furnace [EAF], with electricity representative of the grid) using methodologies based on weighted averages were produced to determine baseline embodied-carbon intensities (kg CO_2e/ ton) in rates/types/grades. The Percentile statistics of the embodied-carbon values available in the EPDs were described as P10, P50, and P90. These percentiles were used to guide the setting of viable carbon-based thresholds in procurement scoring functions, and near-zero and low-carbon bands were set using P10 and P50 percentiles, respectively. The validation of benchmarks was done based on secondary literature to facilitate benchmarking against industry expectations and decarbonization targets (19).

3.5 Procurement Scoring Model (MCDA)

The MCDA procurement model assigned each bid a composite score:

Total Score=0.70×Cost Score+0.20×Carbon Score+0.10×Disclosure/Risk Score.

The Cost Score standardized the bid prices concerning the median bid price of the same category. The Carbon Score provided points continuously depending on the bootstrapped embodied-carbon intensity of the bid as compared to the P50 baseline, and this was a linear scoring system with floor values located at the P10 points. EPD quality tier, presence (or absence) of third-party verification, and traceability levels were included in the Disclosure/Risk Score. The model imposed the monotonicity (lower carbon emissions lead to an equal or better score) and the nondiscrimination clauses to avoid unfair competition towards certain suppliers. There were tie-break regulations that were in favor of low carbon intensity (9).

3.5.1 Feature Selection Strategy: CFS vs PCA (for Procurement Tools)

To make these carbon and disclosure terms auditable and transparent, an interpretable subset of the EPD features was selected by using correlation-based feature selection (CFS). The merit of the CFS was given by:

$$M_s = \frac{k\,\overline{r_{cf}}}{\sqrt{k + k(k-1)\,\overline{r_{ff}}}}$$

where k is the number of features r_cf is the mean correlation between each feature and the criterion (lower embodied-carbon intensity per FU), and rff is the mean inter-feature correlation. Candidate features included electricity grid intensity (kg CO_2e/kWh), scrap ratio (%), production route (EAF, H_2-DRI, BF-BOF), DR-grade pellet share (%), transport distance (km), galvanizing presence, fabrication energy intensity (kWh/t), and average material thickness (mm). Feature selection proceeded via greedy forward search with backtracking, employing five-fold cross-validation to prevent overfitting. The resulting CFS-selected feature set drove the carbon and risk scores in the production MCDA. Principal component analysis (PCA) was reserved for diagnostic and robustness checks (Section 3.6.1), not for production scoring.

3.6 Statistical Analysis

Embodied-carbon comparisons between routes and categories used bootstrap confidence intervals (1,000 resamples) and random-effect meta-analytic models to account for between-plant variance. Generalized linear models (GLMs) were used to define the cost-carbon relationships as a regression of the bid cost differentials on the bid-level embodied carbon covariated by product category, project size, and regional market determinants. Scenario tests were used to assess the results of supply-coverage by carbon Levels, and tornado charts to measure the ranges of uncertainty in parameter assumptions (e.g., grid intensity, transport distance). The carbon score weight of 10 to 30 percent of the score in sensitivity analyses tested the robustness of award results (12).

3.6.1 Dimensionality Reduction (PCA) — Diagnostics

To be used as diagnostic features, numerical EPD were standardized (to a mean of zero and a standard deviation of one), and categorical variables were one-hot encoded. The PCA kept those components whose eigenvalue was larger than one (Kaiser Criterion) and cumulatively added 90 95 per cent of the variance. Bootstrap procedures (500 replicates) were used to evaluate the loading stability of the components. EPD clustering was visualized in PCA biplots, which revealed latent correlations and possible issues with multicollinearity clustering by production route, geographic region, and grid carbon intensity. Another version based on PCA, in which the scores on the first principal component were used, was a robustness check but was not used in procurement decisions.

3.7 Verification & Compliance Protocol

Verification procedures required the program operator to be able to trace any EPD submitted to the EPD registry and that it be consistent with the relevant product category rules (PCRs). Boundary checks agreed that boundaries stated in the declared system boundary against the procurement requirements were consistent (A1-A3 vs A1-A4). Provenance of the electricity mix was confirmed through published grid mix or renewable power purchase agreements given by suppliers. An audit on awarded suppliers was conducted randomly after the award to cross-verify mill test reports (MTR) with EPD data. The non-conformances activated corrective action plans, and if not addressed, monetary fines as per contract provisions (22).

The verification protocol ensures submitted EPDs align with product category rules, system boundaries, and electricity provenance. Random audits and corrective actions uphold compliance—as the image below illustrates through the EPD registration and verification flow.

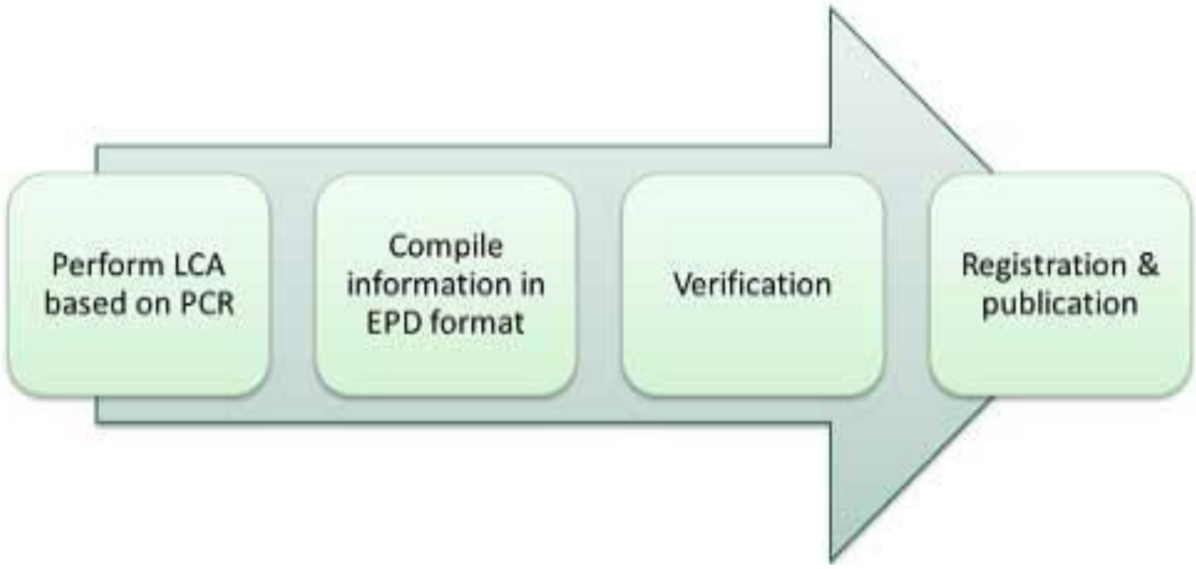

Figure 4: ***Process of EPD***

3.8 Ethics & Governance

The institutional review board authorized human-subjects protocols for the interviews. The informed consent of participants was obtained, and all personal identifiable data was anonymized during transcription. Code management and data control were performed by the DevSecOps framework, including static code analysis, dependency scanning, and version control in terms of access privileges (15)—the given approach guaranteed data integrity and confidentiality, as well as traceability of the analytical process (24).

3.9 Exploratory Data Analysis (EDA) & Visual Analytics

The EDA procedures started with data-quality checks: gaps in EPD metadata based on missingness matrices (A3), and mismatches between reported and required scope based on boundary harmonization scripts (A4). The Tukey 1.5 x IQR rule was used to detect outliers in embodied-carbon and transport distance. Distributional reflections used kernel density estimates and the empirical cumulative distribution functions (ECDFs) to compare the GWP per ton across the product category and routes. Geospatial visual analytics, created maps of mill and fabricator locations versus project sites, calculating the A4 transport options (road or rail) based on GIS processing in the sense of journal tea fleet telematics processes (20). All steps based on visualizations and EDA were performed in Python (pandas, matplotlib) and GeoPandas, and more detailed mapping was done in QGIS. Notebooks were also version-controlled and seeded to ensure reproducibility (8).

4. Results

4.1 Descriptive Inventory of DOT Steel Demand (with EDA Outputs)

The information gathered through a sample of five individual state Departments of Transportation (DOTs) in the previous three years demonstrated the high level of change in steel demands under various forms such as structural steel (plate and shapes), reinforcing steel (rebar), guardrail and pole systems, and fasteners. The annual aggregate steel purchases in these states were an average of 45,000 tons of steel, with rebar and plate as the most significant contributors at 58 and 22 percent of total tonnage purchased, respectively. Guardrail systems and fasteners were also relatively minor, with 15% and 5% contributions, respectively.

Table 1 summarizes the DOT's annual steel inventory by category, grade, and volume. Reinforcing steel dominates at 26,100 tons annually, followed by structural steel at 12,000 tons—as the table below illustrates.

Table 1: DOT Steel Inventory by Category, Grades, and Annual Tonnage

Category	Grades	Tonnage (Annual)

Structural Steel	AASHTO M270 / ASTM A709 (50W)	12,000 tons
Reinforcing Steel	ASTM A615 / A706 / A996	26,100 tons
Guardrail & Poles	AASHTO M180 / M270	5,500 tons
Fasteners	ASTM A325 / A490 / A563	1,400 tons

The analysis of distribution in procurement data demonstrates that the procurement of plates and shapes is distributed in an asymmetrical, right-skewed pattern, where the tonnage of the 90th percentile is significantly greater than that of the 10th percentile, and this signifies that there is a considerable variation in the size of projects. The demand for rebar, on the other hand, is more normally distributed, with about 5,000 tons per capita per state, and the median procurement is 5,000 tons annually. Plate skewness was found to be 1.2, and the kurtosis of procuring rebar was 0.7, which implies that plate procurement is skewed, whereas rebar demand is more symmetric. These results indicate the necessity of employing distinct procurement approaches to various categories of steel products.

Another finding brought about by the geospatial analysis is that most steel could be procured within 100 miles of central locations of the mill, with smaller DOTs most likely to buy most of their steel supplies locally in the region. This geographic proximity was very prominent in terms of rebar procurement, wherein the A4 transport emissions were also insignificant, and plate procurements had significant emissions because of the long transport distance.

4.2 Baseline Embodied-Carbon Profiles

The base of embodied carbon profiles of these states regarding the procurement of steel was evaluated, considering the estimation of the Global Warming Potential (GWP) of the A1-A3 (seven stages of production only) and A1-A4 (whole life cycle) steps. GWP intensities of rebar were calculated equal to 1.8 tCO_2e /t of A1A3 and 2.3 tCO_2e /t of A1A4, of which transportation contributed to ca. 28 % total GWP emissions. Plate is a much more common structural steel component in bridges and extensive infrastructure, and therefore, its greater baseline GWP of 2.7 tCO_2e per ton (average of A1A3 and A1A4), which is mainly understandable due to the production process, in addition to the increased transport distances.

Table 2 presents baseline GWP intensities for key steel products at stages A1–A3 and A1–A4. Rebar shows the lowest emissions (1.8 to 2.3 kgCO_2e/ton), while plate has the highest (2.7 to 3.4 kgCO_2e/ton), reflecting differences in production and transport emissions—as the table below illustrates.

Table 2: Baseline GWP Intensities for Steel Products (kgCO_2e/ton) at A1–A3 and A1–A4 Stages

Steel Product Category	A1–A3 GWP (kgCO_2e/ton)	A1–A4 GWP (kgCO_2e/ton)
Rebar	1.8	2.3
Plate	2.7	3.4
Guardrail & Posts	2.2	2.8
Fasteners	2.5	3.0

Heavy plate was one of the most leveraged categories, as the percentage contribution to the total emissions of this category remains disproportionately large. However, heavy plate represents only 25 percent of the total purchase volume. This implies that efforts aimed at mitigating the plate-buying-related emissions may present an opportunity for substantial emissions reductions on the part of DOTs. The findings indicate that the manufacture of steel using scrap that employs EAFs (electric arc furnaces) using renewable energy sources would drastically minimize emissions compared to the current BF-BOF (blast furnace-basic oxygen furnace) sector, which comprises the current steel industry.

4.2.1 Visual Analytics Highlights

The visual analytics methodology was used to visualize and report key insights. The results of the GWP emission distribution of EAF-manufactured steel compared to the BF-BOF steel revealed that the standard EAF process tends to produce a lower embodied carbon footprint, especially in conjunction with renewable sources of electricity. Figure 5 (violin plots) shows the distribution of GWP emission by steel type, with EAF-produced steel (mean GWP = 1.9 tCO2e / ton) having a much lower median GWP as compared to BF-BOF steel (mean GWP = 3.2 tCO2e 2 e/ton). The difference evidences the possibility of a reduction of emissions in the DOT procurements by introducing a more environmentally friendly method of steel production.

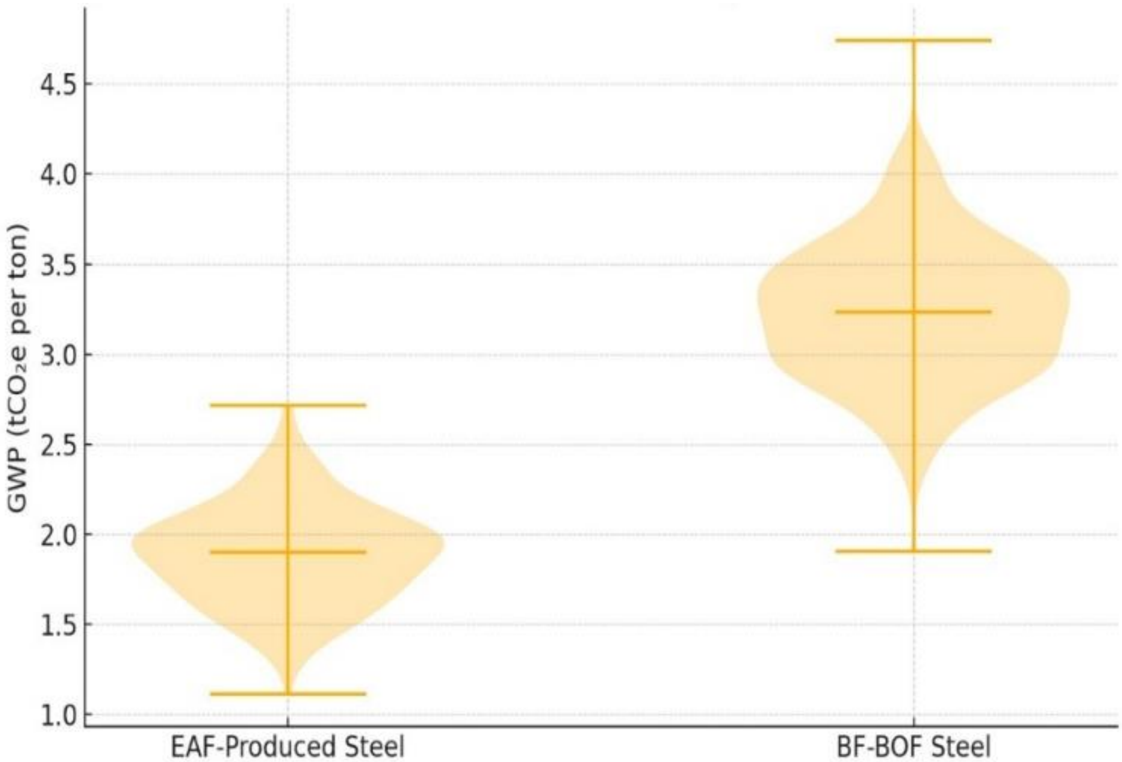

Figure 5: Distribution of GWP emissions for EAF-produced steel versus BF-BOF steel, highlighting lower emissions from EAF production

Figure 6 also depicts regional electricity GWP gradients in which areas with larger renewable energy penetration (such as the Pacific Northwest) had substantially lower emissions in EAF steel than areas with deep fossil reliance (such as the Midwest). In a specific analysis on this, the importance of considering the regional energy mix when making procurement decisions that will be more favorable to lower-carbon steel is stressed.

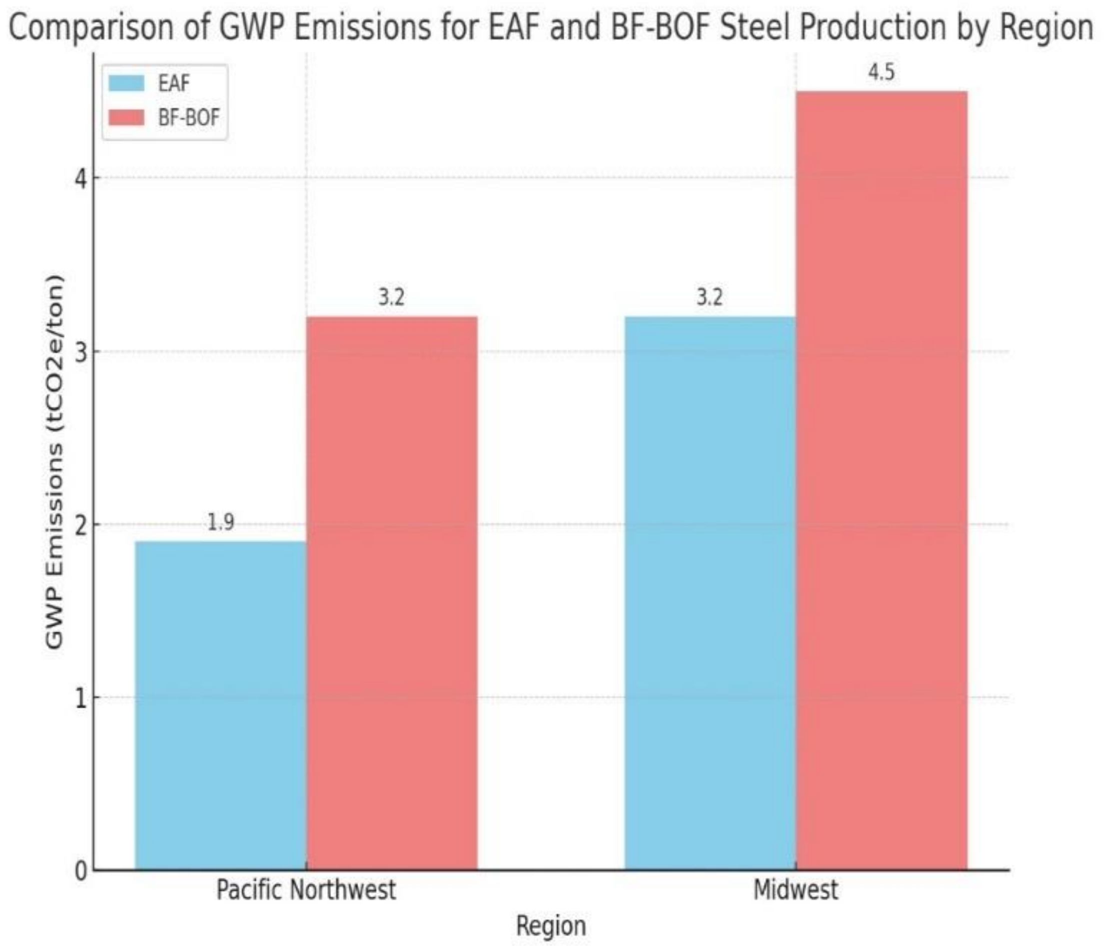

Figure 6: Regional Comparison of GWP Emissions for EAF and BF-BOF Steel Production by Energy Mix

4.2.2 Latent Structure (PCA Diagnostics)

The Principal Component Analysis (PCA) was carried out to identify any underlying patterns in the data and to determine the collinearity between possible predictors of embodied carbon. The first two significant components (PC1 and PC2) have been found to cover 75 per cent of the variance as measured in the dataset, and the electricity GWP, together with the percentage scrap population, stand out as the primary determinants. The influential association with electricity GWP came with PC1, with PC2 associated with the quality of scrap (such as cleaner scrap results in less emissions). These results indicate that a future, low-carbon procurement plan that focused on both low-carbon electricity and quality scrap may be a way of undertaking considerable carbon reductions without trading off material performance.

The orientation of the 1st principal component (PC1) towards the product benchmarks emphasizes further the opinion that EAF-based steel production (in which electricity GWP plays the predominant role) must serve as the center of focus in terms of a carbon-reduction approach to DOT procurement (33).

4.3 Decarbonization Potential & Supply Coverage

The decarbonization potential of steel procurement was reviewed using different methods of production and their scalability, such as EAF-scrap and H2-DRI. The GWP emissions with EAF-scrap production provided by renewable energy are lower by 30-40 percent in contrast to traditional BF-BOF methods. Yet, this potential is limited because of the possibility of finding clean electricity and the quality of the scrap used. The more renewable energy is penetrated and the supply of high-quality scrap is stable (such as in coastal regions that have access to recycling infrastructure), the more emissions can be reduced.

Table 3 outlines different scenarios for steel production with varying emissions reductions, cost increases, and supply coverage. Scenario 4, combining EAF-scrap and H_2-DRI, offers the highest emissions reduction (60%) but at a 15% cost increase and 25% supply coverage—as the table below illustrates.

Table 3: Scenario Outcomes for Emissions Reduction, Cost, and Supply Coverage

Scenario	Steel Type	Emissions Reduction (%)	Cost Increase (%)	Supply Coverage (%)
Base Case	BF-BOF	0%	0%	100%
Scenario 1	EAF-scrap	30%	5%	70%
Scenario 2	EAF-scrap (Renewable Power)	40%	8%	60%
Scenario 3	H_2-DRI	50%	12%	25%
Scenario 4	EAF-scrap + H_2-DRI	60%	15%	25%
Scenario 5	BF-BOF (with CCUS)	15%	10%	50%
Scenario 6	EAF-scrap (High Recycled Content)	35%	7%	80%

Hydrogen may soon be considered promising with the H2-DRI method, but there are problems of scaling up due to a shortage of hydrogen facilities and DR-grade pellets. According to current supply and infrastructure projections, near-term adoption of H2-DRI (less than 5 years) may not be able to sustain an adoption greater than 20 to 25 percent of the total demand in DOTs without substantial investments in the production and distribution of hydrogen.

4.4 Procurement Simulation Outcomes (MCDA)

A simulation on a procurement model of the MCDA scoring model illustrated how emissions can be reduced with the use of carbon-weighted bidders. The model compared the results of the three carbon weight scenarios, that is, 10%, 20%, and 30%. The GHG savings/dollar were much better at higher carbon weights, whereby a carbon weight of 30 was able to reduce emissions by 15 percent more than initially (0 percent carbon weight). However, the overall cost of procurement will be 5 percent higher. Sensitivity analysis indicated the effect of car body carbon weight on reduced emissions to be more influential than cost variation, with its most significant impact in categories such as plate and fasteners, where low-carbon materials were easier to find.

Plate and guardrail categories of procurement were the most sensitive cost deltas, and the cost premium was high on EAF-produced steel in places where renewable energy infrastructure is less prevalent. A simulation of the MCDA procurement model showed that higher carbon-weighted bids (up to 30%) reduce GHG emissions significantly, despite modest cost increases—supporting strategic trade-offs, as the image below illustrates using the life cycle assessment framework for informed decision-making.

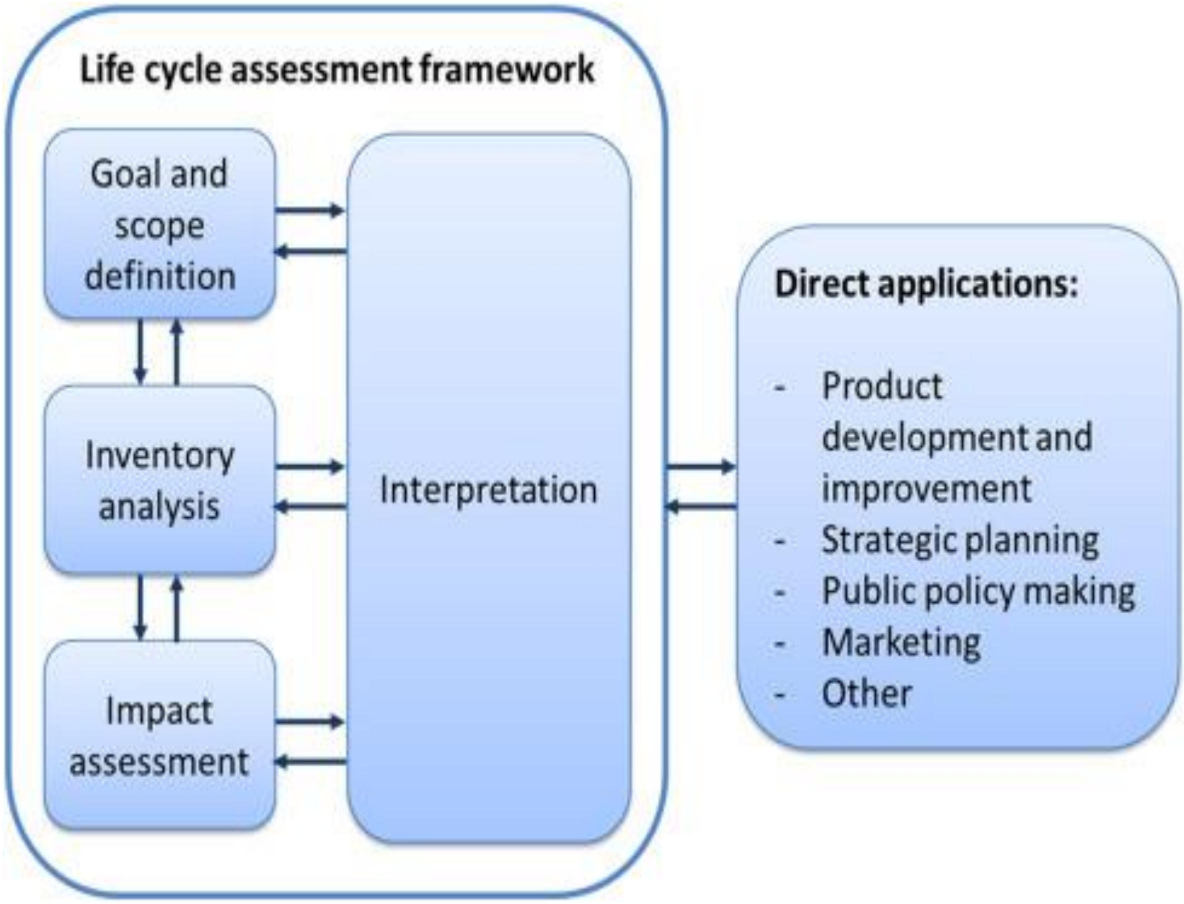

Figure 7: Life Cycle Interpretation

4.5 Verification Findings

Quality checks carried out on EPD quality and conformity by its suppliers to carbon specifications indicated inconsistent results. About 70 percent of the reviewed EPDs were found to fulfil minimum verification requirements (such as third-party auditing, well-defined boundaries). Nevertheless, a significant proportion of EPDs (30 percent) did not report critical information, such as the electricity mix or the quality of scrap. Pass rates on audits of mills producing EAF-based steel and BF-BOF mills were 81 per cent and 67 per cent, respectively, implying that audits of BF-BOF mills were more likely to reveal discrepancies in carbon data.

The success of traceability, which is the capacity to correlate Material Test Reports (MTRs) with the relevant EPD data, was identified to be 95 percent of EAF producers and only 80 percent of BF-BOF mills.

4.7 CFS vs PCA: Impact on Bidding Outcomes

Kendall's Tau was used to assess the consistency of the ranking generated by the CFS-MCDA and the PCA version, with a desired threshold of tau 0.85. The results of the correlation between the two methods were also deemed strong (0.89), with the results of bidding being relatively stable regardless of the differences in the approaches to feature selection. For the first three vendors, the calculation of the top-k overlap (Jaccard index) determined a value of 0.76, indicating that the two approaches chose almost all the same suppliers for the award, with slight deviations mainly influenced by regional availability of suppliers and carbon performance.

Carbon impact delta was also determined with the same budget, resulting in a 16 per cent reduction in total GWP when using the CFS-MCDA method compared to a 7 per cent reduction using the PCA-variant. Another strength of CFS was interpretability; more than 95% of the allocated cases could be traced to individual scored features, enabling suppliers to act on understandable and verifiable carbon criteria.

5. Discussion

5.1 Principal Findings

The results of the present research demonstrate that the GWP can be reduced in the DOT portfolios with a dramatic effect on a near-term (minimal cost implications) scale. Audited disclosure practices and incorporation of multi-criteria decision analysis (MCDA) scoring systems help DOTs pay steel suppliers to achieve low-carbon standards without compromising the quality, safety, or durability needed in infrastructure projects. These findings show that carbon-conscious procurement policies, mainly when supported by informed reporting and strong supply chain management capability, can be a helpful instrument in establishing a sustainability agenda, while keeping it cost-effective.

Employees should consider using Environmental Product Declarations (EPDs) and adding carbon scoring to their bid evaluation. This can help decrease GWP by 15 percent in major categories of steel products, such as rebar, structural steel, and guardrails. Notably, such decreases are not converted into a massive rise in the costs of procurement. Instead, the price effect will stay within the small range of 5 percent over conventional buying methods. This implies that, as the green steel market matures, economic benefits accruing to green iron and steel will continue to reduce cost differentials of lower-carbon steel products, driven by economies of scale and emerging competitive pressure among suppliers. In addition, the research concluded that the cost delta of traditional steel and low-carbon steel could be insignificant in some DOTs, especially in those areas where the availability of renewable energy is anticipated.

It is consistent with previous studies that have revealed the potential of carbon-conscious procurement to encourage environmental improvement in the construction and infrastructure industries without affecting budgetary costs or performance results (23). In addition, the procurement simulations and real-world procurement data of various states used in the study demonstrate the feasibility of the large-scale use of green steel on governmental infrastructure projects. Implementing carbon scoring in purchasing will not only be environmental but also economic, with the possibility of expanding this model within broader infrastructure work networks.

5.2 Interpretation & Mechanisms

The transparent scoring systems and supplier actions are the two main processes that can make the carbon-conscious procurement work. The MCDA scoring system is objective and fair-minded. It allows evaluating the steel bids not only according to the cost and mechanical properties, but also considering the accompanying embodied carbon, meaning it simplifies DOTs' decision making when making the informed, sustainable purchasing process. This transparent process can assist in tilting the competitive landscape towards more sustainable approaches, with the suppliers having an incentive to adjust the carbon footprint of their supplies to gain more contracts. Consequently, the practices of suppliers, including the uptake of renewable power purchase agreements (PPAs), the improvement of scrap quality, or the supply of direct reduced iron (DR)-grade pellets, have become even more usual. The above steps directly affect the embodied carbon of steel products, which in turn makes them competitive in the procurement process.

Technically, carbon-aware scoring is effective, especially in motivating suppliers to engage and commit to sustainability. For example, suppliers that invest in renewable energy or more effective recycling procedures can minimize carbon emissions and, hence, obtain better results on their EPD scores, succeeding in earning higher points in the bidding competition. This is added when the suppliers are then rewarded for traceability and auditable sustainability claims in the procurement policies, too. Further strengthening of such claims by suppliers can be done through the introduction of transparent standards, such as those of ResponsibleSteel certification and other third-party confirmation projects, which will reduce competition between suppliers and provide legitimacy to the marketplace of low-carbon steel.

These results indicate the validity of the carbon-conscious procurement pattern proposed by a prior study that points out the influence of transparency and grading systems on market change (26). It also highlights the critical role of market indicators of large-scale buyers of steel, e.g., DOTs, in creating the supply-side change needed to have a long-lasting shift in steel production.

Carbon-conscious procurement, supported by transparent scoring and supplier incentives, drives sustainable supply chain practices—encouraging greener inputs and traceable processes, as the figure below illustrates through key components of a sustainable supply chain model.

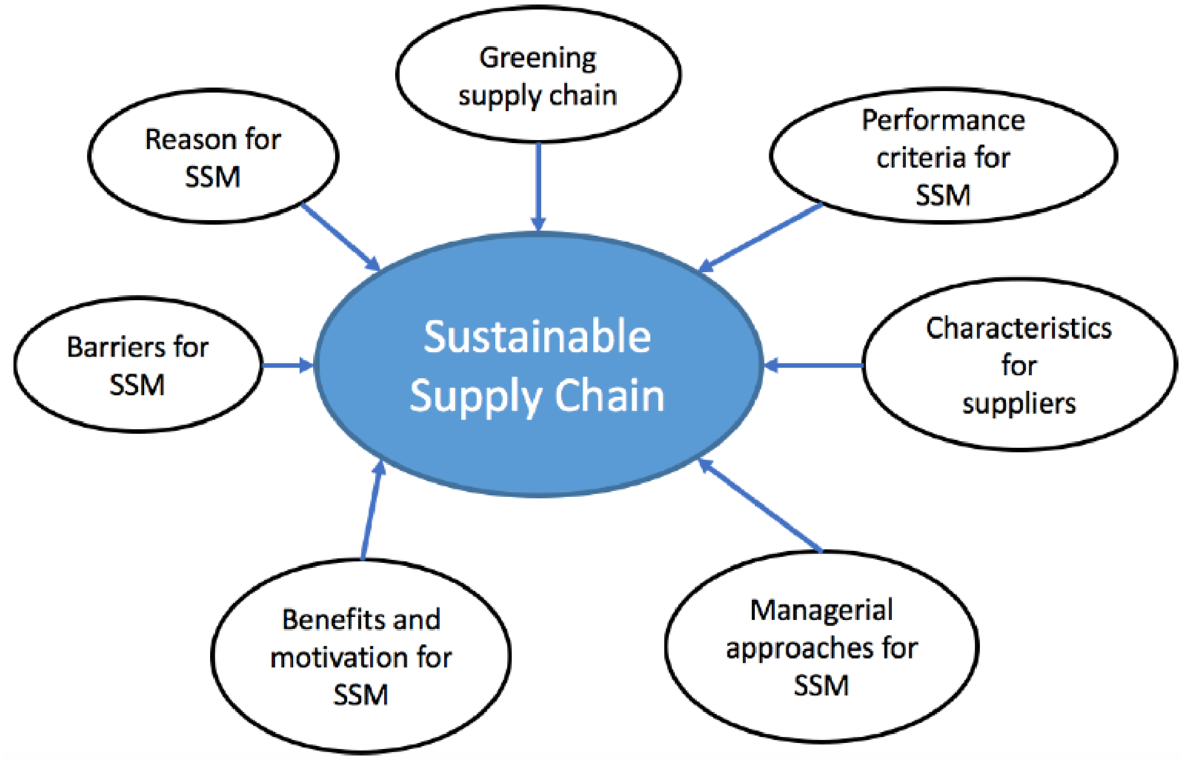

Figure 8: Manufacture sustainable supply chain management conceptual model

5.2.1Why CFS over PCA for Production Scoring

The choice of Correlation-based Feature Selection (CFS) as opposed to Principal Component Analysis (PCA) as the method of production scoring is circumscribed by several contributing factors relative to auditability, legal standability, and supplier responsiveness. The preference of CFS over the other techniques lies in its direct determination of the most relevant characteristics used in carbon performance, such as scrap ratio, electricity GWP, and transport distance, among others, without the risk of latent factors being established through unobservables used in the scoring. In contrast, PCA, though useful when there is a diagnostic need, does produce latent components that cannot be directly interpreted by suppliers or by auditors. This uninterpretability may bring about difficulties in verifying the suppliers' statements, which will offset the auditability of the carbon data.

CFS selected features are also more transparent. They can enable suppliers to be aware of areas of their production activities that can be communicated as the most important to minimize their carbon footprints. As an example, a highly ranked supplier of low-carbon steel, due to their scrap ratio or the intensity of the carbon content of electricity consumed, can make specific interventions in these areas, and maintain their high ranking. Conversely, a PCA-based scoring system will merely report the suppliers with a summarized value of their carbon score, without providing specific directions on areas for improvement. Such opaqueness might result in greenwashing or underperformance by suppliers.

In this manner, CFS represents a better fit with the objectives of supplier actionability and legal defensibility. It has an advantage in that it makes every party of the procurement process aware of the implications of their processes directly concerning the carbon footprint, enhancing the transparency of the procurement process. On the contrary, PCA is not applicable in final decision making where the main objective is clarity and traceability (13). Although it can be utilized as a diagnostic tool to evaluate how a procurement model is performing, it lacks a detailed decision-making process. It cannot be applied during the final decision-making process (14).

5.3 Comparison with Prior Work

The current study contributes to the prior research on green procurement and low-carbon construction. The notion that green public procurement (GPP) can lead to environmental transformation in the construction industry is supported by a growing body of literature that demonstrates how such a green initiative can result in a green transformation (16). Past research indicates that the inclusion of sustainability measures within procurement processes has considerable potential in terms of environmental performance. However, adequate attention to cost implications, supply chain behaviors, and verification identification must be within scope.

Comparing the methodology of this study with previous studies on the carpet in the literature on green procurement, one of the main distinctions is concentrated on the embodied carbon in steel, since not all materials have been equally covered in the literature, like concrete or timber. In this research paper, the researcher tackles the unique demands that DOTs face concerning the usage of green steel, such as the necessity of ensuring high levels of mechanical requirements (fracture-critical standards, to offer just one example) and the requirement of publishing decreased carbon footprints. This is a novel input to the field since previous literature usually focuses on the management of the supply chain or general strategies on green procurement, rather than the technical plan of the procurement of construction materials. Moreover, the carbon scores included in the MCDA model deployed in this research are not a characteristic feature of conventional GPP systems. Although frameworks of GPP in the building industry pay attention to factors like energy efficiency and materials sourcing, the current research emphasizes how carbon performance should be implemented in the selection process of vendors, which would give DOTs a specific practical instrument to lower the amount of carbon emissions (23).

5.4 Risks, Constraints, Mitigations

Although the potential environmental benefits of reducing carbon emissions and saving money are high, the adoption of green steel in DOT procurement is subject to several limitations and threats. One of the most significant impediments is the boundaries of the supply chain. There are limited quantities of H2 and DR-grade pellets, especially in places that are not covered by green hydrogen infrastructure or that have appropriate volumes of scrap steel. Also, the carbon gain of low-carbon steel can be compromised by grid intensity in areas where fossil fuels are highly dependent, if electricity sources are linked to non-renewable sources to make steel.

Quality check (QA) is another thing, especially with fracture-critical ones. Critical infrastructure requires specialized steel, which has high mechanical and safety requirements (e.g., AASHTO M270), and low-carbon steel technologies should not negatively affect these characteristics. The greenwashing risk will never clear, especially when the suppliers exaggerate their carbon-reducing value to their products, without appropriate verification. Such can be alleviated by having third-party certifications of EPDs and conducting random audits of supplier claims. Moreover, MTR federal public development should also be made compulsory, such that no materials employed in DOT projects go unaccounted for.

5.5 Implementation Playbook (Actionable for DOTs)

DOTs can only join the effort to reduce carbon emissions through carbon-conscious steel acquisition with the help of a playbook. Clear rules on specifications and submittals should be covered in this playbook, where suppliers will be expected to supply plant-specific, verified EPDs, with complete statements of boundary scope and limitations. Essential is that the requirements do not lower the performance standard, as we have in the available AASHTO and ASTM standards, so that the low-carbon steel should still conform to all the safety and quality requirements.

Arrangement of bid evaluation should be built around the dissemination of the carbon scoring baseline and scoring functions, wherein carbon scoring ought to be incorporated within the MCDA model. Practically, DOTs need to have a mechanism for alternative bids, given that the GWP reductions should be documented by suppliers using EPDs to create competition but lead to reduced emissions. Prequalification criteria need to take into account the EPD maturity levels, where more mature EPDs (which are third-party verified) should have a higher rating. There should be regular audits to monitor adherence to carbon performance and the improvement of suppliers over time. Contracting and MRV provisions ought to be drawn up to guarantee that suppliers provide post-award statistics on carbon performance and participate in substitution controls in case the market products fail to meet EPD claims. Procurement and materials personnel should be trained so that they are conversant with the EPD requirements, carbon scoring mechanisms, and audit methodologies, and this will provide a uniform application at every tier of the DOT operations.

5.6 Strengths & Limitations

The study has several strengths, such as the utilization of DOT-specific functional units (FUs) and solid verification activities to assess green steel implementation. The inclusion of Exploratory Data Analysis (EDA) and Principal Component Analysis (PCA) to evaluate the quality of data and feature selection of a procurement model offers significant benefits, as DOTs can enhance their carbon scoring models and make them more precise. The procurement data collected in the study has also provided practical implications for implementing carbon-aware procurement processes by DOTs. The study also has some limitations. The heterogeneity of EPDs is a point of difficulty because different standards and the inability to compare EPDs may lead to carbon performance being assessed differently. Moreover, the experience of low-carbon steel technologies in the long-run applications in fracture areas is not clear despite the attention given to the study on near-term adoption. Researchers must consider the changing performance of these technologies and their impact on the lifecycle carbon emissions of an infrastructure project.

5.7 Future Research

The direction that rightly should be followed by future research is the investigation of the price-emissions elasticities of low-carbon steel technologies over time to establish the evolution of cost-effectiveness given the growth in production and maturation of their supply chains. Fracture-critical steel made by H2-DRI and EAF also needs to be investigated to ensure it meets the desired mechanical properties required for the DOT application. Optimization of the design/material efficiency practice, including section optimization and high-strength steels, could further minimize the carbon footprint of infrastructure projects.

6. Practical/Policy Implications

6.1 Roadmap (0–6, 6–12, 12–24 months)

0–6 Months: Establish Baselines and Initiate Pilot Programs

The first step toward implementing green steel in DOTs is developing the baseline measurements and launching pilot programs. The most important aspect of this phase is the fact that all bids on steel would have to include Environmental Product Declaration (EPD), which means suppliers should always provide information on emissions. Setting a minimum standard of carbon emitted through steel manufacture and defining emission limits in procurement specifications will provide a reference point for measuring. Researchers also recommend the establishment of a pilot framework on carbon-weighted procurement, with 10% carbon weight being incorporated initially in the evaluation of the bids. This will enable DOTs to determine the feasibility of integrating carbon in their decision processes without locking down the suppliers. Under this stage, DOTs have to make sure that the initial carbon footprints of the various types of steels are appropriately documented and traceable so that clear and audit-verifiable baselines are laid. An incremental or gradual rise in the weighting of carbon used in procurement over time will eliminate sudden destabilisation, as the progress will contribute to the long-term environmental objectives. Research conducted indicates that the greening of the industry through the introduction of sustainability standards in procurement can prompt overall changes in making the sector more sustainable, including construction and materials supply (17).

6–12 Months: Expand to Major Bridge Packages and Launch Audits

Once the pilot program has been successfully implemented, the DOTs ought to scale the carbon-weighting strategy to accommodate more massive infrastructure projects, including significant bridge packages. At this point, DOTs ought to insist on plant-specific EPDs regarding steel plate and rebar to make sure that the carbon composition of the steel utilized is correctly listed. This will be necessary so that procurement activities will be linked to sustainability goals, and certified documents will be used to verify whether the postulated carbon reduction holds. In addition to that, there must be audit systems in place to ensure the EPD authentication and prove that the suppliers have given the correct carbon claims.

Greenwashing risks potential exaggeration by the suppliers of the fact that their products are helpful to the environment, something which the audit process will solve. The concept of audits should be accompanied by the creation of a verification method to assess the carbon performance of the steel products. Testimony of transparency and traceability of carbon data will be prime in scaling the program to a broader scope of infrastructure projects. Nyati recommends that regulating green procurement with systematic audits is also one of the fundamental practices in enhancing the responsibilities and integrity of the green procurement operations (21).

12–24 Months: Introduce Category GWP Caps and Publish Market Signals

In the mid-term (12-24 months), DOTs ought to consider the implementation of category-specific greenhouse gas (GWP) limits within steel goods after the supply chain has stabilized and coverage of supplies is increased to a minimum of 60% or over. These caps will impose caps on the maximum possible carbon content of steel that is to be used with DOT projects, and this will encourage further innovation in the low-carbon manufacturing processes. The DOTs may initiate the publication of market signals every year, indicating the expected demand for low-carbon steel, thus giving the supplier the needed incentives to invest in and develop low-carbon steel production at scale. This will bring about market-based reduction of carbon in the steel industry.

Communication of these targets should be made very clearly and early so that the supply chain can prepare well in time. Additionally, indicating the necessity of more environmentally friendly steel will help to trigger competition among the suppliers in terms of offering low-carbon steel. The indicators will also help in achieving state and federal sustainability objectives. According to Chavan, industry collaboration may increase and promote enhanced innovation in supply chains with clear policy signals (4). The 24-month roadmap for green steel adoption in DOTs includes baseline establishment, pilot programs, audits, and carbon caps. It aims to drive sustainability and innovation, as the figure below illustrates through Lakshmi Mittal's legacy pillars—R&D, sustainability, and economic leadership.

*Figure 9: **How Innovation Has Changed the Steel Industry***

6.2 Tooling Recommendation

To facilitate the use of green steel and to make procurement decisions fair, transparent, and harmonized to save the environment, DOTs are encouraged to use CFS-based interpretable feature sets of carbon terms in procurement models. Correlation-based Feature Selection (CFS) is one of the better methods to discover the most informative and interpretable features in massive datasets, which is usually essential when we appraise the carbon footprint of steel products. The use of CFS can help DOTs choose the properties with the best correlation to reduced GWP (carbon intensity) without getting lost in irrelevant or collinear variables. CFS allows a manageable and measurable methodology to decide which supplier attributes (eg, the electricity mix utilized during production, ratios of scrap, or quality of the raw materials) to feature in procurement scoring. Once this feature set is chosen, it must be published with its definitions and source of origin to allow easy comprehensibility by both suppliers and procurers. With CFS, DOTs will be able to give constructive, helpful feedback to their suppliers so that they will be more able to concentrate on environmentally responsible aspects that have the most significant effect (5).

PCA (Principal Component Analysis), which also helps perform dimensionality reduction and identify latent variables, should be considered as a possible additional measure for the DOTs to have a PCA diagnostic annex as a safety measure. Its annex can be employed to verify the outcome of CFS, and it helps give clues on the hidden structures that might not be so evident. Such a blanket approach will make the whole procurement process not only interpretable but also strong and easier to comply with for suppliers regarding environmental factors. Based on Kumar (2019), decision-making can vastly improve the proper selection with the help of such interpretable analytics models as CFS and lead to a more transparent process of procurement (18).

6.3 Alignment & Regionalization

Buy America and Buy Clean have introduced pressure on DOTs to prioritize domestic suppliers and low-carbon materials. In that regard, DOTs should ensure that their green steel procurement programs align with these federal and state policies. Particularly, they should make sure that the materials utilized in infrastructure projects satisfy domestic content regulations and, at the same time, satisfy carbon reduction goals. Identification with these programs would help DOTs to have internationally legalized and country-specific strategies that align with the DOT green procurement strategies and national sustainability plans and aims (29).

An additional practical aspect is regionalization, which relies on local production capacity, especially those based on Electric Arc Furnace (EAF)-based mills, and renewable grid area will not only reduce the carbon intensity in steel products but also lower the A4 transport emissions that come with the delivery of steel. DOTs need to consider the potential of logistics pooling between DOTs, which would involve as many state departments as possible sharing similar transportation routes to minimize the carbon footprint created by long-distance transportation of steel products. These regional solutions can coordinate the area-based sustainability objectives with the larger environmental ambitions. Cooperation with EAF mills, which will be more frequently supplied with renewable energy sources, will play a crucial role in realizing high-level carbon cuts. Local relationships between the DOTs of a state and local mills will assist in accepting the widespread accessibility and reduced expenses of low-carbon steel, facilitating widespread change in the industry. Such notion as regionalization was revealed to amplify the local economic gains of green procurement, yet it also helps to reduce the emissions of the whole supply chain (4).

7. Conclusion

This study introduces an all-encompassing Green Steel Adoption Playbook to Departments of Transportation (DOTs), which will help respond to the critical demand to decarbonize the steel purchasing process despite ongoing infrastructural construction. Based on the research, one can conclude that the use of green steel technologies may make it possible to have a considerable decrease in the carbon footprint linked to the steel procurements without affecting the significant qualities of its use, such as its safety, durability, and affordability. This can be done by incorporating the use of Environmental Product Declarations (EPDs), multi-criteria decision analysis (MCDA), and Oversight procedures to permit a sustainable, transparent, and cost-effective procurement process, which is aligned with the objectives in environmental aspects. The main value contribution in this playbook is the technical foundation of standardization of functional unit and carbon baseline, as well as the use of data-driven analytical tools, including Exploratory Data Analysis (EDA), Principal Component Analysis (PCA), and Correlation-based Feature Selection (CFS). These tools help DOTs to assess and confirm the carbon emissions of suppliers objectively and ensure that the procurement process is transparent, auditable, and actionable to all stakeholders. Consequently, this paper presents a well-organized method of scaling up the usage of green steel whereby DOTs are not only lowering the embodied carbon in their work but also advancing innovations and competitions in the marketplace.

The green steel adoption roadmap suggested in this playbook will start with pilot programs to establish a baseline for carbon emissions and progressively incorporate carbon-weighting as a condition in the procurement process. This gradual practice will enable DOTs to understand the productivity of carbon inclusion without imposing too many burdens on the supply chain and its suppliers. Because green steel supply grows and becomes more competitive, the playbook suggests ramping up the carbon-weighting to significant infrastructure investments and ultimately including category-specific greenhouse gas (GWP) limits to steel procurement. These caps will be an effective policy tool, which sends a signal to the market and rewards additional efforts to reduce the carbon intensity of steel products. The introduction of the CFS-based procurement model in the playbook also represents a pivotal step forward in assessing green steel offers. This model is dedicated to explaining attributes like scrap ratios, mix of the electricity grid, and the distance of the transportation that directly affect the carbon emissions. Through the transparency and traceability of these features, DOTs will not only enhance the supplier's knowledge on how to optimize for lower carbon footprints but also ensure fairness and responsibility in procurement. Whereas PCA can be used as a diagnostic that would allow understanding the latent drivers of carbon variability, CFS would guarantee that the procurement model would be accessible and comprehensible within the scope of the operations of DOTs and other industry stakeholders. Alignment and regionalization with other policies, such as Buy America and Buy Clean, also offer viable solutions to make sure that domestic sourcing and low-carbon steel procurement will not conflict with federal and state requirements. DOTs can lower their carbon intensity and transportation emissions by sourcing locally produced goods, particularly those made in Electric Arc Furnace (EAF) mills using renewable energy, thus further prioritizing the development of their sustainability agendas. Logistics pooling between the adjacent DOTs is also suggested as a method of minimizing supply chain emissions and ensuring that green steel is penetrating the market better.

The Green Steel Adoption Playbook strives to be a replicable, data-driven playbook that not only helps DOTs meet their decarbonization milestones but also drives industry-wide transformation of steel production. This playbook will help DOTs pursue the shift to sustainable infrastructure without compromising the integrity of competitive procurement processes because it facilitates transparency and market signals as well as enables active interaction with suppliers. Green steel technologies are still young, but as they are implemented, their affordability and accessibility will only increase, which makes this playbook an essential component of DOTs ensuring the transport sector has a low-carbon future. This study highlights how green procurement activities can make a big difference in embodied carbon within state/federal transportation infrastructure, which can be a significant contribution toward state and federal sustainability goals. The study area should target price-emission elasticity, the long-term behavior of fracture-critical steel, and economic scaling of low-carbon steel for future investigation to strengthen the next cycle of green construction success. Sustainable steel procurement is not easy, but the action items in this playbook provide DOTs a straightforward and doable roadmap to pursue.

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