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EXTENDING IFC DATA STRUCTURE FOR CARBON DIGITAL TWIN: AN IFC ROAD EXAMPLE

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Abstract

The construction sector must accelerate progress towards net-zero targets. Current digital twin (DT) frameworks lack integrated carbon data, limiting their effectiveness for sustainability. Industry Foundation Classes (IFC), as an international open data standard, offer the potential to address this gap without exacerbating interoperability issues. This paper proposes extending the IFC schema to include carbon data, focusing on road infrastructure. This study maps the key entities for carbon management to a granular level and adds new carbon property sets to the key entities. It is essential for a carbon digital twin (CDT) that requires exchanging information across lifecycle stages and stakeholders for computational carbon management of road infrastructure.

Introduction

The construction and infrastructure sectors face growing pressure to achieve net-zero carbon targets, requiring innovative approaches to manage and mitigate carbon emissions. The engineering and construction industry has recognized the potential of DTs for carbon data integration. While DTs have advanced for various applications, including structural monitoring and process optimization, their use for carbon management remains in the infancy stage, particularly for infrastructure such as roads. Existing DT implementations often omit carbon data, resulting in missed opportunities for comprehensive lifecycle carbon management.

A CDT offers a transformative solution for highway infrastructure, integrating dynamic, fine-granular carbon data into digital platforms to support lifecycle carbon management and data-informed decision-making (Xu and MacAskill, 2024b). A CDT extends the concept of a DT — a virtual replica of a physical asset — by embedding carbon information as a critical data layer. He et al. (2023) proposes a closed-loop DT system with a product carbon footprint analysis model to assess product carbon impact. Zhang et al. (2024) combined DT with carbon emissions accounting and estimation of residential operation carbon reduction potential. Elghaish et al. (2024) reviewed the potential of DT for carbon emission prediction. While previous research has mainly explored the carbon estimation and prediction power of DT, its great potential in real-time monitoring, analysis, and optimization of carbon performance, helping to align infrastructure management with sustainability goals, has yet to be unlocked.

However, developing CDT presents challenges related to data interoperability, consistency, and trustworthiness (Xu and MacAskill, 2023). Carbon data comes from various sources, such as drawings, building information models (BIM), bill of quantities (BoQ), procurement records, site logs, energy bills, environmental product declarations (EPD), Internet of Things (IoT), carbon factor databases, etc. Data from different sources have different structures that bring up the data interoperability challenge. Previous research has highlighted that the lack of a standardised carbon data structure hinders the trustworthiness and granularity of carbon data needed for fine-granular analysis (Xu and MacAskill, 2024a). The Industry Foundation Classes (IFC) standard, widely adopted as an international open data schema, provides a promising framework to address these challenges (Leal et al., 2020). IFC Road, a specialized extension of the IFC schema for road infrastructure, can facilitate seamless data exchange across stakeholders and lifecycle stages for road carbon management (Floros et al., 2019). Expanding the IFC Road schema to include carbon data can bridge gaps in current practices, ensuring that carbon data is collected, organised, and shared consistently among stakeholders into structured carbon datasets. IFC is not used to develop the database but the properties of the database to allow interoperable data exchange among different stakeholders. The structured carbon datasets are essential for computational analysis of hotspots, carbon efficiencies, and carbon-cost optimisation, which will support better decision-making across the lifecycle of road infrastructure.

This paper explores how carbon data can be integrated into the IFC Road schema to enhance data interoperability and support lifecycle carbon management in the construction sector. Using road infrastructure as the research context — where carbon integration into digital workflows is less mature compared to building assets — this study develops a schema to align carbon data with IFC Road standards. By addressing the current gap in the lack of clearly mapped entity relationships and clearly defined carbon-relevant property sets, this research aims to enhance data consistency and interoperability for standardised carbon management

in road infrastructure.
The paper is organized as follows: After a brief "Introduction" section, the "Research methods" section outlines the methods and tools for expanding IFC Road to include carbon data. Then, the existing carbon -related properties in the buildingSmart Data Dictionary (bSDD) is reviewed to present the status quo and set the scene for the "Proposed data schema" section which presents the mapping of carbon-relevant entities, including material/product, process, project, user, and asset, for lifecycle carbon integration in DTs. The carbon property sets for each entity are developed to capture carbon data. Also, the relationship between different property sets is mapped. The data schema is tested with a small road section DT model. The last section discusses the findings and concludes with key insights and future research directions.

Research methods

This section describes the research methods adopted to systematically develop and validate an extended IFC-based schema for integrating carbon data into DTs of road infrastructure. The process follows a structured approach comprising six key steps. This paper presents the key results of the last three steps.

Define Objectives and Scope

The objective is to focus on integrating fine-granular carbon data into DTs of road infrastructure. The scope includes identifying critical lifecycle stages—design, construction, operation, maintenance, and demolition—and selecting key attributes such as embodied carbon, operational carbon, and lifecycle stage carbon. The entities and properties are further aligned with IFC Road standards to ensure relevance to road infrastructure and compliance with international interoperability protocols.

Gather Requirements

A comprehensive review of relevant literature, standards, and best practices was conducted to gather requirements for carbon data integration (Xu and MacAskill, 2024a). This included analysing regulatory documents, industry standards (e.g., ISO 19650), and previous studies on carbon data collection and management. A design-thinking workshop and 12 focused interviews with professionals in the road sector were conducted to identify the carbon data value and requirements. The outcome of this step was published in a previous paper, i.e., (Xu and MacAskill, 2024a), and this paper used the results directly.

Create the Conceptual Model with Protégé

Protégé, an open-source robust tool for ontology-based schema design, was used to develop a conceptual model that maps the semantic relationships and hierarchies between carbon data entities. Creation of conceptual model with Protégé is used for semantic modelling of the things (e.g., process, project, product) and their relationships involved in construction projects with a focus on tracing carbon flows.

Map Ontology with IFC Road

The classes in the ontology developed by Protégé were mapped with the IFC entities in the bSDD, which is an IFC-specific tool to standardize entities, attributes, and property sets. A mixed method of manual mapping and programmatic mapping was used. The Protégé ontology was extracted as an RDF file. Firstly, Python-based programmatic mapping was used to calculate the semantic similarity of entities in the developed ontology and bSDD through its API. Then, a screening was conducted to identify which entities had not been well mapped, where a manual mapping was supplemented. Iteratively, the entities in the ontology and the bSDD are mapped, as well as their relationships. The ontology is created for knowledge sharing and reuse, which are the purposes of Linked Data. However, mapping information requirements in the ontology into IFC property sets requires additional efforts. Herein, ontology serves as a flexible knowledge modelling tool, in comparison with IFC, which is a data standard. That's why the IFC entities are defined with ontology instead of using the native IFC format.

Extend property sets

Property sets of the mapped entities in the bSDD are extracted to check whether they are sufficient for carbon management; if not, what other properties should be added. The extended carbon properties are identified from the design-thinking workshop and they are mapped to the key carbon entities.

Implementation and Testing

The validated schema was implemented and tested using a simple road IFC file. A UK road use case embedding carbon data into DT model was implemented.

Existing carbon-related IFC properties

Acknowledging that construction products have an important impact on our environment in production and disposal, the buildingSMART Sustainability Strategic Group has developed some LCA indicators and modules by incorporating life cycle stages and environmental impact indicators into the bSDD. However, the main purpose of developing the LCA indicators and modules was to allow a fair and reproducible environmental assessment in the early planning stages for buildings. The integrated indicators include primary energy and global warming potential (GWP) which represent the relevant emissions to global warming during the production and disposal of construction materials as carbon dioxide equivalent. Such a common machine-readable digital framework of life cycle phases and environmental impact indicators based on a common digital language represents a significant initiative to allow manufacturers to provide their environmental product declarations (EPD) in a decentralized way or to refer to the corresponding generic EPD.
There are currently 49 LCA property sets in the bSDD, including indicators and modules covering Acidification,

Biogenic carbon content at the factory gate, Environmental information describing output flows (i.e., exported electrical/thermal energy, exported materials for re-use/energy recovery/recycling), Eutrophication, GWP, Human health, Inventory indicators describing resource use (e.g., primary energy and resources), Land use related impacts, Ozone Depletion, Ozone Formation, Resource depletion, Resource use (e.g., secondary materials and fuels, water), Scenarios (e.g., Transportation), and Waste. Among them, the GWP property set is most relevant to carbon data properties. It includes four class properties: GWP-biogenic, GWP-fossil fuels, GWP-land use and land use change, and GWP-total by referring to EN 15804:2012+A2:2019. Specially, GWP-biogenic corresponds to the carbon content of products, bio-fuels or above ground plant residues such as litter and dead wood. GWP-fossil covers greenhouse gas (GHG) emissions to any media originating from the oxidation and/or reduction of fossil fuels by means of their transformation or degradation (e.g. combustion, digestion, land-filling, etc.). GWP-luluc describes the potential radiative forcing impact of carbon uptakes and emissions (CO_2, CO, and CH4) originating from carbon stock changes caused by land use change and land use over a given period of time. GWP-total accounts for the total global warming potential arising from fossil, biogenic and land use and land use change emissions.

These four GWP properties are developed to store data from construction product EPDs. While acknowledging that EPDs are very important granular product-level data for carbon management, how they relate to and accumulate to other levels of entities needs to be streamlined. Meanwhile, more properties for different levels of entities should be developed to ensure clearer communication and storage of carbon-specific data. Therefore, this paper aims to define the carbon properties for carbon management, with a focus on IfcRoad, while acknowledging that they can also be used for buildings with least modification.

Proposed data schema

The proposed data scheme includes three hierarchical levels of entities and their relationships to support the data flow. The definition of some of the entities is adjusted for the road domain and its carbon management purposes. Newly carbon property sets are defined in addition to existing property sets to store carbon-specific data.

Hierarchy Overview

Figure 1 maps the IFC entities that are relevant to carbon reporting. The highlighted entities are the key data points for carbon management while others aggregate or link to them. *IfcProject* sets at the highest hierarchy and it is then connected with *IfcSite* that is connected with *IfcRoad*, which then be part of *IfcAsset*. *IfcRoad* is aggregated by *IfcRoadPart* which encompasses many different categories of elements. *IfcRoadPart* is an *IfcProduct* that is assigned to *IfcProcess* and *IfcResource*. While different types of resources are assigned to *IfcProcess* that is also aligned to *IfcActor* which includes *IfcOccupant* that uses *IfcAsset*. Embodied carbon comes from different resources used to construct roads, as well as the fuels and energy consumed by labor, crew, actor, and equipment during the construction, in-use, and end-of-life stages. Operation carbon is generated from the operation energy and water and user (i.e., *IfcOccupant*) carbon. It needs to be clarified that only *IfcRoadPart* is connected with *IfcProcess* and *IfcResource* just to illustrate their relationships. Other entities, such as *IfcPavement* that are aggregated to *IfcRoadPart* and other products that aggregate to *IfcRoad*, also connect with *IfcProcess* and *IfcResource*, but for the simplicity of illustration, they are not shown in Figure 1 .

***Top Level**: IfcProject*

IfcProject serves as the umbrella entity, encompassing all relevant information of the entire project. It contains *IfcSite* for site-specific information, *IfcRoad* for road infrastructure information, and *IfcAsset* which is a group of road sections.

***Second Level**: IfcSite, IfcRoad and IfcAsset*

IfcAsset represents a group of road infrastructure. *IfcRoad* defines the physical and functional structure of the road, it is part of *IfcAsset* and encompasses different *IfcRoadPart* which can be linked to *IfcGRoadSegement*, *IfcGeotechnicalElement*, *IfcBuiltElement* (e.g., *IfcCourse*, *IfcKerb*, *IfcPavement*), *IfcFurnishingElement*, *IfcDistributionElement*, etc., via *IfcRelContainedInSpatialStructure*. All the structures and components under *IfcRoad* contribute to the embodied carbon of the road asset. This level is a connecting level between the first level and third level.

***Third Level**: IfcProcess, IfcResource, IfcActor*

IfcRoadPart is a *IfcProduct* which is assigned with *IfcProcess* and *IfcResource* to be constructed and maintained, as well as used by *IfcActor* (to be more specific, *IfcOccupant*).

IfcProcess is one individual activity, task, or event that is interrelated or interacted with other processes, which transforms input (i.e., *IfcResource* or *IfcProduct*) in output (i.e., *IfcProduct*). *IfcProcess* tracks construction and maintenance activities contributing to carbon emissions.

IfcResource stores data related to embodied carbon in various construction resources such as materials, products, equipment, crew/labor.

IfcActor defines all actors or human agents or organizations involved in a project during its full life cycle. It represents workers and users influencing embodied and operational carbon emissions through behaviors (e.g., traffic patterns, vehicle types, and traveling distance).

Extended Carbon Property Sets

Since different levels of entities have different carbon data requirements Xu and MacAskill (2024b), for example, for projects, data such as the targeted overall carbon emis-

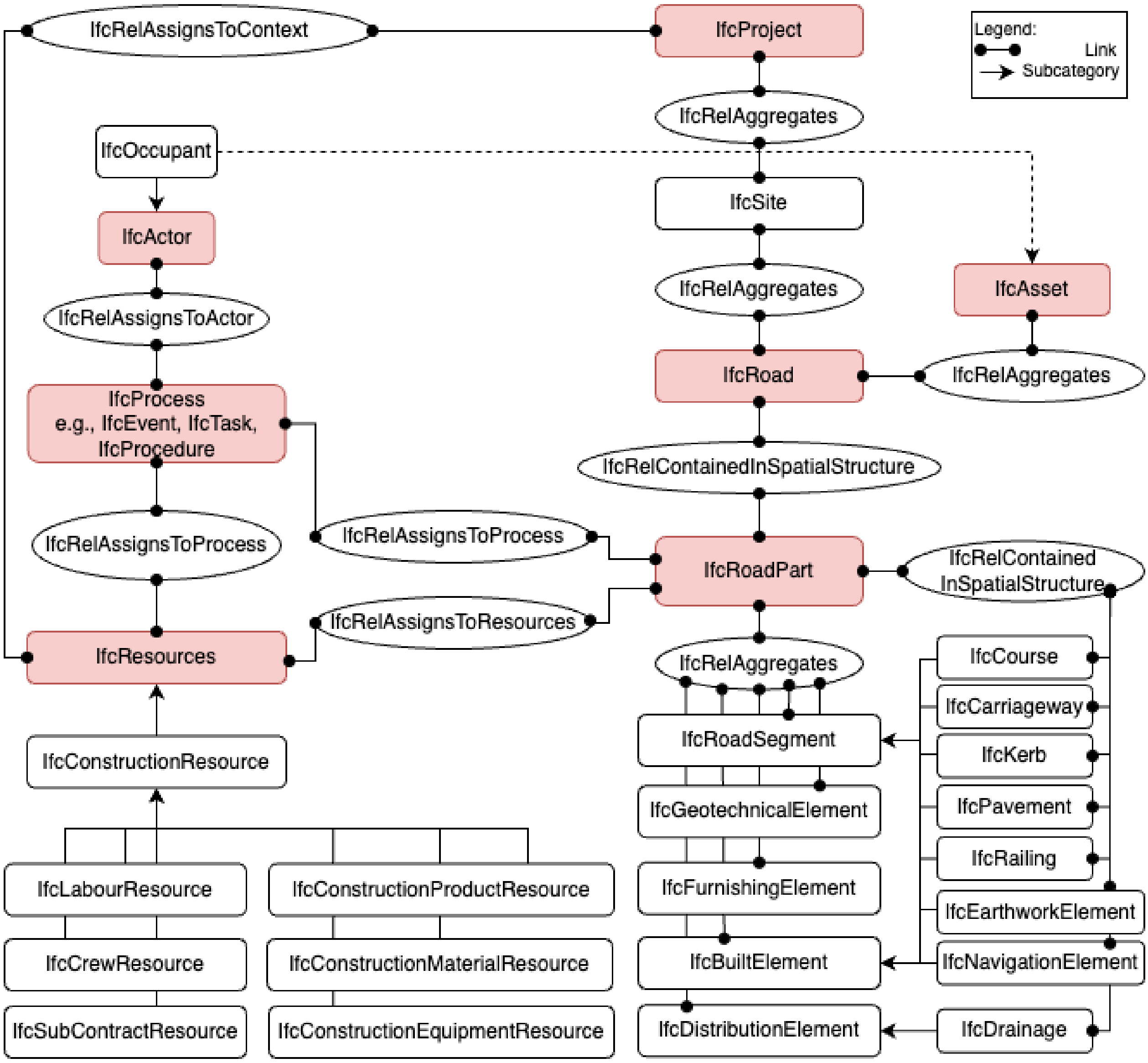


Figure 1: Mapping carbon data related IFC entities

sions, the overall carbon emissions avoided across the project lifecycle, and the carbon emissions for each lifecycle modules (A0-C4), different carbon property sets are needed for each different class. While for most of the entities in the second and third levels, such as IfcRoadPart, it is possible to accumulate the data from IfcProcess and IfcResources, in this case, existing property sets are utilized as much as possible. Therefore, we extended the existing carbon-related IFC properties to a new set of carbon property sets, which will be explained in the following subsections.

1. *IfcProject* carbon property set *Pset_ProjectCarbon*:

- *ProjectCarbonTarget*: Targeted overall carbon emissions of the project.
- *ProjectCarbonActual*: Actual overall carbon emissions of the project.
- *ProjectCarbonAvoided*: Overall carbon emissions avoided across the project lifecycle.
- *ProjectEmbodiedCarbon*: Embodied carbon emissions of the project across its lifecycle.
- *ProjectOperationalCarbon*: Carbon emissions of the project of operation throughout its service life.
- *ProjectLifecycleStageCarbon*: Carbon emissions for each lifecycle stage (A0–C4) referring to standard BS EN 15978, including E_{A0}, E_{A1}, E_{A2}, E_{A3}, E_{A4}, E_{A4}, E_{A5}, E_{B1}, E_{B2}, E_{B3}, E_{B4}, E_{B5}, E_{B6}, E_{B7}, E_{B8}, E_{C1}, E_{C2}, E_{C3}, and E_{C4}.

* The property sets data type: *IfcReal*, and their unit: $kgCO_2e$.

2. Second-level entities with similar properties as *IfcProject* contain the middle level of accumulative number of the carbon properties. For example, *IfcRoad* carbon property set *Pset_RoadCarbon* :

- *RoadCarbonTarget*: Targeted overall carbon emissions of the road.
- *RoadCarbonActual*: Actual overall carbon emissions of the road.
- *RoadEmbodiedCarbon*: Embodied carbon emissions of the road across its lifecycle.
- *RoadOperationalCarbon*: Carbon emissions of the road of operation in its service life.
- *RoadLifecycleStageCarbon*: Carbon emissions for each lifecycle stage, similar to *ProjectLifecycleStageCarbon*.

3. *IfcProcess* carbon property set *Pset_ProcessCarbon*:

- *ProcessEquipmentEnergyType*: The type of energy needed for the equipment of a process (Type: IfcString; e.g., electricity, diesel).
- *ProcessEnergyConsumption*: Energy consumption of an individual process, (Type: IfcReal; Unit for fuel: liter, Unit for electricity: kWh).
- *ProcessWaterConsumption*: Water consumption of an individual process (Type: IfcReal; Unit: kg).

There are resource type and quantity properties for different resources that can be used for carbon calculation and analysis. Apart from those, additional *IfcResource* property sets for carbon management include *Pset_IndividualResourceCarbon*, *Pset_ProjectResourceCarbon*, and *Pset_ResourceQuantities*.
4. *Pset_IndividualResourceCarbon* has properties (i.e., GWP-biogenic, GWP-fossil, GWP-luluc, GWP-total) that are already in the bSDD and additional ones for each individual product type are as follows:

- *CarbonEmissionSource*: Source of carbon data (Type: IfcString, e.g.: EPD, IPCC).
- *EpdId*: The unique ID of EPD or digital product passport associated with the resource (Type: IfcString).
- *EmbodiedCarbonIntensity*: Embodied carbon per unit of resource (Type: IfcReal; Unit: $kgCO_2e/t$, $kgCO_2e$ $/m^3$, $kgCO_2e/m^2$, $kgCO_2e/m$, $kgCO_2e/l$, $kgCO_2e$/each).
- *ResourceTransportDistance*: The distance for material or product resources to be transported from suppliers to construction sites (Type: IfcReal; Unit: km).
- *ResourceEnergyType*: The energy type used by equipment (Type: IfcString; e.g., electricity, diesel)..
- *MaterialLifecycleStage*: Applicable lifecycle stage (Type: IfcString; e.g., A1, A2, ..., A5, B1, B2, ...B8, C1, ..., C4).

5. *Pset_ProjectResourceCarbon* includes project-level resource properties:

- *ReusedMaterialPercentage*: Percentage of reused material (Type: IfcReal; Unit: %).
- *RecycledMaterialPercentage*: Percentage of recycled material (Type: IfcReal; Unit: %).
- *ReducedMaterialPercentage*: Percentage of reduced material (Type: IfcReal; Unit: %).
- *MaterialWastePercentage*: Percentage of material that goes to waste (Type: IfcReal; Unit: %).

6. *Pset_ResourceQuantities* has properties:

- *MaterialQuantity*: Quantity of each type of material used (Type: IfcReal; Unit: kg, m^3, m^2, m, liter).
- *EnergyQuantity*: Quantity of each type of energy used (Type: IfcReal; Unit: kWh, liter).
- *WaterQuantity*: Quantity of water used (Type: IfcReal; Unit: kg).
- *WasteMaterialQuantity*: Quantity of material wasted (Type: IfcReal; Unit: kg, m^3, m^2, m, liter).
- *MaterialReduced*: Quantity of waste material reduced (Type: IfcReal; Unit: kg, m^3, m^2, m, liter).
- *WaterReduced*: Quantity of water saved (Type: IfcReal; Unit: kg).

7. *IfcActor* carbon property sets *Pset_ActorCarbon*:

- *TravelPattern*: The travel patterns of an actor (Type: IfcString, e.g., "Train", "Bus", "Car").
- *VehicleType*: Vehicle type (Type: IfcString, e.g., electric vs. combustion).
- *TravelDistance*: Vehicle type (Type: IfcReal, e.g., km).
- *OccupancyRateImpact*: The impact based on vehicle occupancy rates (Type: IfcReal; Unit: %).

Table 1 summarises the key entities, their carbon properties, and relationships.

Data Flow

The data flow between the key entities is illustrated in Figure 2. Activity data comes from *IfcProcess* (which captures task-level data), *IfcResource* (which tracks material and equipment-level embodied carbon), and *IfcActor* (which records operational impacts). Then *IfcRoadPart* consolidates emissions data from its components and *IfcRoad* rolls up carbon data from *IfcRoadPart*. *IfcProject* delivers project-wide lifecycle carbon analytics. *IfcAsset* accumulates carbon of a group of road sections at the network level. Data collected during each project

Table 1: Key Entities, Key Property Sets for carbon and their relationships

Category	Mapped IFC Entity	Key Carbon Property Sets	Relationships with other entities
Asset	*IfcAsset*	Pset_RepairOccurrence, Pset_AssetCarbon	Aggregates *IfcRoad* and *IfcActor*.
Project	*IfcProject*	Pset_ProjectCommon, Pset_ProjectCarbon	Aggregates *IfcContext*, *IfcSite*, *IfcRoad*, *IfcFacility*, *IfcExternalSpatialElement*.
Road	*IfcRoad*	Pset_RoadDesignCriteriaCommon, Pset_SpaceOccupancyRequirements, Qto_BodyGeometryValidation, Pset_RoadCarbon	Links to *IfcRoadPart* and *IfcGeotechnicalElement*, *IfcBuiltElement* (e.g., *IfcCourse*, *IfcKerb*, *IfcPavement*), *IfcFurnishingElement*, *IfcDistributionElement*, etc.
User	*IfcActor*	Pset_ActorCommon, Pset_ActorCarbon	Supertype of *IfcOccupant* which refers to the road users, linked to *IfcAsset* via *IfcRelAssignsToActor*.
Process	*IfcProcess*	Pset_ProcessCarbon	Supertypes of *IfcTask*, *IfcProcedure*, *IfcEvent*, Linked to *IfcProject*, *IfcRoadPart*, *IfcResource*, and *IfcActor* which refers to workers in this case.
Resources	*IfcResource*	Pset_IndividualResourceCarbon, Pset_ProjectResourceCarbon, Pset_ResourceQuantities, Pset_ConstructionResource, Qto_ConstructionEquipmentResource BaseQuantities	Include different types of resources, linked to *IfcProduct* via *IfcProcess* and *IfcSchedulingTime*, and *IfcResourceLevelRelationship*.

phase (i.e., design, construction, operation, and end-of-life) feeds back into *IfcProject*. The origin activity data can be sourced from existing data systems or sensors/IoT devices for traffic monitoring, water and material usage, and equipment operations and vehicle tracking systems to measure energy consumption. Essentially, the activity data originated from how much water is used during construction and maintenance processes, how much energy is used during transportation, construction, maintenance, operation stages, and from road users, and how much materials are used for the construction and maintenance of roads. Emission factors are sourced from updated emission factor databases (e.g., EcoInvent, ICE 4.0).

Data processing and analysis

Once activity data are collected and mapped with emission factor data, they can be further processed for calculation and analysis.

At the asset and/or project level, by comparing the aggregated actual carbon data against targets (*ProjectCarbonTarget* vs. *ProjectCarbonActual*), one can assess the *ProjectCarbonAvoided* and the performance of carbon management. In addition, with the breakdown of different lifecycle stages and different sources of emissions, we can also identify the carbon hotspots to dynamically adjust processes and resources to reduce emissions. Specifically, we can use *Pset_MaterialCarbon* to simulate and compare carbon emissions of various design alternatives at the design stage; track *Pset_ProcessCarbon* to monitor emissions from equipment and processes during the construction stage; monitor operational emissions via *Pset_AssetCarbon* and make adjustments based on user behavior captured in *Pset_ActorCarbon*. At the end-of-life stage, we can calculate decommissioning emissions using attributes like *ReusedMaterialPercentage* and *RecycledMaterialPercentage* from *Pset_ProjectResourceCarbon*. We can also look at how much material, energy, and water are reduced through *ProjectCarbonAvoided*, *ReducedMaterialPercentage*, *MaterialWasteReduced*, *WaterReduced* to as key performance indicators to incentivize contractors to reduce emissions. Moreover, we can investigate the user influence on road asset emissions and use that for planning future pathways to reduce user emissions.

At *IfcSite* and *IfcRoad* levels, we can compare the total emissions and carbon intensities between sites and road sections to evaluate the carbon management performance of different schemes, materials, methods, and business models/contract types.

At *IfcProcess*, *IfcReource*, and *IfcActor* levels, we can track the transformation of *IfcResource* and *IfcProduct* during tasks or activities to monitor carbon-intensive activities (i.e., *IfcProcess*), as well as tracking human and organizational influence on asset carbon emissions.

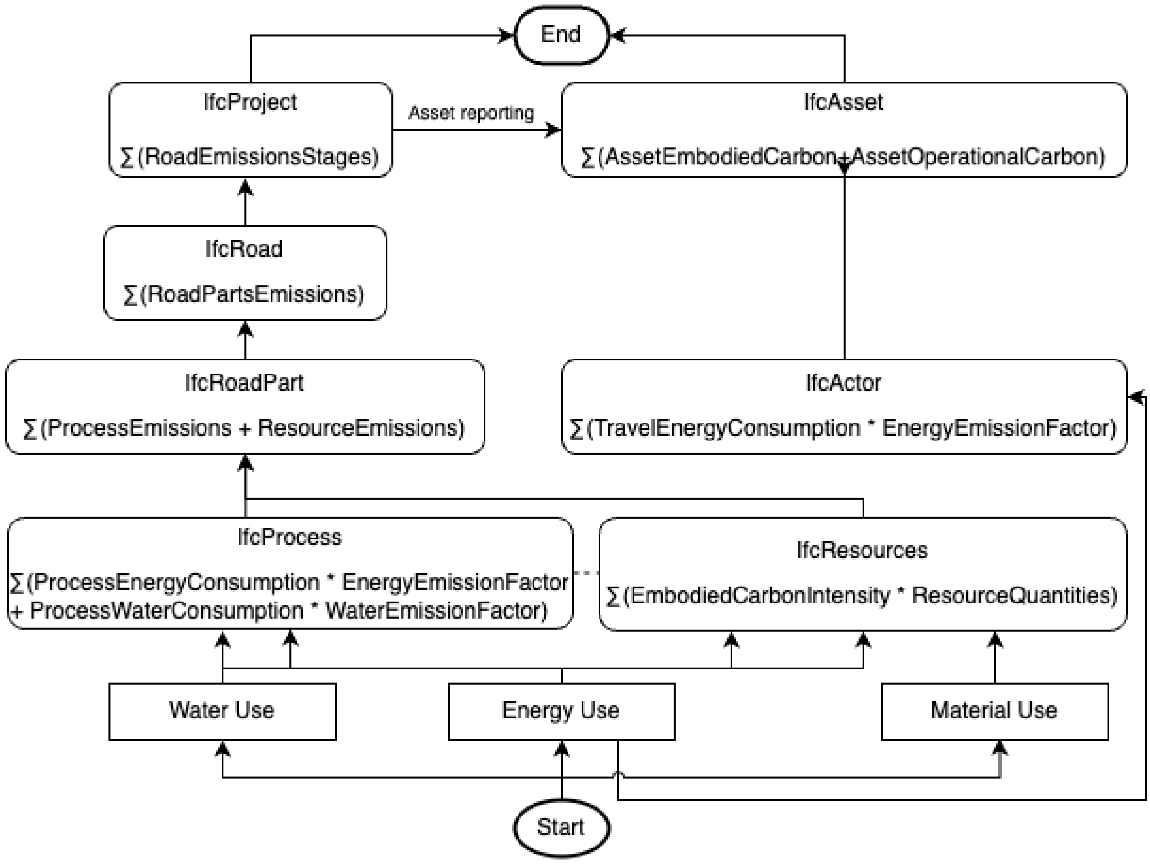


Figure 2: Carbon data flow between key IFC entities

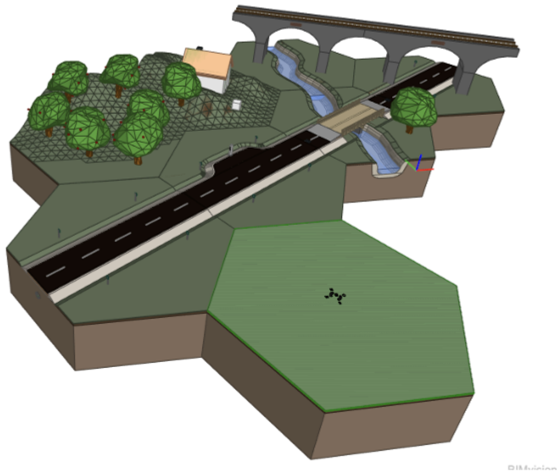
Validation and Results

IfcOpenShell was used to extend the property sets to the entities with a simple IFC road model to verify that the entities and carbon-relevant properties are feasible. Figure 3 (a) shows the model and the project carbon property set. The asphalt road is 87 meters long and 3.65 meters wide with a thickness of 10 cm. The proposed new carbon-relevant property sets are created and added to the relevant entities. Values of the property can also be imported from the resource and schedule list. It took 10 days to build the road with 5 types of equipment (*IfcConstructionEquipmentResource*), including an excavator, a compactor, an asphalt road roller, a dump truck, and a water tank, which are lined to *IfcRoadPart* and *IfcProcess*. The materials (*IfcConstructionMaterialResource*) and manpower (*IfcConstructionLabourResources*) are linked to *IfcProcess*. Figure 3 (b) shows the number of different levels of Pset contained in the IFC model. A resource list can then be extracted from the IFC model and by matching them with a carbon factor library, the *ProjectCarbonActual* with a value of 10,304.81kg can be calculated and fed back to the model. Other properties in *Pset_ProjectCarbon* are missing in this example, so they are defined as -1.000, but technically, they can be added if data was available.

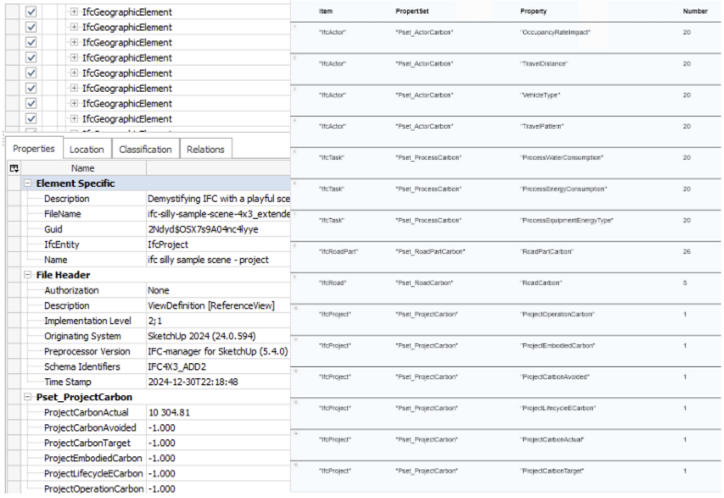
This example demonstrates that it is feasible to extend the carbon properties to IFC models for carbon emission calculation and analysis. This experiment has not calculated the operational carbon and user carbon due to the limitation of data. With the processes and resources being correctly tracked and updated to the model, we can track the carbon emissions in real time and also provide traceable data with good granularity. The source of this demonstration can be found at: `https://github.com/BIM-Tools/SketchUp-IFC-Manager/tree/main/sample`.

Discussion and Conclusions

This paper has presented how to map the ontology-based road entities to bSDD and extend the entities with new carbon-relevant properties. Key entities such as project, asset, roadpart, resource, process, and users were mapped out for different levels of carbon calculation and analysis. Carbon-relevant property sets were added to each key carbon entity, which can be found at GitHub. A simplified data flow was also created to illustrate how carbon data is being accumulated. Finally, a very simple road IFC model was used to verify and implement the concept of including carbon properties in IFC models. It successfully showed that it is technically feasible to add carbon properties to IFC models once the relationships between the entities are clear and real data of the processes and resources are available. It should be noted that the carbon property sets for roads could also be used by buildings to supplement the



(a) Road IFC model



(b) Carbon property set search results

Figure 3: IFC Model and carbon properties in the model

current carbon property sets of building products in the bSDD. By integrating carbon data into IFC data scheme, this paper facilitates the data foundation for CDT and computable sustainability management for the building and infrastructure sector.

Regarding the user carbon, which accounts for a significant proportion of road asset life cycle carbon, the authors found it difficult to map road user emission with the existing IFC data scheme. The *IfcActor* defines all actors or human agents involved in a project during its full life cycle, the *IfcOccupant* type includes assignor, assignee, lessee, lessor, letting-agent, owner, and tenant, which are mainly the typical actors in a building property. We need to better define infrastructure users and their connections with the asset and their emissions.

While this study has demonstrated the technical feasibility, it should be acknowledged that due to the complexity of nested entities of road domain entities, it still needs more efforts to map out all the relevant entities, especially how each subtype of *IfcRoadPart* is connected with *IfcProcess* and *IfcResource* (more specifically, *IfcConstructionMaterialResouce*, *IfcConstructionEquipmentResouce*, *IfcConstructionLabourResouce*, etc.). A detailed survey of their mapping relationships using machine learning models will be the future work.

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