Value Stream Mapping of Project Lifecycle Data for Circular Construction

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Abstract –

With the aim of shifting from the traditional linear flow of resources in the construction industry into a circular model, several studies have focused on the reuse and recycling of construction and demolition waste. The present study focuses on the End-of-Life (EoL) decision-making for built facilities, including buildings and infrastructure, to support such a shift. We look at the involved EoL decisions through the lens of 'information requirements' and try to envision an information supply chain, in parallel with the facilities' lifecycle stages, to support such decisions. We examine available data acquisition techniques, data analysis tools, and information standards that can help in creating and maintaining an up-to-date view of the built facility's materials/components/ subsystems and their location, condition, residual value, remaining life, second life attributes, etc. through digital twins. We suggest a value stream map for capturing and updating such information and identify technological requirements and barriers to its realization in practice.

Keywords –

Construction Supply Chain; Circular Economy; Digital Transformation of Construction; Value Stream Mapping; Digital Twins

1 Introduction

The construction industry is the largest consumer of raw materials globally. Most existing buildings and civil infrastructure follow the conventional *cradle-to-grave* model and are typically not designed to be 'deconstructed' or 'disassembled' so that their subsystems, components or materials can be reused or recycled ultimately. Construction, Renovation and Demolition (CRD) waste accounts for 20-40% of the total urban municipal waste. The majority of CRD waste is often sent to landfills, instead of being recycled and reused. CRD waste recycling rates are only 16% and 37% in Canada and the US, respectively [1]–[3]. The large amount of CRD waste sent to landfills results in wastage of resources and becomes a challenge for landfill operation. Improper disposal of CRD waste can cause land depletion and deterioration, and the transportation process can also negatively affect the urban environment in terms of noise pollution and gas/dust emission [4]. Therefore, appropriate CRD waste management is essential for mitigating the negative impacts caused by such waste.

The so-called '3Rs' principle, referring to *Reduce, Reuse*, and *Recycle,* is currently the main guidance for CRD waste management [5]. Several factors can affect the recycling and reuse of CRD waste, such as the regulatory framework, local CRD waste recycling system, and recycled product market [6]. CRD waste generation can be significantly reduced by design error detection and waste management using technologies such as Building Information Modelling (BIM) [7]. When joined with other technologies, BIM can also help control CRD waste throughout various phases of procurement, construction, operation, and eventually, End of Life (EoL) of buildings and infrastructure. During the construction and operation phases, a more holistic approach to evaluating the effect of recycled/reused content on embodied energy should be utilized for providing a broader view of the impact throughout the project whole lifecycle. Previous studies suggest that material substitution can decrease embodied energy by approximately 20% or more [8], [9]. Therefore, evaluating the trade-offs between embodied and operational energy in this context would be required for decision-making with regards to reusing/recycling some building materials [10].

As the AEC/FM (Architecture, Engineering, Construction/Facility Management) industry is highly fragmented, capturing project lifecycle data for facilitating circular construction is difficult; and the need for efficient information sharing and exchange between various stakeholders throughout the lifecycle is evident. With Industry 4.0 revolutionizing the use of sensors and the Internet of Things (IoT) in the building and infrastructure sector, there is a massive amount of data generated during various phases of the built facility's lifecycle, as related to various components, systems, and subsystems. In many cases, this data is passively stored in the form of construction production reports and/or maintenance records. However, big data analysis tools and technologies present an opportunity to turn this large volume of data into useful information and knowledge extraction for various purposes, including reduction, reuse and recycling of CRD waste.

Moving from a linear to a circular supply chain can be considered a paradigm shift for the built environment. The implementation of deconstruction practices depends on several factors, including improvement of deconstruction techniques' maturity and management, augmentation of deconstruction awareness among stakeholders, advancement in environmental regulations [11], and effective collection and management of lifecycle data for EoL decisions.

Value Stream Mapping (VSM), as an effective lean-management tool, can help to identify the opportunities and prevent wastage of the information and data generated throughout the lifecycle, which is essential for EoL decisions. Accordingly, this paper looks at the whole project lifecycle of building and infrastructure (here referred to as 'built environment' or 'built facility') through the lens of circularity to identify EoL decision-making information requirements as well as opportunities to collect and store such information. The main objective of the study is to propose a roadmap to the value-stream mapping of built facilities' lifecycle data through the design, construction, operation, renovation, and deconstruction phases based on the 3Rs principle (Igwe et al., 2020). The emphasis of this paper is on the reuse of building systems, subsystems, and components, as well as the recycling of materials.

2 Construction Project Lifecycle and Circularity

A better understanding of reclaiming building and infrastructure materials and components is required to establish an effective deconstruction planning process. Additionally, the built facility's characteristics play an essential role when it comes to disassembly. Such characteristics, at a high level, can be classified into the following groups: (i) *transparency*, i.e., the level to which building systems can be identified and accessed easily; (ii) *simplicity* i.e., the straightforwardness of connection system as well as limited types of materials being used; (iii) *use of homogeneous materials* rather than mixed material grades or composite materials; (iv) *safety*, i.e., avoiding the use of hazardous materials; (v) use of *standard and regular* (i.e. repetitiveness of elements), rather than non-standard components; and (vi) *components' sizes*, i.e., the use of a limited number of components with large dimensions rather than smaller ones. Figure 1 summarizes building characteristics for easy (and difficult) disassembly/deconstruction.

Figure 1. Building characteristics and their influence on 'deconstructability'

Beyond these rudimental characteristics, however, there is a large number of aspects of the project lifecycle that can affect EoL reusability and recyclability of materials, components, sub-systems, and systems as explained below.

2.1 Design for Disassembly and Deconstruction

In response to the high consumption of resources and low recycling rate within the construction industry, the idea of Design for Deconstruction (DfD), which requires detailed planning early on at the design phase, was established. DfD proposes alterations in the building design that lead to an EoL dismantling in a coordinated way. It can also offset the incurred building removal costs through salvaged material and lesser use of landfills [11].

Different materials typically vary in terms of reusability and recyclability. Wood is a perfect building material for reuse. Wooden structures can be disassembled in a scheduled manner to protect lumber, doors, windows, and other components in their complete functional form. An evaluation of different wooden building types, performed by [12], indicated that light-frame wood structures are most difficult to disassemble due to small member sizes and effective use of fasteners, and post-and-beam wood structures are the simplest to disassemble. Brick, on the other hand, has an excellent salvage value as long as lime mortars are used, since they can be easily removed. However, the choice of Portland cement mortar makes it challenging for bricks to be salvaged. Steel structures can also allow recycling of material, but concrete is difficult, as in-situ concrete cannot be recovered. Precast concrete components are considered reusable due to their standard (modular) sizes and the option of connecting them using fasteners. Table 1 summarizes the recommendations for DfD using wood, steel, masonry, and concrete structural systems.

Table 1 Recommendations for DfD using different building materials [13]

Material	Recommendations
Wood	• Use screws and bolts instead of nails • Consider using lime mortars • Use robust moisture management techniques to protect the wood from decay and insect damage • Use timber-frame construction instead of dimension lumber
Steel	• Identify grades and shapes directly on members • Use bolted connections • Use precast decks
Masonry	• Avoid cast-in-place members • Allowance should be given for thermal movement at connections to avoid cracks in members • Permanently label each member. The label should include concrete strength and member reinforcement
Concrete	• Avoid using mortar • Avoid using grouted reinforcement • Investigate using mechanical fasteners in place of mortar to secure blocks

2.2 Procurement and Offsite Manufacturing

Since the construction industry has lower productivity than several other industries such as manufacturing, offsite construction (OSC) has been attracting attention to accelerate project schedule, reduce project costs, and minimize weather impacts on traditional stick-built construction processes. Besides these advantages, the OSC is meant to help with waste reduction through factory production processes, as well as reuse and recycling of materials and components, due to the essentially different nature of offsite and prefabricated construction. The OSC inevitably disrupts traditional construction project planning and management by adopting three phases: (i) manufacturing; (ii) logistics; and (iii) assembly process on-site. While phases (ii) and (iii) can also be discussed from the CRD waste management perspective, the focus here is on the manufacturing phase. To improve the manufacturing process in a factory, OSC adapts Design for Manufacture and Assembly (DfMA) methods and integrates the procedure with BIM to support the OSC design process [14], [15].

As a continuous effort to improve productivity by focusing on the planning, monitoring, and control of the manufacturing process, researchers have adopted several technologies such as tracking components through Radio Frequency Identification (RFID), audio signals, Machine Learning, simulation models, and optimization algorithms [16]–[18]. These works have also proposed an integrated production planning and control system based on the application of advanced technologies used to collect the production data (e.g., process times of workstations to complete one single module component and locations of modules). In addition, lean tools and techniques have been adopted in the manufacturing phase to reduce waste [19]. Most importantly, OSC significantly increases the potential of the components' re-use at the facility EoL.

While OSC material properties can be tightly controlled as part of the factory manufacturing process, the quality of their on-site assembly should also be closely audited during the operation, since it has a significant effect on the building performance, e.g., energy use [20]. This information, however, will be also extremely helpful for the EoL decision making, by providing a full history of the materials and systems' exposure and performance.

2.3 Construction, Installation, and Commissioning

Tracking and tracing technologies such as RFID can be used as an automatic data collection and local storage solution during and following the construction. RFID tags can be permanently attached to the facility components and the tag's memory can be populated by accumulated lifecycle information of the components, taken from a standard BIM database, as proposed by [21]. The memory space on the tag can be virtually partitioned into fields such as component ID, specifications, installation status, and other relevant data. This information is used as a kind of component passport to enhance lifecycle processes [21]. The same approach can be extended to bulk materials (e.g., steel bars). Iacovidou et al. (2018) explored the potential pre-conditions for RFID to facilitate construction components reuse. They developed guidelines for promoting their redistribution back to the supply chain [22]. Focusing on the construction phase, tags or barcodes attached to material or components can be automatically scanned upon arrival on site through readers fixed at the gate. This can be helpful for site management, by helping to locate the materials/components on a large site, to monitor the progress of installation, or to improve the quality control process as described by Montaser and Moselhi (2013). But under a circular scenario, the mission of such tags can be extended throughout the facility's lifecycle, towards the EoL.

2.4 Operation and Maintenance

The application of preventive and predictive (rather than reactive) maintenance will help to reduce the waste by extending service life of components, systems, and subsequently, the entire facility. On the other hand, the reuse/recycling of building and infrastructure materials and components can pose potential challenges during the facility's operation phase, especially with regards to their effect on energy consumption vis-à-vis new materials with high thermal properties. Therefore, the availability of data regarding materials and their properties is critical to ensure they can meet new and more stringent energy efficiency requirements [23], [24]. To this end, information sharing and data exchange proposed in the design and construction phases can facilitate early evaluation of the effect of different recycled materials on energy performance.

On the other hand, the applications of big data analytics in built facilities' maintenance management practices are emerging [25], benefiting from the adoption of Artificial Intelligence (AI) and machine learning techniques. These applications initially focus on the use of statistical data-mining techniques to identify trends and patterns for reoccurring repairs based on failure modes (causes), rate, and effects [26]. With the growth of AI, there is now a shift towards using big data analytics in the development of failure detection mechanisms and tools to improve the reliability of components and systems [27], [28] and reinforce the adoption of data-driven predictive maintenance tools for failure detection, diagnosis, and prognosis. In the infrastructure sector, Structural Health Monitoring (SHM) plays a similar role and has been following the same path.

There is also an emerging trend to link data-driven predictive maintenance systems to wider facilities maintenance management practices on resource allocation (labor, skills, spare parts, equipment, etc.) and work order management (scheduling, process planning, etc.) Resource allocation aims at optimal alignment of available resources (workers, parts and equipment) to requirements of maintenance activities (Yousefli et al., 2021). These issues and trends are particularly of growing importance due to the dependency on the state of suppliers and supply chain's complexity, for spare parts and equipment, resulting from overseas manufacturing of these requirements, and thus, networked and highly interdependent distribution channels [29]. In this regard, predictive analytics applications in facilities management shall go beyond failure prediction and diagnosis towards an intelligent and interconnected asset management platform to enhance resilience and efficiency of resource supply chains [30].

These emerging needs call for a paradigm shift towards integrated (IoT-enabled) information systems for value-chain-centric facilities maintenance management. These systems can be used for monitoring, tracing, and analysis of physical assets, resources, and supporting supply chain's data, enabling linking failure predictions to the estimation of resource and supply chain flows. While such data is originally collected for the above-mentioned purposes, it can be extremely valuable in the EoL decision-making and must be stored, processed, and archived properly throughout the life of the built facility.

2.5 Deconstruction and Demolition

Determining the 'residual value' of EoL materials and components is necessary for CRD waste management. The residual value of CRD waste can be affected by various factors, such as material types, physical conditions (which were discussed in the previous sections), and recycled products market. Material type is the key factor to affect the waste residual value. For example, a material like ferrous metal has a high recycling rate due to its relatively high price, while most concrete waste is not. Physical conditions of materials affect the building material and component residual value as well. In addition, the CRD recycling facility specifications and recycled product markets can affect CRD material recycling and reuse decisions. All these factors, not only affect the selection of deconstruction technology but are also affected by the availability of disassembly and dismantling means and methods.

3 EoL Decision Making Requirements

Realistic knowledge of the EoL decisions' nature and expectations will be necessary to best understand the information requirements and plan ahead for the collection and proper aggregation of relevant data. While details in this regard will depend on the type of facility and its upper level (urban/civil) context; generically, three main applications will be of interest: assessing the physical condition of materials and components close to the facility's EoL; planning for CRD waste management; and planning for disassembly and deconstruction.

3.1 Condition Assessment and Recording

There is a wide range of technologies and methods for reality capturing, inspection, and condition assessment of built facilities. They largely depend on the type of facility (e.g., building, sewer, water distribution, road networks, bridges and overpasses, etc.) and on the materials used in these facilities and their components (e.g., reinforced concrete, asphalt, steel, PVC, etc.). Technologies used for condition assessment and rating can be grouped in two clusters; the first focuses on the diagnosis of defects and their intensity; and the second on identifying locations. Commonly used technologies in the first cluster are those capable of capturing inspection data, such as digital imaging (Adhiraki, et al. 2016), infrared (IR), Ground Penetrating Radar (GPR), 3D laser scanning, acoustic and vibration-based methods as described by Saleh, et al. (2017). The localization technologies of the second cluster include GPS (Global Positioning System), RFID, and UWB (Ultra Wide Band), and one here needs. It is important to note that these technologies can be used individually as well as jointly by making the use of data fusion algorithms (Moselhi et al, 2017). The data captured by inspection-related technologies shall be further processed using AI, machine learning, and deep learning, to assess the residual value of material, components, subsystems, and systems.

3.2 CRD Waste Management

The collection and sorting of recyclable materials are among the most important steps in CRD waste management. On-site sorting requires a viable management system and will be associated with higher labor costs, thus it is still not widely used by contractors [31]. To achieve sustainable CRD waste management, a method called ‘selective demolition’ has been proposed by the European Union [32]. It consists of a series of demolition activities to allow for the separation and sorting of building components and valuable building materials, such as metal, windows, doors, tiles, bricks, etc. [33]. The materials and components of the building must be characterized in advance of the selective demolition to determine their residual values. Materials with a high residual value, such as metal and uncontaminated gypsum boards, could be selectively removed and collected for further recycling and reuse. Yet, the selective demolition may not be able to completely separate all building components from one another (e.g., brick from mortar). The mixed CRD waste needs to be sent to off-site sorting and recycling plants for further processing.

3.3 Deconstruction Management

Finally, awareness is required to recognize that the process of deconstruction must be done with the required quality, within a realistic time frame and cost. As a freshly growing notion, deconstruction encompasses an exclusive management paradigm and is not only limited to environmental protection. There is also a need to modify the established methodologies in construction management, incorporating the management of deconstruction. The implementation of contents shown in Figure 2 can improve management of deconstruction.

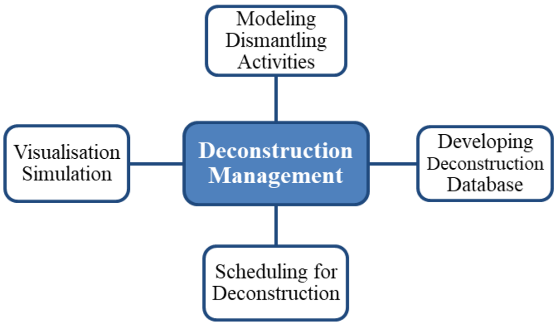

Figure 2. contents of deconstruction managements (based on C. Liu, Pun, and Itoh 2003).

4 Circular Data Stream Proposal

Data-driven EoL decision-making requires collection, compilation, and integration of the data explained in the previous sections. This must, on the one hand, include the lifecycle information of the built facility, which we refer to, as ‘micro-level’; and on the other hand shall support its contextual information in a larger-scale context, i.e., ‘macro-level’ urban model. In this section, we revisit the capacity of existing data models for accommodating such data structure. We focus on open and extendible data standards that are most common in digital twinning of the built environment; since providing meaningful and practical solutions requires a collective effort of multiple researchers and stakeholders, which should be performed in a bottom-up manner.

4.1 Micro-level Digital Twins – BIM

The information about an individual facility’s material, components, subsystems, and systems can be made accessible to all stakeholders through a shared BIM. However, coupling this information with actual development of the project at different phases of its lifecycle requires frequent updates to be done automatically (as well as manually) to track the information of building/infrastructure elements, related to the design, manufacturing, supply chain, construction, maintenance, and decommissioning processes. In addition to the obvious benefits of identifying and locating components using sensors (such as RFID tags and barcodes as discussed in 2.2), having BIM data chunks stored on the tags provides a distributed and dynamic database. The information extracted from continuously processing such data (ideally through edge computing) shall be stored in a distributed/federated BIM, which allows access to the information for all stakeholders in real-time, without the necessity of having a central database in place [21]. This will be helpful, specifically with the privacy, security, and trust issues that may exist throughout the whole lifecycle supply chain. Modern technologies, e.g., block-chain and federated data mining, details of which are beyond the scope of this paper, can support such dynamic/distributed BIM.

Furthermore, to capture the operation phase information, data exchange between Building Management Systems (BMS) and BIM through open standards such as gbxml, IFC (Industry Foundation Classes), etc., allows for utilizing long term performance of materials and components [35], [36]. In heavy infrastructure, besides the data from operation and service, SHM systems' data reflecting the structural condition of the facility can be linked with the BIM. Using automated monitoring systems can also help to evaluate materials' and components' performance during their second life and beyond. Data collected through such systems, processed, and integrated within the distributed BIM will be essential to support decision-making for selective demolition. Hence, the data standards must be upgraded and extended to support the storage of such data, in association with the facilities' digital twins.

IFC, as the most comprehensive open BIM data schema, has the capacity to accommodate the majority of inputs required for EoL decisions. Static information regarding the design and construction phases, including geometry, material characteristics, structural attributes, etc., are already fully stored in IFC4. Furthermore, several extensions are offered for accommodating dynamic information, collected through sensors, e.g. [37], [38]; RFID tags, e.g. [39]; and other sensor networks. On the other hand, COBie data model, which is considered a subset of IFC, has been originally developed to support facility management data exchange and can capture most of the information discussed in Section 2.4, including maintenance and repair work orders' information. Nevertheless, as confirmed in other studies, the existing IFC standard lacks all features required to support circular construction [40] and future studies must focus on developing such extensions. For example, while structural properties and construction costs are covered by IFC classes and relationships, attributes, such as deterioration condition and residual value, are not currently supported by the IFC schema. Best practices and guidelines such as 'Materials Passport' developed by TUM (Technical University of Munich) and BAMB

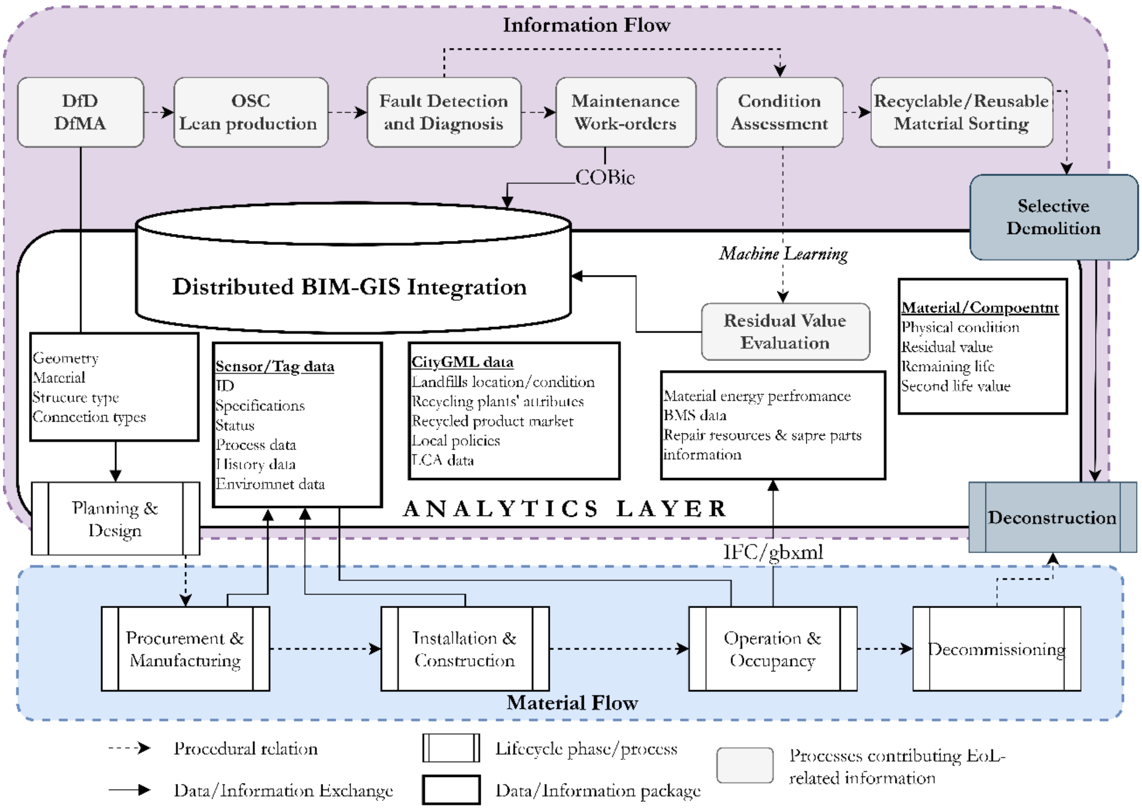

Figure 3. Proposed value stream map for critical lifecycle data to support EoL decision-making

(Buildings As Material Banks) [41] provide a good taxonomy for mapping the required (and enhancing the existing) classes, subclasses, and attributes.

4.2 Urban-scale Digital Twins

The abovementioned distributed BIM can help to support data-driven EoL decision-making for an individual facility. However, as discussed earlier, information will also be required at a macro-level, for integrated decision-making regarding deconstruction, reuse, and recycling of materials and components. Such information includes, but is not limited to, (i) typical GIS data, such as the location and attributes of landfills, recycling plants, etc.; (ii) local policies concerning recycling and reuse of CRD waste; and (iii) data required for a full lifecycle assessment (LCA). Data schema to support such information is required to be open, extendible, and integrable with BIM data standards. CityGML is an XML-based open data model that can store and exchange virtual 3D city models at various levels of detail, and has these characteristics. The data schema organizes basic entities, attributes, and relations of a 3D city model in a semantic format; but is also extensible through its Application Domain Extensions (ADEs). This capacity can be used to accommodate the macro-level information required to support EoL decision-making, taking the bigger picture of the urban context into consideration.

The closest ADE to such a macro-level LCA is Energy-ADE (briefly introduced in Figure 4), which extends CityGML by characteristics and properties essential to perform urban energy simulation and store the corresponding results [42]. To date, for most of the cities around the world, LCA data requirements have not been adequately integrated into the CityGML format, nor its ADEs [43]. The most relevant module for LCA in the Energy ADE's is the 'Material and Construction' module. In it, building construction parts and components are physically characterized with details of their structure as well as their thermal and optical properties. For a comprehensive deconstruction plan, information related to the four following categories are needed: (i) Embodied carbon and embodied energy of utilized raw or reused/recycled materials in the construction phase; (ii) Types and amounts of materials needed for refurbishment and renewal of internal and external finishes; (iii) Disposal of the materials that are not reusable or recyclable; and (iv) Discount of CO_2 equivalent emissions attributed to the reuse and recycling of components.

In the Energy ADE, data specifications are available related to the embodied energy and embodied carbon of materials used in the production phase. This data allows doing a cradle to grave LCA. However, the data related to the other three phases (refurbishment, disposal, and recycling) are still not being supported and must be added, perhaps through new ADEs. In addition, transport related carbon should be included in each of the phases, separately, for a comprehensive LCA. To provide a comprehensive data model, the new ADEs must also cover soft aspects such as policies and regulations regarding emission, recycling, and reuse.

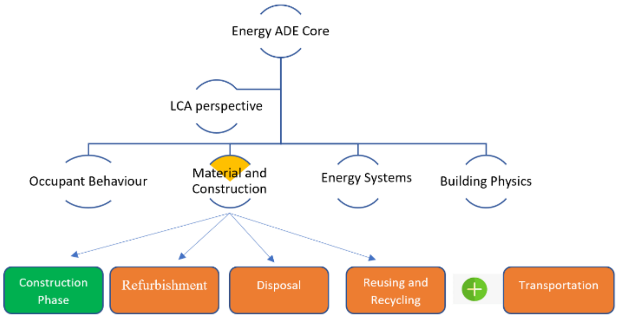

Figure 4. Energy Application Domain Extension in the CityGML standard and life cycle related missing features.

4.3 Integrated Data Model

While a large amount of data is being generated and can be virtually collected throughout the comparatively long lifecycle of built facilities, it would be the processed information, rather than the raw data, which should be stored and documented for EoL decision-making. Machine learning and data mining techniques are to be used for processing data into actionable information. For example, 3D laser scanning and digital imaging used in the assessment of structural defects in sewer mains are jointly used with artificial neural networks (ANN) for diagnostic of a set of functional defects in the sewer networks such as tree-routes penetration, joint misalignments, and debris blockages (Reference?). Similarly, IR ad GPR data is used in condition assessment and rating of reinforced concrete bridge decks and overpasses (Moselhi et al, 2017). These technologies jointly with AI are used for identification, classification and severity assessment of different types of defects such as cracking, rusting of reinforced bars, spalling of concrete, etc.

Aside from inspection and condition assessment data capturing utilizing the technologies and methods highlighted earlier, maintenance records are useful in the condition assessment of near EoL built facilities and in projecting their condition in targeted time horizons to support optimized intervention plans and related budget allocations. Accordingly, the information flow tier of the circular construction VSM should include an analytics layer to process data into the actionable information and integrate the two sources of macro- and micro-level information within digital twin models of the built environment.

Figure 3 provides a schematic view of the proposed VSM, structured around the distributed (and federated) BIM/GIS-based digital twins. This figure is not meant to document every single data exchange and/or procedural relationship throughout the whole lifecycle. Rather, it highlights the flow of major events during the lifecycle of the built facility, metaphorically called the flow of material, that leads to the CRD waste at the EoL; together with general activities that provide critical information for the EoL decisions. As suggested by the figure, a data/analytics layer is required around the centrality of BIM/GIS for managing information and supporting data-driven EoL decision making. The main requirements for the analytics layer include (i) upgrading and extending open BIM/GIS data schemata and enriching them with EoL-related attributes, with emphasis on selective demolition, recycling, and reuse of the built facilities; (ii) enhancing distributed processing methods for data collection and analysis (including edge computing and federated machine learning) and information recording (such as block-chain) to manage the distributed information model; and (iii) developing AI-based models for processing lifecycle data collected through IoT and other sensory networks into actionable information, to support EoL decision-making. Future studies are expected to focus further on these requirements, as well as the development of quantitative decision analysis models and tools to use the collected information/ analytics for selection of the most suitable deconstruction alternatives.

5 Conclusion

Shifting from a linear to circular flow for materials and components in the construction industry will be a long endeavor, and requires effective contributions from various levels of stakeholders. While in this paper we solely took the perspective of information requirements for making better decisions at EoL under the criteria of circularity, a large gap still exists in current practices for collecting data; processing/reprocessing it to actionable information; and continuously recording up-to-date information for making such decisions. Bridging this gap requires approaching the problem (i) from three angles (i.e. collecting, processing, and recording); (ii) at various levels of micro (i.e. individual facility) and macro (i.e. urban) contexts; and (iii) throughout various phases of the facility's lifecycle (i.e. from design and procurement to construction, operation, repair/rehabilitation, and finally, deconstruction). IoT and other digital data acquisition tools; open standards for building and urban information modeling; and distributed and federative data processing offer promising tools to tackle this problem. Nevertheless, it should be emphasized that the technological aspect of the problem is less challenging than other 'soft' aspects such as the high-level regulation and de-regulation strategies, industry-wide culture, market value of material and components at their second lives, etc. Any future research agenda in the area of circular construction must adhere to these constraints and their dynamism.

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