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FORMALIZING INFORMATION FOR DISASSEMBLY POTENTIAL OF BUILDINGS USING BIM AND LABELED PROPERTY GRAPHS

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Abstract

Building circularity assessments aim to reduce waste and primary material demand. Indicators like the disassembly potential (DP) assess the detachability of elements and layers, but Building Information Modeling (BIM) lacks sufficiently detailed DP information in early design stages. Key information, such as connection types between elements and components, is missing in open BIM formats such as Industry Foundation Classes (IFC). To address this, we propose a new method using labeled property graphs to represent component-specific archetypes based on BIM. Tested in a case study, this approach enhances assessments of DP, providing designers with improved insights for early-stage circularity decisions.

Introduction

Buildings and the construction industry have a significant impact on global resource demand and waste generation. In the European Union, construction and demolition waste is responsible for almost 40% of all waste generated (García et al., 2024). The Organisation for Economic Co-operation and Development (OECD) predicts that global resource consumption will increase in the coming decades, mainly in minerals which include construction materials and metals (OECD, 2019). This will also increase environmental emissions. Greenhouse gas (GHG) emissions are projected to increase from 3.5 to 4.6 Gt CO_2 equivalent per year by 2060 (UN Environment Programme, 2024), making it challenging to limit the increase in the global average temperature to well below 2°C above pre-industrial levels, the target set by the Paris Agreement.

These challenges call for a transformation from a linear to a circular economy. Circular economy in the context of buildings focuses on minimizing resource consumption and waste by designing structures that enable the reuse, recycling, and recovery of materials. Circular buildings prioritize modularity, adaptability, and disassembly, ensuring that materials can remain within closed loops throughout their life cycle. The main aim is to reduce environmental impacts and meet environmental targets by integrating principles of durability and material regeneration into construction and demolition practices.

Motivation and Research Gap

Current metrics for assessing building circularity are the Material Circularity Indicator (MCI) by Goddin et al. (2019) or disassembly potential (DP) following the Design for Disassembly (DfD) approach by Durmisevic et al. (2003). However, calculating these metrics is not yet standardized. Doing so requires specific domain knowledge about these metrics and disassembly practices, and it is time consuming. Although a few approaches include Building Information Modeling (BIM) to automate these assessments, manual enrichment steps are still needed. This is one reason why these circularity assessments have not yet been widely used in practice.

In this study, we aim to automate BIM-based enrichment in early design stages to reduce manual work and incorporate domain knowledge. This publication seeks to answer the research question on how detailed information for calculating disassembly potential can be formalized based on BIM models in early design stages. Therefore, we propose a novel approach using labeled property graphs to formalize all relevant information of element archetypes for calculating the DP of buildings based on BIM models.

Background and related work

Circularity assessments and disassembly potential

The overall goal of building circularity assessments of buildings is to evaluate and optimize the circularity performance by minimizing waste, maximizing the reuse and recycling of materials, and reducing the usage of virgin materials. Thus, the Ellen MacArthur Foundation developed the MCI by Goddin et al. (2019).

The DP assesses how building components can be disassembled or dismantled to facilitate reusing or recycling materials. The concept of DP in the context of DfD was introduced first by Durmisevic et al. (2003). It considers ”aspects” such as systematization, geometry, connection and assembly, which is of particular importance because recent practices often neglected systematization. The aspect of geometry includes the sub-aspects ‘geometry of product edge’ and ‘standardization of product edge’. The aspect of accessibility consists of the sub-aspects ‘assembly direction’ and ‘assembly sequences’. Finally, the aspect of connections differentiates between the sub-aspects ‘type of connection’, ‘accessibility’, ‘tolerance’, and ‘morphology

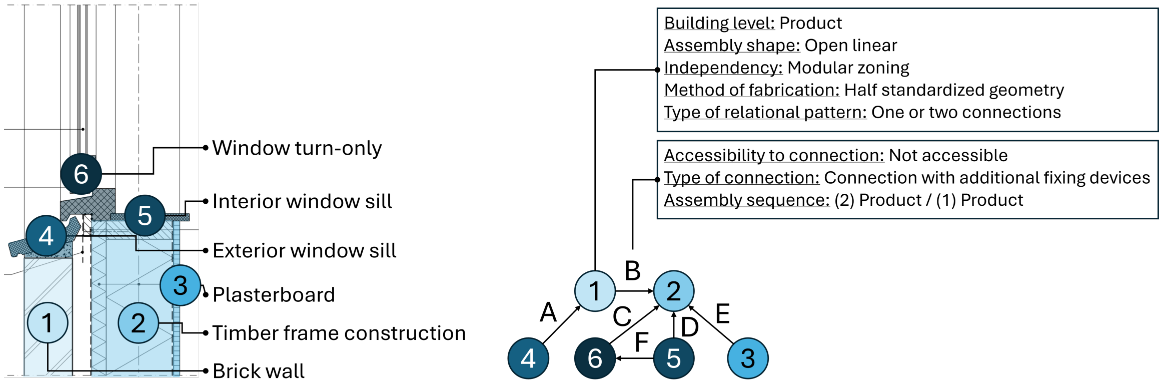


Figure 1: Example of information for disassembly potential of a wall and window according to van Vliet (2018)

of joint'.

Durmisevic's DP is combined with the MCI to holistically assess building circularity, e.g. by Verberne (2016) and van Vliet (2018). Van Vliet also focused only on the technical requirements of Disassembly Factors, not considering preconditions such as deconstruction safety, disassembly instructions, disassembler expertise and number of operations, or drivers such as disassembly costs (van Vliet, 2018). The Dutch Green Building Council considers an environmental cost indicator (ECI), which represents the environmental shadow price of a product or project as a weighting factor to determine the DP of buildings (van Vliet et al., 2021). ECI is also implemented in the commercial tool Madaster (Madaster, 2024).

Other circularity assessments, such as the Urban Mining Index (Rosen, 2021), use the term 'deconstructability' (Atta et al., 2021) or 'dismantability' in the context of predemolition audits. We neglect these aspects in this study to instead focus on DP information based on van Vliet.

Graph representations for BIM and DP

Graph databases are NoSQL databases relying on graph data models, and their representations can be differentiated between labeled property graphs (LPG) and resource description framework (RDF) graphs. RDF graphs consist of a subject-predicate-object data structure, where the subject is a resource (node), the predicate is an edge (relationship), and the object is another node or a literal value. RDF graphs are used in the Semantic Web technology stack, represent data that can be structured using ontologies, and can be queried using SPARQL. LPGs also use nodes and relationships, as well as properties that can be stored in nodes and relationships. They use CYPHER as a query language. Relationships consist of a direction, a type, a start node, and an end node, while nodes are tagged with at least one label.

Industry foundation classes (IFC) schema can be converted to RDF graphs following the ifcOWL ontology to enable linking to material data, GIS data, product manufacturer data, or sensor data (Pauwels and Terkaj, 2016). Recent approaches also represent BIM as LPGs, e.g., using Neo4j (Xu, 2018; Yang et al., 2023).

Only very few approaches have investigated the use of graph representations in assessing DP. Smith et al. (2012) focused on disassembly sequence structure planning using graphs. Others mainly focus on linked data approaches for formalizing information for Digital Product Passports (DPP), e.g. by proposing ontologies to store information about DP (Bosma, 2024).

As shown in Figure 1, LPGs are identified to be more suitable for formalizing the information for calculating DP rather than ontologies or the current IFC schema. They consist of directed relationships and relationship properties, which are needed for representing the properties, such as "accessibility to connection", "type of connection", and "assembly sequence". Furthermore, LPGs enable automatically enriching properties due to their formalization and automatically calculate DP, as explained in more detail in the method section. However, the proposed disassembly graph as LPG can also be translated to RDF graphs in the future.

BIM-based calculation of DP

Denis et al. (2017) introduced a conceptual approach using closed BIM and social network analysis (SNA) to support DfD using NodeXL. Their conceptual framework was not implemented and tested, but it identified similarities between graph representations of BIMs and Dumisevic's DP. They give an outlook on how graphs, especially social networks, could enable DfD, including assembly sequence, assembly direction, and group distinction.

Zhai (2020) proposed a BIM-based framework for automating circularity assessment enabling decision-making in early design stages. However, this framework is based on closed BIM and needs a lot of manual input for enriching disassembly codes that evaluate connection types and accessibility to connections, so it neglects further disassembly factors.

Sanchez et al. (2021) proposed a framework for BIM-based disassembly models to support the reuse of building components, defining appropriate Level of Development (LoD) and introducing an information taxonomy. They do not follow Durmisevic's concept of assessing DP but include spatial characterization, deconstruction specifica-

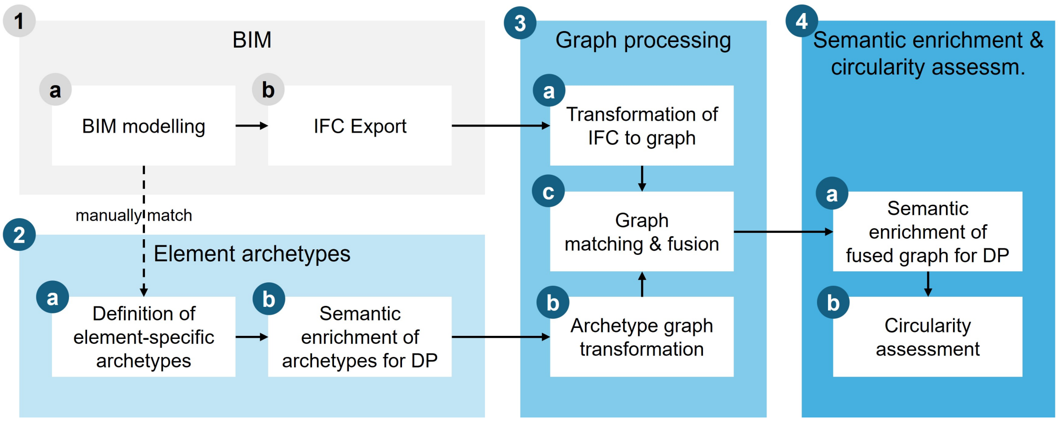


Figure 2: Overview of the proposed framework of deriving disassembly potential using BIM and LPGs

tions besides classification, and building element membership. While the last two groups are derived automatically, the first one has to be defined manually for each IfcElement, making this framework time-intensive in the early design stages. Furthermore, this evaluation only takes place on the element level.

(Atta et al., 2021) include technical, safety, circularity, and disassembly information in their approach to digitizing material passports using BIM. They assess deconstructability, recovery, and environmental scores. However, they also only consider element-specific connection types that are modeled in a closed BIM environment.

Current commercial tools, such as by (Madaster, 2024), use the open BIM data format IFC and their own property set to incorporate relevant information for calculating DP or detachability. However, these properties need to be manually enriched, as they are based only on vaguely modeled elements and materials that are uncertain in early design stages.

In summary, current BIM-based approaches for assessing DP either follow their own metrics, require a lot of manual enrichment, or simplify the one by Durmisevic, the latter of which leads to imprecise results.

Method of formalizing disassembly factors

This study formalizes relevant information for a detailed calculation of the DP at several levels, such as building, element, and component levels. We use project-specific BIM information as well as typical element and component archetypes with more detailed information, and we represent both sources using LPGs. Archetypes of elements or components are typical construction examples, including all layers and materials and their properties, and in this publication, they are based on the Belgian TOTEM database (TOTEM, 2024). We first introduce the overall framework before explaining the schema of the disassembly graph representation and the graph fusion and enrichment process.

Overall framework

The overall framework consists of four main steps with several substeps, as shown in Figure 2. First, BIM models are created (1.a) and exported using the open BIM data format IFC (1.b). The information required for IFC export settings includes base quantities and first-level space boundaries that follow the IFC4x3 schema.

In the second step, element-specific archetypes are defined and manually matched to the elements in the IFC model (2.a). Next, all relevant information for calculating DP is collected and enriched to these element archetypes (2.b). Information retrieval and the matching of the element archetype to the related IfcElement are done manually and are beyond the scope of this study.

The third step consists of three sub-steps for transforming and fusing the IFC model and element archetypes into LPGs. We only use the most relevant information from the BIM model to create the LPG in Neo4j (3.a). This information includes element names, materials, quantities, space boundaries (IfcRelSpaceBoundary), relationships of void elements (IfcRelVoidsElement), and connections between elements (IfcRelConnectsPathElements). We follow the data model from the following section to transform archetypes into LPGs (3.b). The IFC graph and archetype graphs are matched and fused in the final graph processing step (3.c).

Last, we semantically enrich the fused graph with relevant properties for DP calculation, such as connection accessibility and type of relational pattern (4.a). In the final step of the overall framework (4.b), the circularity of the building is assessed by calculating the DP on several levels (element, system, building). However, this study focuses on the formalization process and not on the evaluation of the results of circularity assessment by calculating DP.

Disassembly graph database

Figure 3 shows the data model of the disassembly graph database. It consists of the graph representation of the IFC model on the left in blue, and the element-specific archetypes on the right in black. The orange relations and properties represent information that is manually enriched and not automatically derived by the IFC model or predefined archetypes.

The relations between IfcElements and IfcMaterials (has-

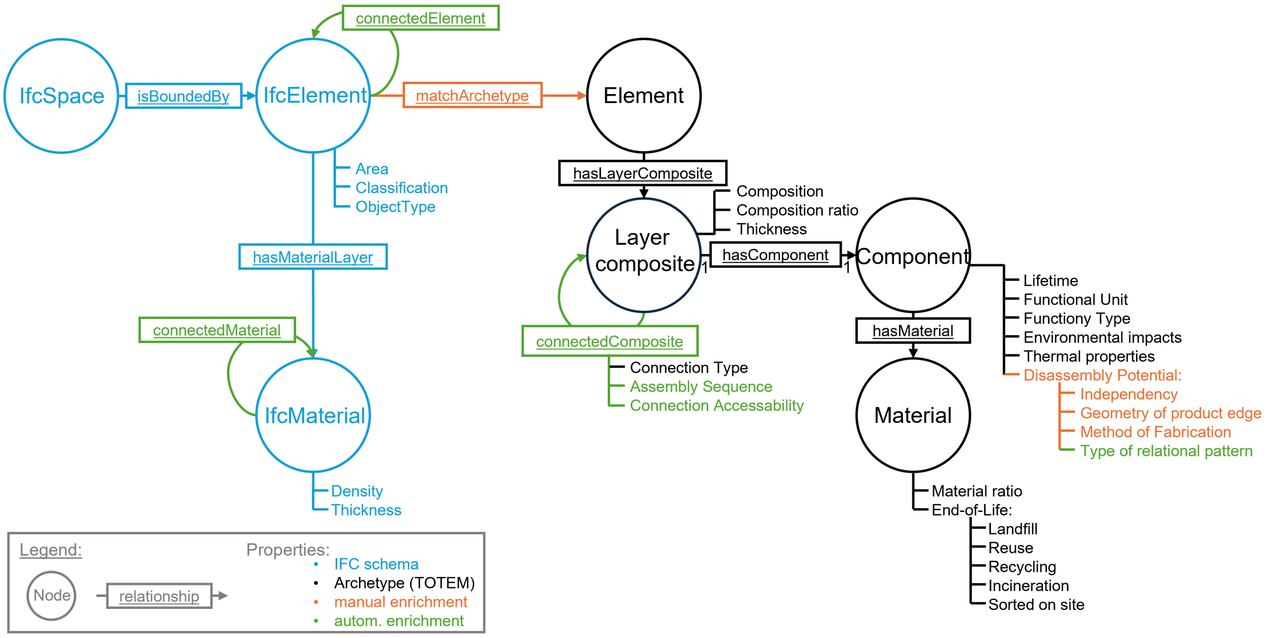


Figure 3: Data model of the graph representation of the IFC model and the element-specific archetypes.

MateriaLayer) is derived by the objectified relationship between a material definition and elements or element types, also known as IfcRelAssociatesMaterial and the related IfcMaterialLayerSet. The relationships between IfcMaterials are derived by assuming that all IfcMaterials of one element are connected in the order of the modeled IfcMaterialLayerSet. The relationship of the connections between different IfcElements (connectedElement) is automatically derived from three different sources in the IFC schema. IfcRelVoidsElement describes the relationship between IfcWall and the IfcOpeneningElement and thus IfcWindows and IfcDoors. IfcRelConnectsPathElements defines the relationships between different IfcWalls or IfcWallStandardCases. IfcRelSpaceBoundary defines the surrounding elements of an IfcSpace. However, this information is used to derive the usual relations between IfcWalls and its horizontal boundaries, such as IfcSlabs and IfcRoofs.

Most of the element-specific archetype information are derived from the Belgian database TOTEM (Tool to Optimise the Total Environmental Impact of Materials), as shown in black in Figure 3 (TOTEM, 2024). It consists of elements, represented in a layer- and composite-specific list of components. Every element layer contains at least one layer-specific composite, but one layer composite includes only one component. One example of multiple composites is a roof structure with the composite (a) wooden beams and (b) insulation between the rafters. Components include thermal properties, such as U-Value, Lambda or R-Value, functional units, expected lifetime, as well as connection types and end-of-life information differentiating materials.

We differentiate between three different types of connected layer composites: those from neighboring layers, those that are in the same layer, both called ”intraCompositeConnection”, and those between composite layers of different elements (”interCompositeConnection”), which will be automatically enriched in the graph fusion step in the following section.

Furthermore, manual enrichment of missing information is needed, including assembly sequence, independence, and geometry of product edge to assess DP according to (Durmisevic et al., 2003). The element archetypes are manually matched to the IfcObjectType, which represents the families of every specific IfcElement. In previous studies, we investigated approaches for automating this matching step in the context of life cycle assessments (Forth et al., 2023) and material passports (Forth et al., 2024) using large language models (LLM) and semantic textual similarity (STS). This automated matching is beyond the scope of this study and is part of future research.

Graph fusion

In this section, we describe which assumptions have been made for automatically connecting layer composites within one archetype element, followed by connecting layer composites between different elements using the connections of IfcElements.

We distinguish between three types of connecting layer composites, one type considering those connections within one element and two between different elements. The direction of layer composite connections within one element follows the order of element layers. However, we assume that the load-bearing composite of one element is usually assembled first, and all other ones afterwards. Furthermore, in an element layer with multiple-layer composites, we connect the composite of the previous and following layers with both composites. This leads to composite connection relations within one element as shown in Figure 4. These assumptions for directions allow us to assess the accessibility to connection, as well as the type of relational pattern.

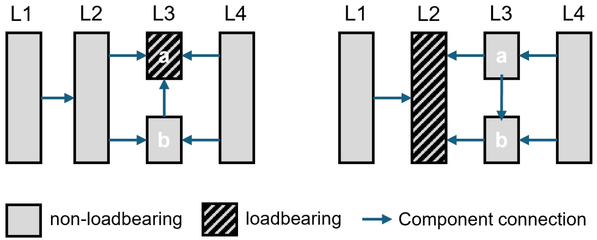


Figure 4: Layer composite connections directions based on assembly of load-bearing

The previously derived connections between IfcElements are used as a basis for connecting composites of different layers. However, defining the functions for every composite is needed using the classification by (Kaltenegger et al., 2024). Besides non-load-bearing and load-bearing, insulating, glazing/ opening, and finishing, we also add interior and exterior window sills as an additional function class. For every element archetype, we also define which element is connected to which IfcElementType and its connected composite function, as well as the connection type.

Graph enrichment

In the following, we explain how DP properties for enrichment are automatically derived, such as assembly sequence, connection accessibility, and type of relational pattern, using the fused graph. The assembly sequence is assumed on the level as we define all connected nodes as layer composites.

Following different classifications, there are either eight (Durmisevic et al., 2003), six (van Vliet, 2018) or five (van Vliet et al., 2021) different connection types. We are following the last one, as it also includes more detailed examples of connections as shown in Table 1. However, the TOTEM database does not follow this classification and needs to be aligned with van Vliet's classification and score as shown in Table 1.

The type of relational pattern either consists of one or two connections (1.0), three connections (0.6), four connections (0.4), or five or more connections (0.1) according to van Vliet (2018). This property gets updated after the creation of composite connections, counting all incoming and outgoing connections of one layer composite. As we model all connections on the component level, the assembly sequence is on the same level with a score of 1.0, as all connections are modeled on layer composite levels.

The accessibility to connections refers to physically being able to access the connections between products without demolishing (parts) of the product. It describes if the connection is directly accessible (1.0) or with additional operations, which cause no (0.8), reparable (0.6), or normal damage (0.4) or not being accessible (0.1) according to Durmisevic et al. (2003). We propose to derive the accessibility to connections based on the direction of the previously derived connections and their connection types. If the start node has no incoming connection relation, the connection is directly accessible. The level of damage depends on the type of connection. The more damageable connection types are in the relationship chain, the less accessible the connection is. The component-specific DP and BCI scores are calculated using the fused and semantically enriched graph.

Table 1: Types of connections according to van Vliet et al. (2021).

Connection Type	Examples	Score
Dry connection	Loose (no fastening material), Click, Velcro, Magnetic	1.0
Connection with added elements	Bolt and nut, Spring, Corner, Screw, Connections with added connection elements	0.8
Direct integral connection	Pin, Nail	0.6
Soft chemical connection	Caulking, Foam (PUR)	0.2
Hard chemical connection	Adhesive, Dump, Weld, Cementitious, Chemical anchors	0.1

Case study and results

First, we describe the chosen case study, followed by the technical details for the prototypical implementations, before finally describing and highlighting the fused graph for the case study and its DP results.

Case study

We created a simple case study modeled with Autodesk Revit, as shown in Figure 5. We used the version of IFC4x3 to export the IFC model, including first-level space boundaries, IfcBuilding as facility type, base quantities, and all material properties. The case study consists of one living room bounded by four external walls, a ground slab, and a roof made of wooden beams and stone wool insulation covered by tiles. The three triple-glazed windows with aluminum frames open the exterior load-bearing walls, which are made of bricks with XPS insulation. The slabs are made of reinforced concrete cast in situ and finished with cement screed and ceramic tiles.

Prototypical implementation

We manually selected six archetypes from the TOTEM database (TOTEM, 2024) and manually matched them with the related IfcElements according to their semantic similarity of the materials and layer of the elements used.

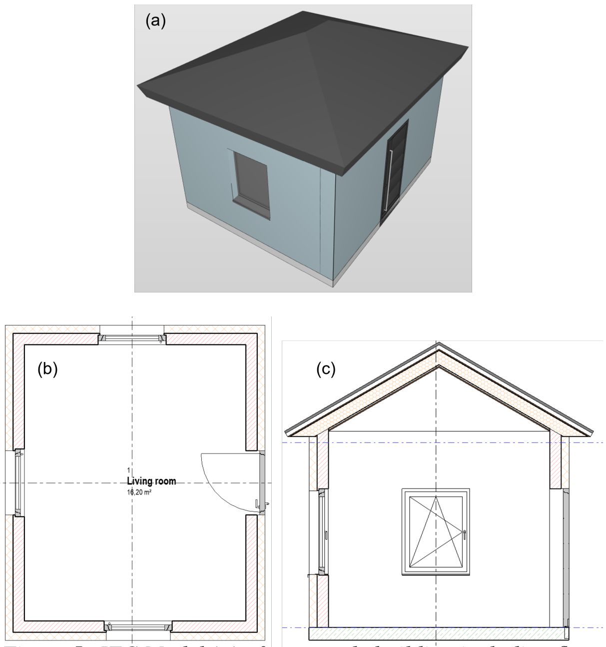


Figure 5: IFC Model (a) of case study building including floor plan (b) and section (c).

These element archetypes represent one window, door, external wall, internal wall, slab, and roof. Next, we manually retrieved the data from the online database due to the lack of API and save them in a CSV file to automatically transform them later into CYPHER commands, creating LPGs. Furthermore, we save the manual matches of each IfcElements to the element archetypes in this CSV file. In addition to thermal properties and environmental impacts in this database, we mainly used the connection type as relevant information to calculate the DP. However, this information does not follow the classification by Durmisevic but is manually alligned.

IfcOpenShell and COMPASIFC enable parsing all relevant information from the IFC model (IfcOpenShell, 2024; COMPAS, 2024). For creating the LPGs, we used the Neo4j Desktop version (Neo4j, 2024) and created a CYPHER command in a Python environment. We executed them in the locally connected database.

Results and discussion

We evaluated the proposed framework by qualitatively analyzing the result of the implemented case study. Figure 7 shows the graph after fusing the transformed IFC graph of the case study and the related element archetypes from the TOTEM database. Figure 6 exemplarily highlights the formalized graph of one element and shows a zoom on the roof element. We selected this example as it represents a complex multi-layer element with several layer composites connected to the four room-bounding walls , highlighting the load-bearing wooden beam as layercomposite following the assumptions from Figure 4.

The bottom left legend applies also to the overall fused graph in Figure 7. The nodes of the different IfcElements are highlighted by large nodes and different colors, such as brown for the four space-bounding IfcWalls, its openings IfcWindows and IfcDoors in light blue, IfcRoof in green, and IfcSlab in dark blue. In Figure 7 we visualized these nodes around the orange IfcSpace node in the center.

Every IfcElement consists of one or more IfcMaterials represented by small purple nodes, which are also connected following the same logic as layer composites. Furthermore, every IfcElement has an element archetype in grey, consisting of several layer composites. These layer composites are represented as smaller yellow nodes.

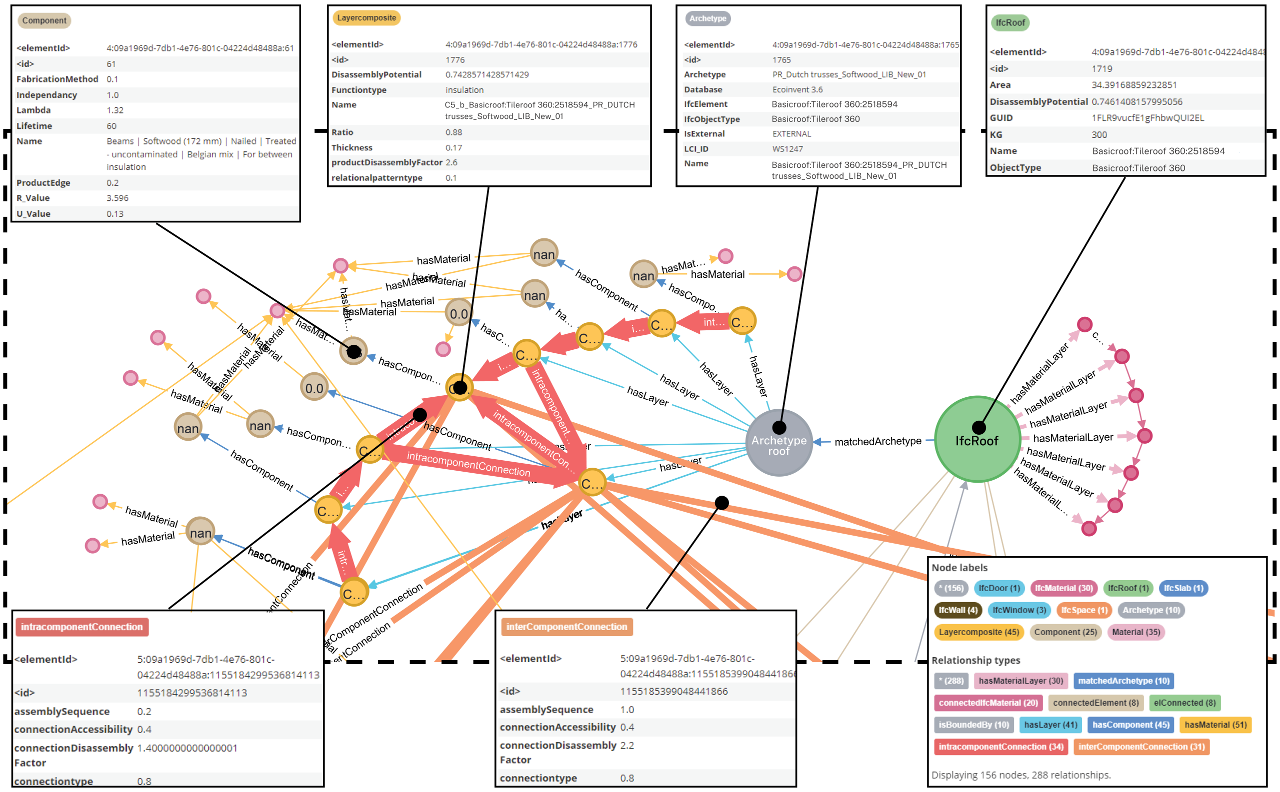
Each of the 45 layer composites has one component assigned. There are only 25 different components. This allows for efficient data storage with less redundancy. Every component consists of one or more raw materials from the TOTEM database. In total, there are 35 different materials in the disassembly graph, represented with small pink nodes. Similar to components, one material can be assigned by multiple components. We manually align the connection description of each layer composite of the selected element archetypes from the TOTEM database to the classification and score according to van Vliet (2018).

We highlight the connected layer composites within an element in red (”intraCompositeConnection”) and those between different elements in orange (”interCompositeConnection”) in Figure 7. It shows that a simple one-room case study connecting not only element layers, but also those between elements, increases the complexity of the graph from 34 ”intraCompositeConnections” to 31 ”interCompositeConnections”. This increase for a simple case study indicates the necessity of an automated formalization and enrichment approach, as manually modeling these connections at this level of detail causes a significant amount of manual work.

Figure 6 highlights the roof element as an example to show the derived semantic enrichments. The relational pattern was enriched on the layer composite level and the connection accessibility on the connection level. The other product- or connection-specific disassembly factors were manually defined. The disassembly factors and DPs were automatically calculated on several layers, such as composite connections, layer composites, and IfcElements. Finally, we calculated the building circularity indicator (BCI) based on all elements and their volumes as weighting factors. The BCI for the one-room case study is 0.586.

Limitations

The proposed approach for formalizing DP-related information using BIM and LPGs has limitations. We manually retrieved the archetypes from the TOTEM website and manually matched them to the IfcElements , as an automated matching approach is out of scope for this publication. Furthermore, relevant information about assembly sequence, independency, geometry of product edge, and method of fabrication is missing in TOTEM and is manually enriched for each archetype once, but can be used for future projects. Next, domain knowledge defines the functional layers and connection types to connect composites



Component

<elementId>	4:09a1969d-7db1-4e76-801c-04224d48488a:61
<id>	61
FabricationMethod	0.1
Independancy	1.0
Lambda	1.32
Lifetime	60
Name	Beams | Softwood (172 mm) | Nailed | Treated - uncontaminated | Belgian mix | For between insulation
ProductEdge	0.2
R_Value	3.596
U_Value	0.13

Layercomposite

<elementId>	4:09a1969d-7db1-4e76-801c-04224d48488a:1776
<id>	1776
DisassemblyPotential	0.7428571428571429
Functiontype	insulation
Name	C5_b_Basicroof:Tileroof 360:2518594_PR_DUTCH trusses_Softwood_LIB_New_01
Ratio	0.88
Thickness	0.17
productDisassemblyFactor	2.6
relationalpatterntype	0.1

Archetype

<elementId>	4:09a1969d-7db1-4e76-801c-04224d48488a:1765
<id>	1765
Archetype	PR_Dutch trusses_Softwood_LIB_New_01
Database	Ecoinvent 3.6
IfcElement	Basicroof:Tileroof 360:2518594
IfcObjectType	Basicroof:Tileroof 360
IsExternal	EXTERNAL
LCI_ID	WS1247
Name	Basicroof:Tileroof 360:2518594_PR_DUTCH trusses_Softwood_LIB_New_01

IfcRoof

<elementId>	4:09a1969d-7db1-4e76-801c-04224d484
<id>	1719
Area	34.39168859232851
DisassemblyPotential	0.7461408157995056
GUID	1FLR9vucfE1gFhbwQUI2EL
KG	300
Name	Basicroof:Tileroof 360:2518594
ObjectType	Basicroof:Tileroof 360

intracomponentConnection

<elementId>	5:09a1969d-7db1-4e76-801c-04224d48488a:1155184299536814113
<id>	1155184299536814113
assemblySequence	0.2
connectionAccessibility	0.4
connectionDisassembly Factor	1.4000000000000001
connectiontype	0.8

interComponentConnection

<elementId>	5:09a1969d-7db1-4e76-801c-04224d48488a:115518539904844186
<id>	1155185399048441866
assemblySequence	1.0
connectionAccessibility	0.4
connectionDisassembly Factor	2.2
connectiontype	0.8

Node labels

* (156) IfcDoor (1) IfcMaterial (30) IfcRoof (1) IfcSlab (1) IfcWall (4) IfcWindow (3) IfcSpace (1) Archetype (10) Layercomposite (45) Component (25) Material (35)

Relationship types

* (288) hasMaterialLayer (30) matchedArchetype (10) connectedIfcMaterial (20) connectedElement (8) elConnected (8) isBoundedBy (10) hasLayer (41) hasComponent (45) hasMaterial (51) intracomponentConnection (34) interComponentConnection (31)

Displaying 156 nodes, 288 relationships.

Figure 6: Fused disassembly graph of case study (roof element, zoomed in from Figure 7) highlighting connection between composites

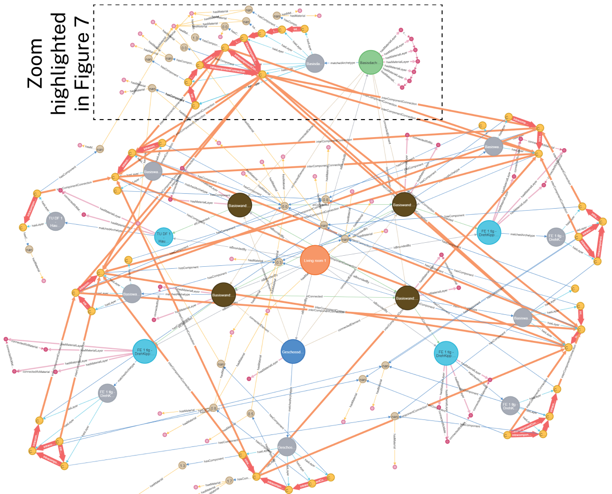


Figure 7: Fused disassembly graph of case study (whole building)

between different elements. However, we have the goal of generalizing these assumptions for similar archetypes of the same element type.

Finally, we used the metrics by van Vliet et al. (2021) to calculate the DP. Other approaches included MCIs or other parameters, such as sales revenue, as weighting factors to derive one holistic BCI (Verberne, 2016; van Vliet, 2018). However, these were not applied to validate the formalization approach as additional information was needed for the calculation of these metrics.

Conclusion and outlook

In this publication, we introduced a novel approach to formalizing relevant information for automatically deriving DP based on BIMs and typical element and component archetypes using labeled property graphs. This method supports automatically creating a disassembly graph for decision-making, e.g. by clients or architects, based on the derived whole building assessments of DP. The automated graph fusion and enrichment are based on assumptions but still need a few manual inputs for missing information in the TOTEM database. This database was selected as it contains relevant information about connection types and further information about thermal properties, environmental impacts, and end-of-life scenarios of elements, components, and materials.

In our future research, we will include the calculation of DP using different weighting factors, such as mass, MCI, or environmental impacts, as it was excluded from this study's scope. These results will be compared to manual calculations of the same case study. Furthermore, we will include an automated matching of the IfcElements to those of the TOTEM database using element, component, and material names and semantic textual similarity (STS). For this step, we need to automatically transform all archetypes from the TOTEM online platform to the graph using web scraping. This can also be used to train a graph neural network (GNN) for predicting connection types between different similar components.

Acknowledgments

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