- CIRCUIT -

Holistic approach to foster CIRCUlar and resilient transport InfrasTructures and support the deployment of Green and Innovation Public Procurement and innovative engineering practices

– Deliverable 1.3 -

Circularity Analytics Tool

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Executive Summary

The document, D1.3 Circularity analytics tool (CAT) is a a result of Task 1.3 within which a tool for the calculation of circularity indexes including reusability and recyclability is performed. The CAT tool can be used for the assessment of the environmental impacts of design, maintenance and end-of-life alternatives for transport infrastructure, where different scenarios can be analysed and compared.

The tool is based on the IFC standard (derived from BIM models) which makes it software independent. Using the IFC model for the selected asset, the tool can calculate circularity KPIs on three levels, system, component and material. Outputs are then linked to the CIRCUIT digital platform and can be used for different purposes, for example to assess the circularity of different design solutions. In the current phase of the tool development, only bridges are used as a proof of concept.

The following steps were performed in the process of development of the tool:

i) Definition of tool requirements including, the associated calculation models, the parameters required to apply them and necessary to perform waste-related calculations.
ii) The development of a circularity analytics tool with a graphical interface to allow users to customize the analyses to be performed.
iii) The final step is updating the API to allow sending the KPI calculation results back to the BIM model and the digital platform.

Using this quantitative tool, stakeholders are able to assess their decision-making alternatives, track their transition towards circular economy, conduct temporal analysis, and benchmark their performance against their peers and industry's standards.

Abbreviation list

Abbreviation	Definition
AC	Accessibility of the Connection
AMS	Asset Management System
API	Application Programming Interface
BCI	Bridge Condition Index
BIM	Building Information Modelling
CAT	Circularity Analytics Tool
CT	Connection Type
DP	Disassembly potential
GE	Geometry of the element edge
IE	Independency of the element
IFC	Industry Foundation Classes
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
PI	Performance Indicator
RI	Recyclability Index

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Glossary of terms

Circularity
An economic concept (also: circular economy) meaning that a product, service or resource is renewed or regenerated, rather than wasted. Key principle of circularity is allowing materials and products to be used more than once in a value chain either processed (e.g. recycled) or unprocessed (e.g. reused).

Life Cycle
Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment (LCA)
A methodology developed to assess the environmental impacts of a building, component, or material. The assessment compiles and evaluates the energy and material inputs and outputs of the material system throughout its life cycle and assesses the relevant environmental impact.

Life Cycle Cost Analysis (LCC)
An analysis of all the costs that will be incurred during the lifetime of the product, work or service. LCC may also include the cost of externalities such as environmental degradation or greenhouse gas emissions.

Material Circularity
The measure describing how much of the total material in the life cycle (%) is being directed back into the life cycle (e.g. recycled and cycled sourced materials vs. non-renewable and virgin material sourced).

Product system
Described by ISO 14040 as a "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product."

Recovery
The process of systematically and intentionally collecting, salvaging and reusing materials from a building or construction site to extend their life cycle and reduce waste.

Recycling
Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.

Reusability
The measure describing how much of the existing structures could be used again at the end of life cycle.

Reuse
The repeated use of a product or component for its intended purpose without significant modification.

1 Introduction

1.1 Objectives

The overall objective of the CIRCUIT project is to develop a holistic approach and associated digital solutions with guidelines to foster circular, smart, and resilient transport infrastructure. The work performed within Task 1.3 aimed to develop one of the digital solutions, namely Circularity Analytics Tool which will support implantation of circular economy into transport infrastructure management along the whole life cycle. The Circularity Analytics Tool (CAT) enables stakeholders' insights into the circular potential of their assets / networks and the designers a starting point for the assessment of different design, repair or reconstruction scenarios. The tool is based on the CIRCUIT holistic framework, developed within Task 1.1 and described in D1.1 Holistic circularity framework (Stipanovic et al., 2024).

The CIRCUIT project puts emphasis on infrastructures upgrading and updating actual engineering practices by following a whole life cycle approach, see Figure 1 and supporting decision making processes along the life cycle. The conceptual framework of the CAT tool includes methods to measure aspects linked to circularity, sustainability and resilience digitized in interoperable environments.

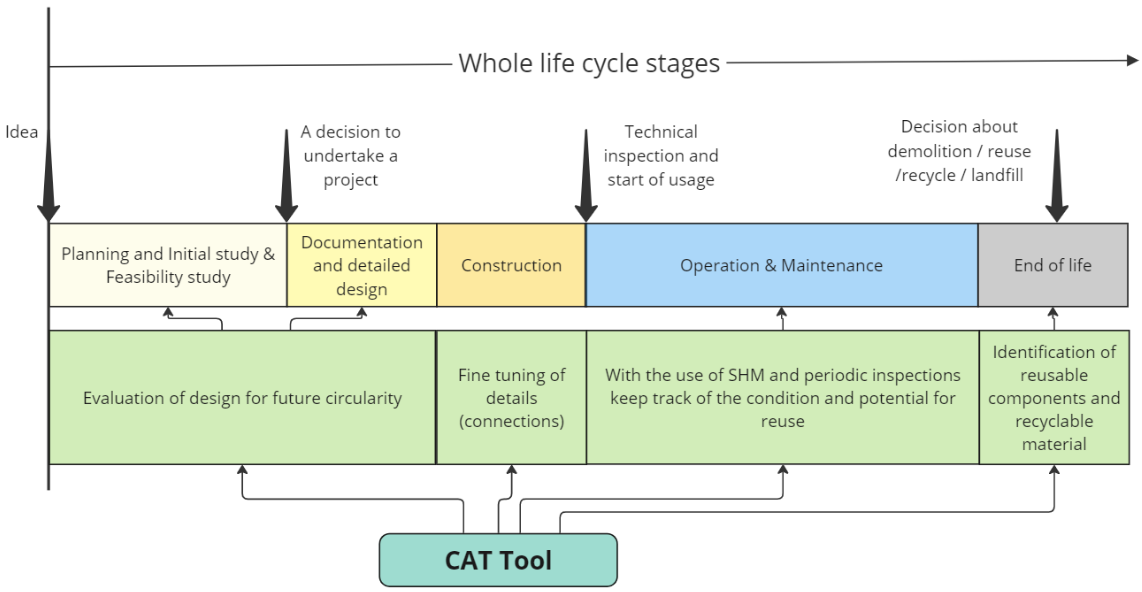


Figure 1 CAT application through the whole life cycle of a structure

1.2 PURPOSE OF THE DOCUMENT

The document aims to provide an in-depth overview of the structure and functionalities of the CAT tool developed to assess circularity and consider possible end-of-life alternatives of transport infrastructure assets. By determining the circularity index, the tool enables stakeholders—such as engineers, asset managers and decision makers—to evaluate the extent to which resources can be reused, recycled, or optimized within an asset's lifecycle. The document provides a comprehensive understanding of the tool's capabilities, its practical applications, and its alignment with the broader goals of achieving sustainable and circular infrastructure systems.

The work starts with the establishment of a robust theoretical foundation by defining circularity principles, metrics, and methodologies. This include reviewing existing standards, frameworks and stakeholder-specific requirements (Circularity indicators, 2019; Gasparri et al., 2023; González et al., 2021; Garbarino et al., 2016; and Dodd et al., 2021). Data inputs required for circularity assessment, such as material flows, lifecycle stages, and resource efficiency parameters were identified and the calculation methods and algorithms that align with the theoretical basis have been developed. Finally, the actual tool is designed to be integrated with existing management systems or databases which ensures compatibility and streamlines data input, enabling the tool to leverage current workflows and infrastructure data.

1.3 STRUCTURE OF THE TOOL

The tool is structured to follow the principle that emphasizes the hierarchy of resource management strategies, prioritizing reuse over recycling to maximize resource efficiency and minimize environmental impact. This principle aligns with the circular economy's goal to keep materials in use for as long as possible, reducing waste generation and reliance on virgin resources. While recycling remains important, prioritizing reuse delivers greater sustainability benefits, see Figure 2.

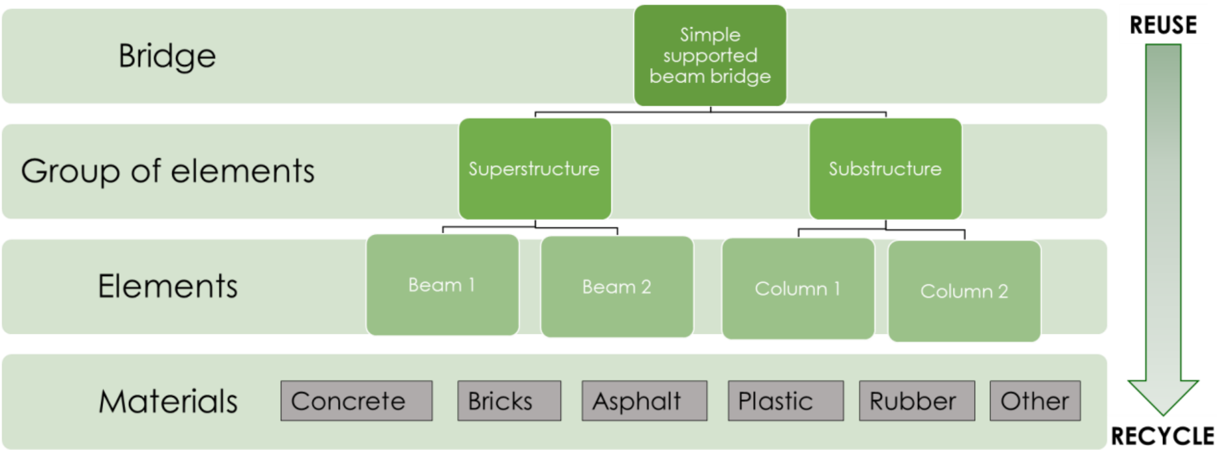


Figure 2 CAT tool concept presented on the example of a bridge as a part of transport infrastructure

Reuse maintains the value and functionality of materials or products without breaking them down, thereby conserving the energy and resources required for reprocessing. Recycling, while beneficial, often involves energy-intensive processes and generates emissions. Reuse, by contrast, extends the lifecycle of items with minimal additional inputs. Reusing materials or products can reduce costs associated with manufacturing, waste handling, and recycling processes.

The creation of the Tool evolves around definition and systematization of each Performance Indicator, PI and associated sub PIs on the element level which sum up to the Key Performance Indicator, KPI Circularity at the asset and /or system level. In that way it enables connecting the existing asset management system with the newly calculated KPIs and integration into a BIM based digital platform. Using this quantitative tool, stakeholders will be able to assess their decision making alternatives, track their transition towards circular economy, conduct temporal analysis, and benchmark their performance against their peers and industry's standards.

2 Circularity assessment framework

A Holistic circularity framework including a set of newly developed circularity KPIs (assessment of recyclability, reusability, and end-of-life value of the existing assets) was developed as a result of Task 1.1 and reported in document, D1.1 – Report on CIRCUIT holistic framework with quantifiable KPIs for circular, smart, resilient, and sustainable transport infrastructure (Stipanovic et al., 2024). Circularity analytics tool is based on the reusability and recyclability PIs, se Figure 3, used to determine overall circularity. Sustainability requirements and the resilience such as multi adaptability, lifespan extension options, high value solutions to improve circular economy targets are considered on different levels, from a material level to element, structure and finally system level.

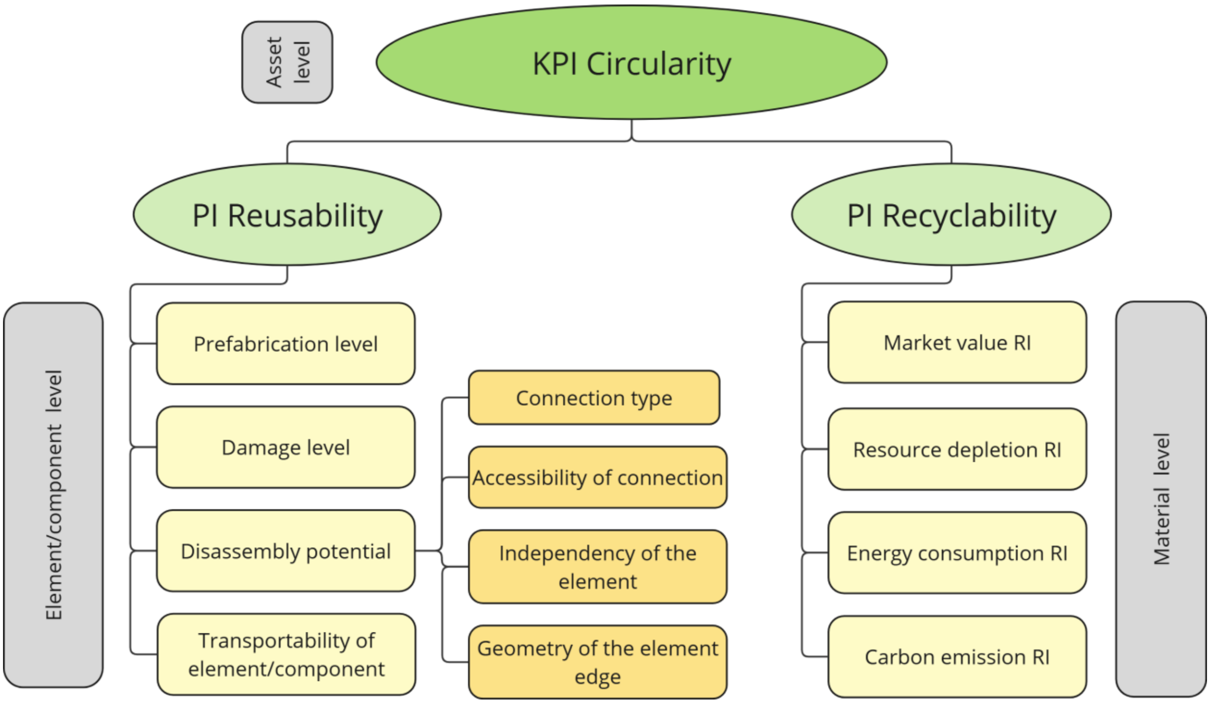


Figure 3 Levels of performance assessment in the tool

2.1 KPI CIRCULARITY

Measurement of circularity of a system requires a complex assessment to quantify how effectively a structure or its components can be repurposed or reused at the end of their initial lifecycle. A comprehensive approach from the level of material to structural element and the whole structure is used to develop a quantitative robust key performance indicator for defining circularity. A systematic evaluation at the structural element level includes the performance indicators reusability and recyclability. These performance indicators are combined and summarized providing a key performance indicator circularity at the structure (e.g. bridge) level. The details of the calculations are given in Chapter 3.

The value of the KPI Circularity ranges from 0 to 1 with 1 being a 100% circular system/structure. The approach and the calculation of KPI circularity can be used through the whole life cycle of a system/structure. In the initial assessment during the planning phase, it is used to evaluate the design for future reusability. In the operation and maintenance phase with the use of SHM and periodic inspections it is used to keep track of the condition and potential for reuse. And finally at the end-of-life evaluation and before decommissioning, a detailed analysis is performed to identify reusable components.

Circularity analysis begins with the establishment of elements as constituent parts of the structure that are reusable. Parts that are not reusable are than analysed regarding recyclability. The suggestion is to use volume of elements/structure for analysis. Once all reusable and recyclable parts are established, lost material and waste generated can be calculated by subtraction of reused and recycled content volume and volume content of material lost in the reuse and recycle process from the total structure volume.

2.2 DEFINITION OF PERFORMANCE INDICATORS

2.2.1 Cir 1 Reusability

A single reusability PI is aggregated from the sub-indicators; prefabrication level, damage level, disassembly potential and transportability.

2.2.1.1 Cir 1.1 Prefabrication level

The prefabrication level of a structural element involves the assessment of the extent to which the element is manufactured off-site and then assembled on-site. It can be quantified based on the proportion of the element that is prefabricated versus constructed on-site and categorized into different grades based on the percentage by mass or volume of prefabricated component.

The literature overview shows that measuring the level of prefabrication adoption is largely inconclusive in terms of definitions, approaches, and results. The measurements can be perceived from two generic categories: quantitative and qualitative (Lu et al., 2018). Quantitative assessments might provide a clear, index-style picture of how much of a building is prefabricated. It may also serve as an independent variable to generate the quantitative relationships between other construction-related variables, such as the amount of energy that may be saved when prefabrication is used to a given degree (Hong et al., 2016). However, in some circumstances, employing the value or volume associated with prefabrication alone as the only measurement could be problematic. This is due to the possibility of using completely different prefabricated elements in assessment for a certain project based only on their prefabrication rate. For assessing the prefabrication level, the qualitative approach: "degree of product readiness when delivered to the site", is preferable (Gibb, 2001; Steinhardt et al., 2014).

In CIRCUIT a four-level scoring system is adopted to quantify the level of prefabrication of single structural elements and is shown in Table 1.

Table 1 Scoring system for structural element prefabrication level

Prefabrication level	Description	Scoring	Example
Level 1	Low prefabrication (0-30%) - The element is primarily constructed on-site, with only minimal or no prefabrication.	0	Deck slab or columns that are cast in-situ.
Level 2	Moderate prefabrication (30-60%) - The element has a balanced mix of prefabricated and on-site constructed portions.	0,40	Deck slab produced as deck panels that are prefabricated but with cast in situ concrete installed upon them with panels being left as lost formwork.
Level 3	High prefabrication (60-90%) - A significant portion of the element is prefabricated, but there may be some on-site construction or finishing required.	0,70	Girders that are prefabricated and produced off site and installed on site, but transversal girders cast in-situ are required for buckling resistance.
Level 4	Fully prefabricated (90-100%) - The element is almost entirely prefabricated, with only minor or non on-site work required (e.g., minor adjustments or connections).	1	Girders that are prefabricated and produced off site and installed on site.

2.2.1.2 Cir 1.2 Damage level

Condition rating is used in order to evaluate the structure's current condition compared to its condition at the time of construction. The condition is most often assessed by means of a visual inspection. Based on the results of visual inspection additional tests are performed and/or structural health monitoring (SHM) systems implemented in order to collect data regularly over time. The reuse potential of structural elements depends largely on their condition rating or damage level. This relationship stems from the need to ensure that reused components meet safety, functionality, and durability standards while minimizing the risk of structural failure.

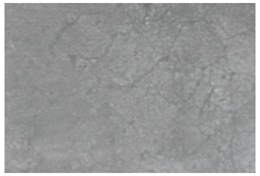
Condition assessment methods differentiate from an element to the structure/system level. Typically condition assessment is performed at the element level and then integrated and/or recalculated into structural level assessment. For example for bridges, element-level condition values must be aggregated to a single system-level condition value, namely the Bridge Condition Index (BCI) (ATKINS, 2002; Chase et al. 2016, Bukhsh et al., 2019).

Calculation of condition index considers different damages per type of structure and different coefficients that allow various attributes, such as importance of an element in the structure or importance of a structure in the whole network, taken into consideration. There are lists of typical damages for different type of structure or material which are available for practitioners involved in condition assessment of structures. Degradation of the structure is occurring with time (i.e., strength loss is occurring due to corrosion as well as fatigue damage accumulation) and, if a particular failure occurs, the specific consequences that may result are taken into consideration and used for risk assessment.

The condition survey as a part of condition control, which also involves condition assessment and condition evaluation, is one of the basic elements for the through-life management of structures. The results of the condition survey can help to obtain a guess or estimation of the reliability index view, see for instance the quality control plan concept of COST TU1406 WG3 (Hajdin, et al., 2018) and IM-SAFE project reports Appraisal of methods for safety evaluation and risk management (Bigaj-van Vliet et al., 2022) and Guidelines for data acquisition, processing, and quality assurance (Rodriguez, A.S., 2022).

In the analysis of circularity of a system and reusability of a structure or its components, condition and reliability index present a starting point for the assessment of different scenarios. Some thresholds are set for the first level of circularity assessment such as if the condition index, e.g. level 4 and 5, is at a certain point the element cannot be used any more or it is not feasible to use it. At condition rating level 1 or 2 it can be reused without intervention and level 3 elements need to be repaired. An example of connecting condition rating of a concrete structure based on type of damages and damage levels with the reusability indicator is presented in Table 2. When it comes to the actual project where the elements are to be reused a comprehensive numerical modelling is to be performed taking into account residual structural capacity, technical lifespan (designed) vs residual lifespan (influenced by deterioration). For a detailed assessment LCA and LCC of different scenarios should be performed to evaluate environmental and economic consequences.

Table 2: Categorization of performance indicator reusability due to damage level with condition index

Condition index	Type of damage	Main performance indicators	Example	CIR 1.2 Damage level relation to reusability	
				Score	Description
0	No damage.			1.00	The element can be used without any repair needed.
I	Smaller defects resulted from the construction process.	- Surface imperfections - Small cracks (shrinkage cracks		1.00	The element can be used without any repair needed.
II	Smaller defects resulted from the exploitation.	- Surface cracks - Delamination of surface cement paste film - Evaporation of Ca(OH)2	 	0.90	The element can be used with minor repair needed.
III	Defects that in long term decrease durability of the structure. Repair is needed.	- Network of cracks in concrete cover - Contamination of concrete cover (chloride, pH) - Concrete loss due to frost and de-icing salts damage	 	0.60	The element can be used after performance of detailed condition assessment and performance of repair works.

IV	Defects that can, in the foreseeable future, decrease the reliability of the structure. Repair is needed now.	- Delamination, spalling of concrete cover (partially) - Honeycombs in concrete - Corrosion of steel visible - Loss of steel cross section due to corrosion	 	0.10	Due to severe damage the element can be used only with high level costly repair. The element will be used only in extraordinary circumstancies with performance of LCC and LCA.
V	Defects that present a serious danger for safety of the structure. Intervention is needed emergently, and if necessary, limitation or shutdown of traffic.	- Delamination and spalling of concrete cover (full) - Advanced corrosion of steel, - Significant loss of steel cross section		0.00	Due to severe damage the element cannot be reused.

2.2.1.3 Cir 1.3 Disassembly potential

The disassembly potential, DP presents the extent to which the connections between structural elements can be broken, so that an object can retain its function and high-quality reuse can be achieved. A decision about the reuse of structural elements depends on the connection between different elements. This can be performed on a small scale, such as figuring out a structural connection's specifics, or on a bigger scale, e.g. identifying the wider network of connections between the components of a structural system. A structural component inventory can be created using a BIM model as its foundation (Wolf et al., 2024). For measuring the disassembly potential in the CIRCUIT project the adapted measurement method developed within the DGBC circularity program was adopted (Vliet et al., 2021).

In Figure 4 a schematic representation of a typical bridge with its constituent elements is shown to highlight the variety of elements, their dependencies and simplify the consideration of connections between them. It is crucial to understand the structure, the static system and distribution of forces to enable definition of connections and associated properties.

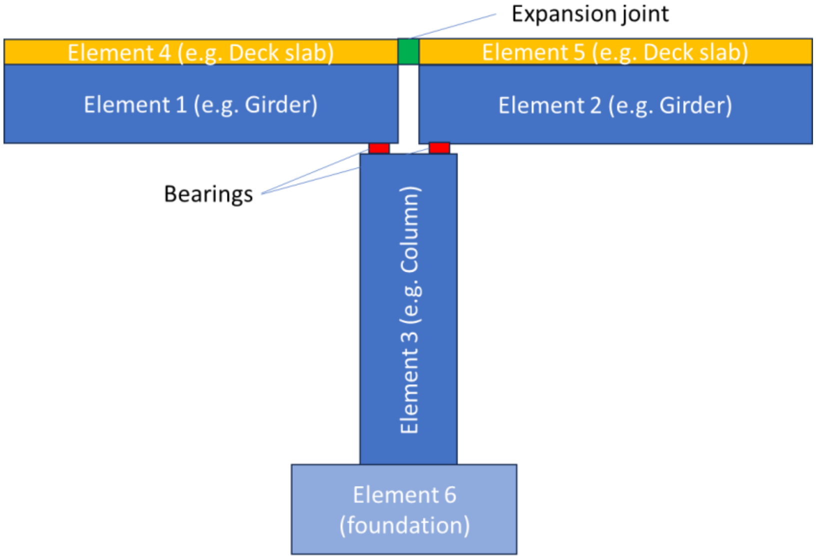


Figure 4 Schematic representation of a typical bridge and its elements

The definition and calculation of DP requires some specific information to enable measurement of how easily an individual component or element can be separated from a larger system. The type of connection directly impacts how easily the element can be detached and different types of connections dictate how components are joined. Components that are easy to access during disassembly lead to higher DP and is influenced by various factors such as the physical location of the component and the ability to see, reach and operate on the connection point without obstructions. If a component is independent, meaning it is not tightly integrated or dependent on other elements, it is easier to disassemble. Highly interconnected or interdependent components reduce DP because removing one may require altering, damaging or dismantling several others. Finally, the shape and structural complexity of a component can affect how easily it can be separated. While simple geometries are easier to handle during disassembly complex or fragile edges may require specialized methods, lowering DP.

In the CIRCUIT methodology the disassembly potential is calculated at an element level. All the connections between the analysed element and any other surrounding element is detected and scored. Weighing factor is determined for each connection and is set taking into consideration its importance and overall dimension. The DP is then calculated as follows:

$$DP_{el_i} = \frac{\sum_{j=1}^{n} w_{con_j} \frac{CT_j + CA_j + IE_j + GPE_j}{4}}{n}$$

Where:

- i - i^th element of the analysed structure
- j – j^th connection of element i
- n - number of connections for element i and surrounding elements
- $w_{con,j}$ – weighing fac connection j
- Connection type – CT (see Table 3)
- Accessibility of the connection – CA (see Table 4)
- Independency of the element – IE – if the elements is completely independent than other parameters are not defined (see Table 5)
- Geometry of the element edge – GE (see Table 6)

Table 3 Connection type with scoring, description and examples

Connection type (CT)	Score	Description	Characteristics and example
Fully detachable connection	1,00	No connection or Connections that are designed for easy disassembly without damaging the connected elements. These connections allow for quick and simple removal and reuse of the components.	**Bolted or Screwed Joints**: Bolts, screws, or similar fasteners that can be easily removed. Disassembly leaves the components undamaged and ready for reuse. **Example:** Bolted steel connections in structural frames, detachable bracing systems, elastomeric bearings on concrete bridges.
Partially Detachable Connections	0,80	Connections that can be disassembled with moderate effort. These connections may require some specialized tools or techniques but generally allow for reuse of the elements.	Welds designed to be cut without significant damage, or mortar fillings between concrete structural elements without anchoring or minor anchoring. Some minor damage may occur, but components can often be refurbished. **Examples**: Welded steel plates designed with access points for cutting, bolted connections with locking mechanisms, mortar fillings with minor anchors that can be cut.
Difficult to Detach Connections	0,60	Connections that can be disassembled but with considerable effort, often leading to some damage to the elements or connections. Reuse may be limited due to the difficulty of disassembly.	Connections using non-structural grout or mortar that must be removed. Disassembly likely causes damage to the elements or connectors. **Examples**: Grouted precast concrete connections, partially welded connections requiring extensive cutting.
Semi-Permanent Connections	0,20	Connections that are not intended to be disassembled. Removal typically causes significant damage to the elements, making reuse difficult or impossible.	**Welded Connections**: Full welds that require extensive cutting to remove. **Bonded Adhesives**: Connections using strong adhesives that cannot be easily reversed. Disassembly leads to significant damage to one or both connected elements. **Examples**: Fully welded steel connections without consideration for future disassembly, glued or epoxy-bonded joints.
Permanent Connections	0	Connections that are permanently fixed and cannot be disassembled without destroying the connected elements. These connections are intended for permanent assembly and do not allow for reuse.	**Cast-in-Place Concrete**: Connections where elements are poured and cured in place with overlapping reinforcement. **Integral Connections**: Structural elements that are monolithically cast or constructed. Disassembly requires complete destruction of the connection and the connected elements. **Examples**: Cast-in-place concrete joints, monolithic concrete connections, fully integrated steel connections in welded frames, elements connected with interlaced reinforcement – monolithic connection, fully anchored elements, welded elements

Table 4 Connection accessibility with scoring

Connection accessibility (CA)	Score
Freely accessible without additional actions	1,00
Accessible with additional actions that do not cause damage	0,80
Accessible with additional actions with fully repairable damage	0,60
Accessible with additional actions with partially repairable damage	0,40
Not accessible - irreparable damage to the element or surrounding element	0,10

Table 5 Independency of the element with associated scoring

Element independency (EI)	Score
Completely independent elements - modular zoning of elements or between different separate layers	1,00
Partial dependency of elements	0,90
Occasional dependency of elements or between different layers	0,40
Full integration of elements or between different layers	0,10

Table 6 Geometry of the element edge with scoring and examples

Geometry of element edge (GE)	Score	Examples
Open, no obstacle to the (interim) removal of products or elements	1,00	
Overlapping, partial obstruction to the (interim) removal of products or elements.	0,40	
Closed, complete obstruction to the (interim) removal of products or elements.	0,10	

2.2.1.4 Cir 1.4 Transportability

A survey was performed among experts in the area of production and transport of prefabricated elements which revealed that everything can be transported but with severe variations in cost and organization. Depending on the geometry and weight of the element determines the mode of transport. In the Exceptional transport rule book issued in the Croatian official gazette there are 5 categories of exceptional transport for roads defined. The last 2 categories refer to single heavy vehicles which is why here only the first three categories for transport of cargo depending on whether the permitted total weights, axle loads and dimensions are exceeded is analysed here:

- Category I - transport by a vehicle that, alone or together with the load, does not exceed 44 tonnes for a combination of up to 5 axles, or 48 tonnes for a combination of 6 or more axles, with a total weight and/or 3 metres wide and/or 4.2 metres high and/or up to 23 metres long and with the prescribed axle loads or axle loads specified by traffic signs;
- Category II - transport by vehicle, which alone or together with the load has the following values of total weight, dimensions or axle loads: above 44 or 48 tons to a maximum of 60 tons of total weight and/or above 3 meters to a maximum of 3.5 meters in width and/or above 4.2 to a maximum of 4.5 meters in height and/or a length of more than 23 meters to a maximum of 30 meters and/or which exceeds the axle loads by a maximum of 20% of the maximum permitted or specified by traffic regulations;
- Category III. - transport by vehicle, which alone or together with the load exceeds the upper limits of total mass and/or dimensions and/or axle loads, for transport II. Categories (RH, 2018).

Based on this categories a scoring system for transportability PI was developed which is shown in Table 7.

Table 7 Categories of exceptional transport with associated element dimension thresholds and scoring (based on RH, 2018)

Type of transport	Element dimension				Scoring
	Weight	Length	Width	Height	
Conventional transport	<25 t	<5,8 m	<2,55 m	<1,5 m	1
Exceptional transport category 1	25 – 30 t	5,8-20,0 m	2,55-3,0 m	1,5-3,0 m	0,7
Exceptional transport category 2	30 – 45 t	20,0-27,0 m	3,0-3,5 m	3,0-3,25 m	0,3
Exceptional transport category 3	>45 t	> 27,0 m	>3,5 m	>3,25	0,1

For road transport there are specific routes defined on the state level that are to be used for exceptional transport. Additionally, transportability of the area of the analysed structure can be performed based on the distance of the analysed location from these defined routes and the roads that lead to them. Also position of certain structural elements based on their micro location, such as bridge column in the riverbed, can also be an input as an indicator influencing transportability. In this analysis this type of assessment was not performed.

2.2.2 Cir 2 Recyclability

Mayer (2024) suggests four methods for assessing recyclability by measuring recycling potential from different perspectives; economic dimensions of the recycling industry; patterns of resource depletion; the energy cost of recycling; and the carbon intensity of recovery processes. Assessing recyclability from these four perspectives provides a comprehensive understanding of its feasibility and sustainability, ensuring better-informed decisions in materials management. This enables a holistic evaluation of recyclability, balancing economic, environmental, and resource-related concerns.

1. Market Value Recyclability Index
   The material's market value changes, particularly between its point-of-sale and end-of-use values, showing that there is a market for the material in its recycled form and that recycling technologies and return supply chains are ready and available (Mayer, 2021). The index represents the ratio of the material's value at the point of sale to its value at the end of use. A higher index value suggests greater recycling potential from a market-value standpoint. The value of this index is calculated as follows:

   $$R_{MV} = \frac{V_P}{V_V}$$

   Where:

   V_V – market value of a primary-use material at its point of sale

   V_P – market value of material at its point of use
2. Resource Depletion Recyclability Index
   This index relates to the problem of resource depletion, focusing on the relationship between the annual production rate of specific materials and their natural reserve availability. The risk of depletion is higher for materials with low natural reserves and high production rates. Materials with low depletion index score are currently used in quantities well below its existing natural reserves. On the other hand, production of certain scarce materials currently exceeds its known natural reserves. This finding indicates that using recycled or reused materials with high R_{RD} is an essential condition for continued usage of that material. The value of this index is calculated as follows:

   $$R_{RD} = \frac{AP}{R_e}$$

   Where:

   R_{RD} – recyclability resource depletion index

   AP – annual production rate (t/year)

   R_E – natural reserves (t)
3. Energy Consumption Recyclability Index
   The index defines ration between energy needed in the recycling process of a material and the energy needed for primary production. A material with a primary production process that uses a lot of energy and a recycling process that uses less energy should ideally move its consumption pattern to recycling, while a material with a recycling process that uses a lot of energy should ideally shift to direct reuse.

An ineffective recycling procedure may also be indicated by high embodied energy. The value of this index is calculated as follows:

$$R_{EC} = \frac{EE_R}{EE_{pp}}$$

Where:

R_{EC} – recyclability energy consumption index

EE_R – embodied energy of the recycling process (MJ/kg)

EE_{PP} – embodied energy of the primary production process (MJ/kg)

4. Carbon Emissions Recyclability Index

The ratio of carbon emissions produced during the primary-use material's production process to those produced during the recycling process is examined by this indicator. The energy used in extraction and manufacturing processes directly contributes to embodied carbon emissions. If there are significant carbon emissions during the recycling process compared to the main production process, it may be more environmentally advantageous to change the material's consumption pattern to one that involves direct reuse or remanufacturing. The value of this index is calculated as follows:

$$R_{CE} = \frac{C_R}{C_{pp}}$$

Where:

R_{CE} – recyclability carbon emissions index

C_R – carbon emission of the recycling process (kg/kg)

C_{PP} – carbon emission of the primary production process (kg/kg)

Table 8 Recyclability indexes for different construction materials

Material	Market Value Recyclability Index	Resource Depletion Recyclability Index	Energy consumption recyclability index	Carbon Emissions Recyclability Index	OVERALL NORMALISED RECYCLABILITY INDEX
Concrete	0,10	0,035	0,02	0,47	0,29
Steel	0,20	0,015	0,27	0,27	0,38
Asphalt	0,25				0,49
Cast iron	0,20	0,015	0,31	0,29	0,35
Stainless steel	0,60	0,013	0,28	0,28	0,46
Aluminium	0,80	0,002	0,09	0,09	0,78
Elastomer	0,30	0,04	0,40	0,42	0,08

Most commonly used construction materials are listed in Table 8 with single recyclability indexes regarding market value, resource depletion, energy consumption and carbon emission normalised and aggregated into an overall recyclability index. The table highlights reveal the following results regarding single Recyclability Indices, RIs:

- Market Value Recyclability Index – Aluminium is 40% more recyclable than stainless steel,

- Resource Depletion Recyclability Index – Aluminium is found to have the lowest depletion index score, meaning that it is currently used in quantities well below its existing natural reserves,
- Energy consumption Recyclability Index - Concrete and aluminium exhibit the lowest index scores, meaning that energy required for their recycling process is very low in relation to the energy that is required for their primary production,
- Carbon Emissions Recyclability Index - Glass and concrete receive the highest index scores in this category, meaning that their recycling carbon emissions are relatively high. These findings suggest that from a carbon emissions perspective, concrete and glass should ideally be re-manufactured or reused rather than recycled (Ashby, 2021).

Regarding the overall normalised RI depending on the analysis weighing factors can be added to put more emphasis on a certain perspective of the analysis. In this study all Ris are used with the same importance weight.

For a more thorough and comprehensive assessment an overall LCA including other environmental impact KPIs besides resource depletion, energy consumption and carbon emission are used. By defining different scenarios of reuse/remanufacture/repurpose/recycle and running the overall LCA for the scenarios in question decisions can be made based on comprehensive quantitative results.

3 CAT DEVELOPMENT AND IMPLEMENTATION

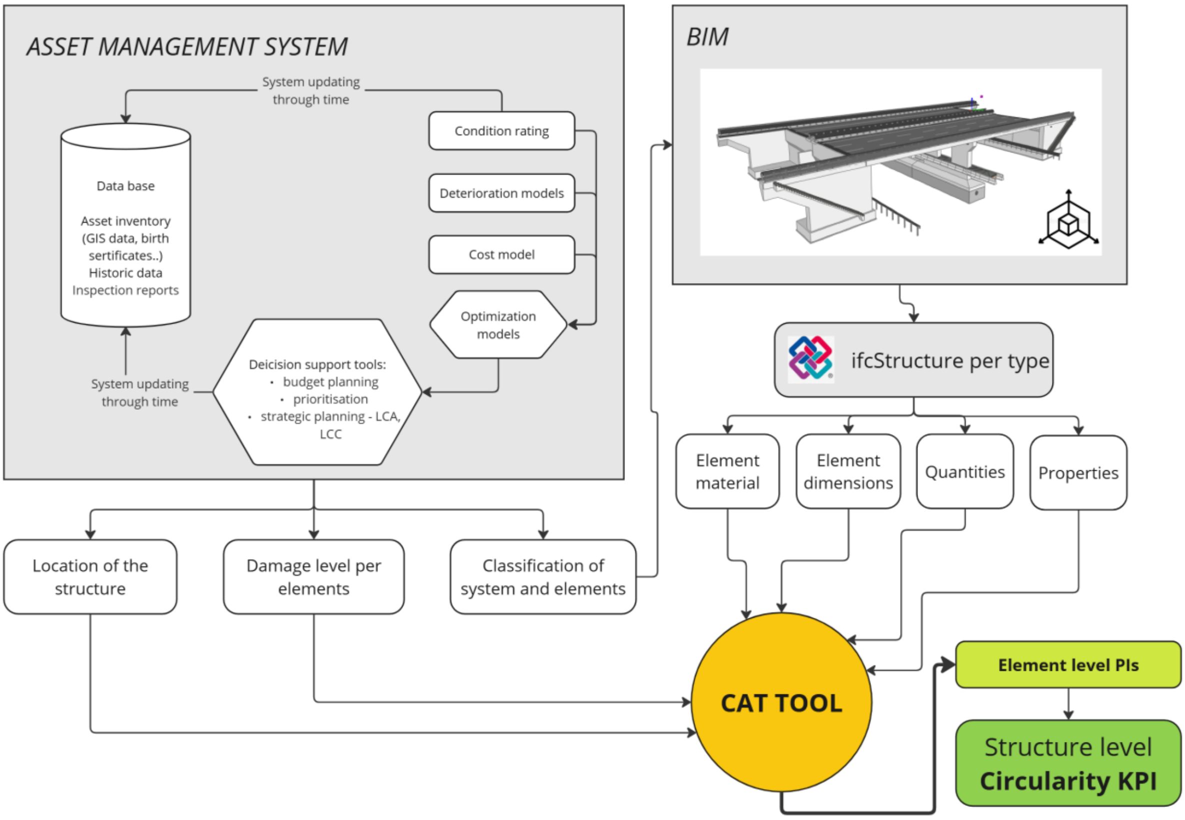


Figure 5 Inputs for the CAT tool and the result

The overall structure of the CAT tool is shown in Figure 5 with the main sources of information the tool uses. The starting point is the existing asset management system with available information about the structures. AMS already has a classification system of the assets/structures and their constituent elements which should provide the basis for the tool. BIM model of each structure is developed if it is not already available in the AMSs. IFC (Industry Foundation Classes) is used as a standardized file format used in Building Information Modelling (BIM) to facilitate the sharing and exchange of information between different software applications. While IFC is commonly associated with buildings, its use has expanded to infrastructure projects. IFC provides a structured way to describe all aspects of a structure, including geometry, materials, structural components, and various property information. CAT tool works with this data to calculate element level PIs and single structure level KPI circularity. The methodology and the process is described in the following chapters.

3.1 BIM STRUCTURE AND INFORMATION FOR CAT

BIM is a digital 3-D model-based process used in engineering and construction to design, construct and manage multi-disciplinary data. It involves creating and managing digital representations of the physical and functional characteristic of assets or infrastructure project. These digital representations are known as BIM models, which contain rich data and are used throughout the lifecycle of a project.

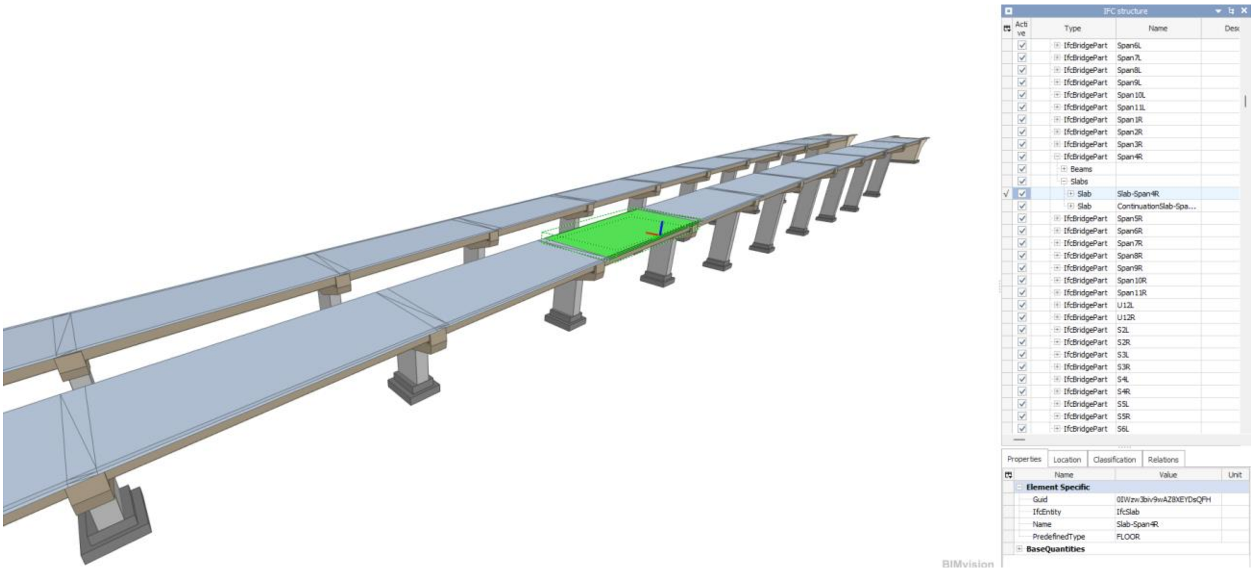


Figure 6 BIM model of a bridge with IFC structure

BIM uses 3D models to represent structures components such as walls, columns, girders and systems like HVAC in a building or drainage system, superstructure or substructure in a bridge. These models are intelligent and data-rich, meaning they include information such as materials properties, dimensions, performance etc. CAT tool interconnects with BIM using it as a source of information for calculation of sub-PIs, PIs and KPI Circularity. While BIM provides a number of information needed for establishing circularity of element or system, getting the information from BIM about connections between elements needed for calculation of disassembly potential is not so simple.

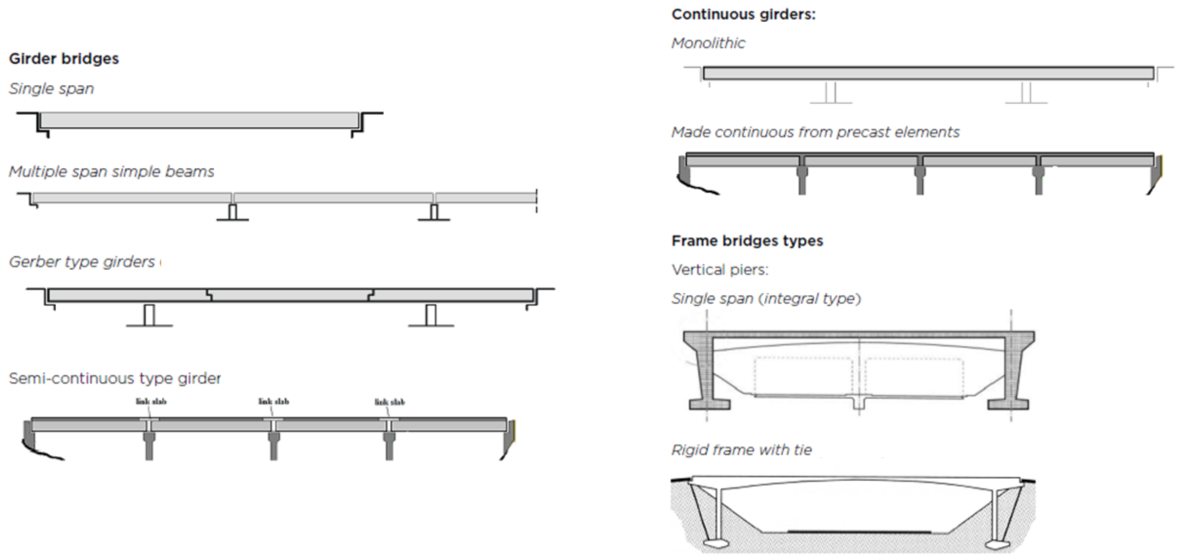


Figure 7 Certain typical bridge types by structural system (COST TU1406 WG3, 2018)

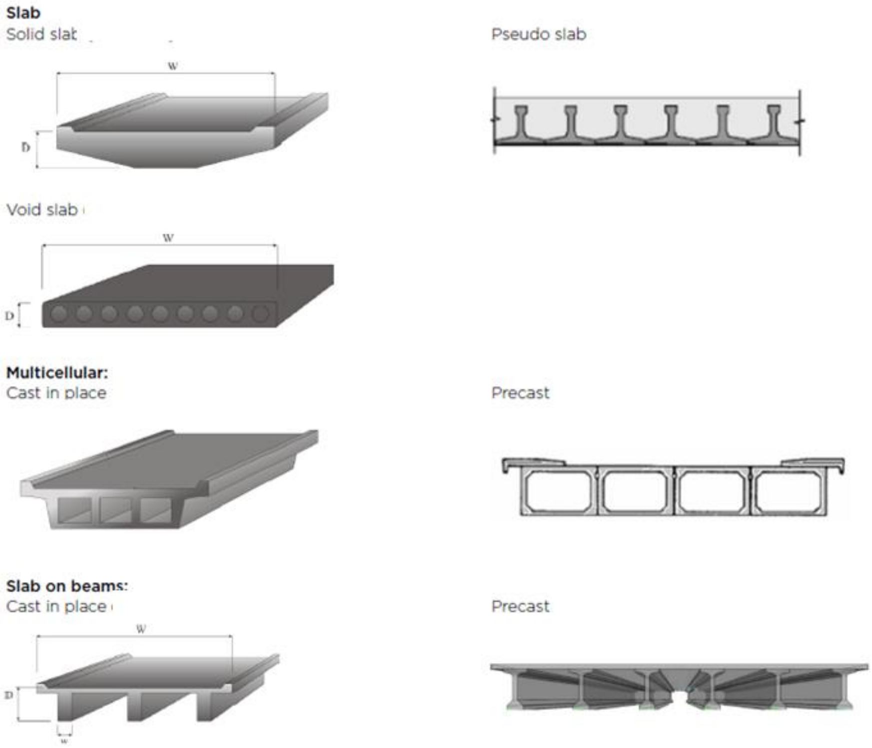


Figure 8 Certain typical bridge superstructure types (COST TU1406 WG3, 2018)

Since the definition of DP is one of the most important features to define the potential for reuse of elements the methodology was developed to determine this indicator. Creating a catalogue of structural systems, with a focus on connections between elements and their disassembly potential involves categorizing systems based on their construction methodology, material composition, and connection types. Some typical structure systems and subsystems for a structure type bridge are shown in Figure 7 and Figure 8. The assumption is that the DP can be predefined through typisation of structural systems and construction methods for the analysed transport infrastructure network by establishing a catalogue of structures. All elements of the structural system are defined by adding information about all connections between a single element and its neighbouring elements. Adding sub-PIs for disassembly potential and the weighing factor for importance of each connection in a system allows for calculation of DP per element per typical structural system and subsystem in a transport infrastructure network.

3.2 INDUSTRY FOUNDATION CLASSES (IFC)

The tool is based on the IFC file Standard (https://www.buildingsmart.org) . Use of the IFC standard is recommended for maximising the compatibility between the different applications used for the management of BIM models. IFC schema contains many different classes that can be used to model object. As the circularity assessment methodology is demonstrated on a model of a bridge, the tool is relying on the IfcBridge object schema, see Figure 9.

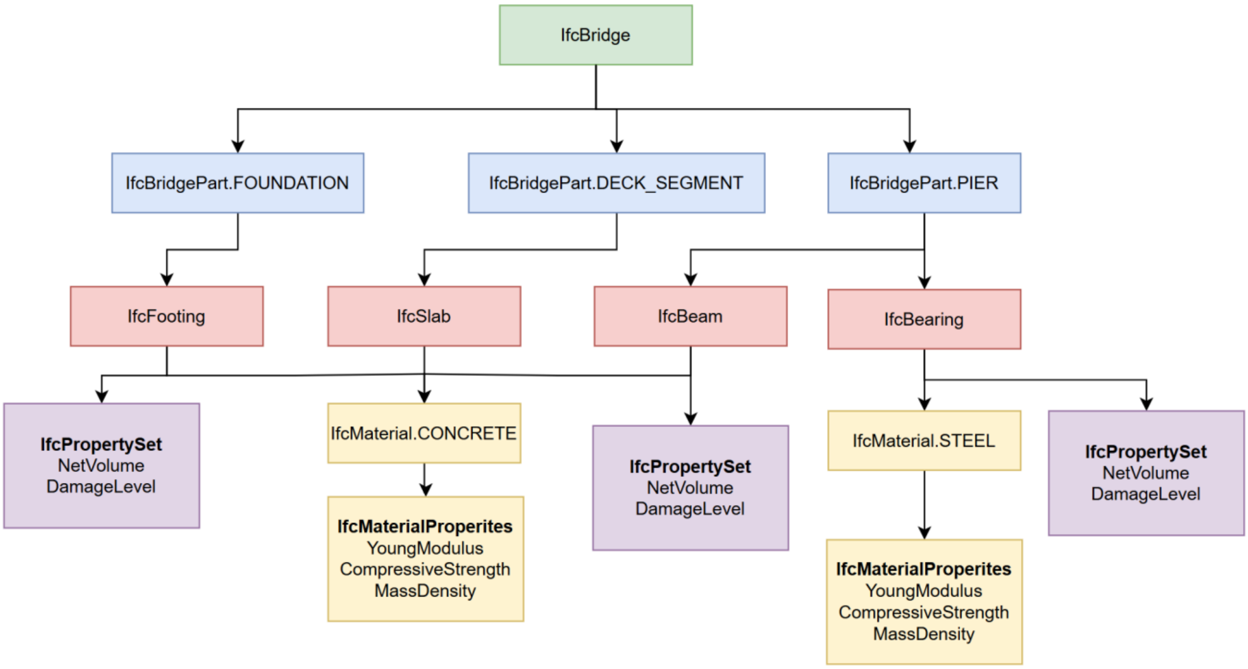


Figure 9 Characterization of structure and its elements in the IFC on an example of a bridge (based on Chacón et al., 2024)

To be able to properly assess the circularity (particularly disassembly potential score), some additional information is needed that goes beyond the scope of the information typically found in the IFC file. One example for this is the connection between the construction elements. While it is possible to define connection types between the elements using IFC standard (e.g. using IfcRelConnectsElements definition), such information requires significant manual work and is rarely present in the BIM models. For that reason, predefinition of DP and its sub-PIs per type of structure and its elements is suggested.

IFC standard allows objects to have a type of USERDEFINED, with the actual object type being stored in the parent definition of IfcObject.ObjectType. The Circularity Analytics tool utilizes this feature to differentiate between certain element types. Some of the custom object (bridge) types that are used are the following:

IfcBridge

1. A1 Simply supported beam
2. A2 Continuous girders

3. A3 Semi continuous type girder
4. A4 Gerber type girders

Differentiating between the typical bridge types explained in the previous section allows the tool to determine connections and DP between elements.

IfcBeam

For the disassembly potential, it's important to differentiate transversal from longitudinal girders. The definition of a transversal girder doesn't exist in the IFC standard, so the tool is using USERDEFINED type with IfcObject.objectType=TRANSVERSAL_GIRDER

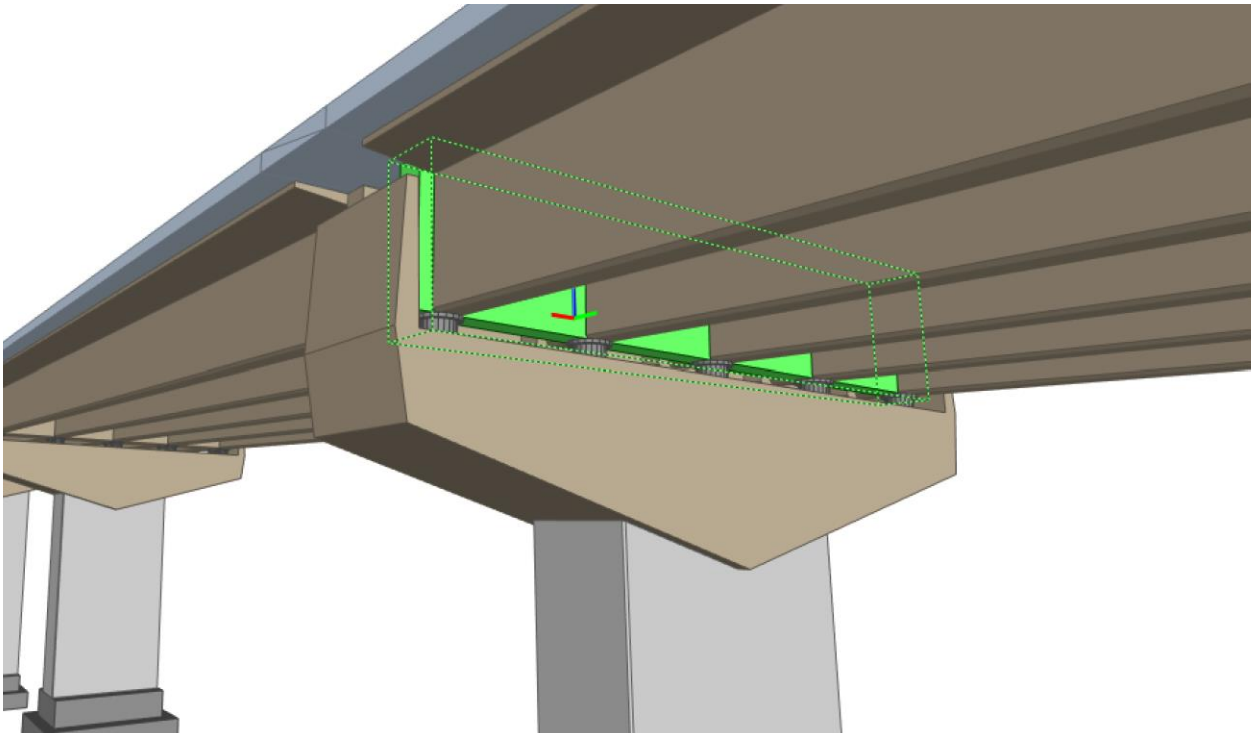


Figure 10 An example of a transversal girder

This allows the tool to simplify the calculation of circularity indicators since different beams will have different disassembly potential scores.

DamageLevel

Another information required for the analysis is damage level of the specific element. IFC Standard lacks the built-in way of storing a damage score for each element. For that reason, the tool is using custom properties, and property sets to define damage level property.

PropertySet : **DamageProperties**
Property: **DamageLevel**

If custom properties are not found in the IFC file, the algorithm gives each element the best possible score (explained in the Chapter 2.2.1.2)

Information outside the IFC Standard

Additional information that is not included in the IFC but is needed for the tool analysis is the object part (super and substructure) types. This information is requested directly from the user if there are multiple options for one of the bridge types. An example of the available options are listed below (for all bridge types):

Superstructure type:

1. Solid slab
2. Void slab
3. Pseudo slab (semi cast in place, semi precast)
4. Multicellular (cast in place)
5. Multicellular (precast)
6. Slab on beams (cast in place)
7. Slab on beams (precast)

For the most bridge substructure elements reusability is not an option because the elements are most often monolithic and cast in-situ. Even for some elements that are party prefabricated, such as columns, the connections between the prefabricated elements are monolithic. The same methodology is followed by establishing the DP potential for these elements but is simplified for this analysis in a way that CT is 0 and the elements go directly in the recyclability analysis. For the purpose of setting the tool framework the following substructural elements were analysed:

1. Pier cap
    a. Pier cap
2. Column pier (single or multi)
    a. Cast in situ
    b. Precast
3. Wall pier
    a. Wall pier
4. Column/wall pier
    a. Column/wall/pier
5. Gravity pier
    a. Gravity pier
6. Abutment
    a. Cantilever abutments
    b. Gravity abutments
    c. Pile abutments
    d. Bank-seated abutments
7. Foundation
    a. Spread footing
    b. Piles
    c. Caissons

3.3 CIRCULARITY ASSESSMENT

The integration of theoretical principles from structural mechanics, data analytics and material properties is performed to deliver efficient and accurate solution by leveraging advanced algorithms, see chapters 3.3.1 and 3.3.2, and computational methodologies see chapter . Each PI and sub-PI is calculated on the structures element level and aggregated on structures KPI level through the development process which combines robust algorithm design with practical software engineering to ensure usability, scalability, and reliability in real-world applications. The following chapters explain the data structuring, background calculations and thresholds used in the tool development.

3.3.1 Element level

The calculation of Performance Indicator Cir 1 Reusability is on the element level as follows:

- Definition of sub–PI Prefabrication level – Chapter 2.2.1.1 includes scoring system for structural element prefabrication level. Information comes from AMS or structures birth certificate.
- Definition of sub-PI Damage level – Chapter 2.2.1.2 includes scoring system to connect condition index and the damage level and the potential of reuse of an element. The developed scoring system is for concrete structures but is generic enough to be used for other types of structures by an experienced engineer. The information comes from AMS or from condition assessment reports.
- PI Disassembly potential – the detailed description of sub-PIs and the algorithms for calculation of DP per element is given in chapter 2.2.1.3. The main premise for definition of all parameters for this PIs lies in defining typical structural systems and subsystems. Through developing a catalogue of typical structures DP is already predefined and precalculated. The process requires a fair knowledge of an experienced engineer to pinpoint all connections between elements and their characteristics and presents the basis of the tool. The process requires some effort at first, but with a well-structured catalogue for different types of structures, the tool becomes generic and enables decision maker to use it for analysis of the whole transport infrastructure network.
- Definition of PI Transportability – Chapter 2.2.1.4 includes scoring system which depends on element dimensions. The information comes from BIM and IFC.

Once all the sub-PIs are defined and the score is assigned the reusability PI is calculated through the following equation:

$$Cir1 = \frac{Cir1.1 + Cir1.2 + Cir1.3 + Cir1.4}{4}$$

The calculation of Performance Indicator Cir 2 Recyclability is on the element level and is defined in Section 2.2.2 based on material. The overall recyclability index is established regarding the four sub indicators related to market value, resource depletion, energy consumption and carbon emissions for construction materials used in this study. The methodology is adapted from Mayer, 2024.

3.3.2 Structure level

Structure level analysis starts with reusability which is prioritized as it retains the highest value of materials, preserves embodied energy, and reduces environmental impact compared to recycling. When a component does not meet the criteria for reuse, it is automatically redirected to recycling analysis, where it is assessed for material recovery and transformation potential. By systematically distinguishing reusable components from those eligible for recycling, this tool aims to optimize circular resource utilization and support sustainable decision-making. Certain thresholds and rules are predefined in the tool to incorporate these premises into calculation:

- In the calculation of circularity the structure is analysed through volume ratios of all elements,
- When aggregating on the structural level through volume ratios the following criteria is followed:
    - Reusability is calculated for all elements except the following:
        - If elements prefabrication level is 0 element goes into recycling,
        - If damage level Cir 1.2 is bellow 0,1 element goes into recycling,
        - If the Connection type (CT) is bellow 0,2 the element goes into recycling,
        - If the Accessibility of Connection (AC) is bellow 0,1 the element goes into recycling,
        - If the Element Independence (IE) is bellow 0,1 the element goes into recycling,
        - If the Geometry of element Edge (GE) is bellow 0,1 the element goes into recycling,
    - Recyclability is calculated for those elements as described in Chapter 2.2.2.

Final analysis of circularity on the structure level is performed through the following equations:

- Each element is expressed as percentage of volume

$$V_{el\ i/j,ratio} = V_{el\ i/j}/V_{Str}$$

Where

- $V_{el\ i/j,\ ratio}$ – percentage of volume of element i or j in the entire volume of the structure (bridge)
- $V_{el\ i/j}$ – volume of element i or j (coming from BIM)
- V_{Str} – volume of the whole structure (coming from BIM)

<u>KPI Circularity</u> is calculated by the following:

$$KPI\ Cir = \frac{\frac{\sum_{i=1}^{n} Cir1,i * V_{iEl,ratio}}{n} + \frac{\sum_{j=1}^{m} Cir2,j * V_{jEl,ratio}}{m}}{2}$$

- i – i_{th} element of the whole structure, for element i reusability is calculated
- j – j_{th} element of the whole structure, for element j recyclability is calculated

- n – overall number of elements in the analysed structure that are reusable
- m – overall number of elements in the analysed structure that are recyclable

3.4 SYSTEM DESIGN

As the basis for the implementation, the Python programming language was selected for its flexibility. This ensured that the base algorithm can be used in both desktop and web applications. The open-source framework ifcopenshell (https://ifcopenshell.org/) was used with Python to manage IFC files. Ifcopenshell contains many utility functions that allow for easier management of IFC files. To demonstrate how the algorithm works, a simple GUI (Graphical user interface) was created using base Python package Tkinter. The algorithm itself was decoupled from both GUI and ifcopenshell package to ensure maximum reusability across other software. The basic structure of the tool is shown on the graph in Figure 11.

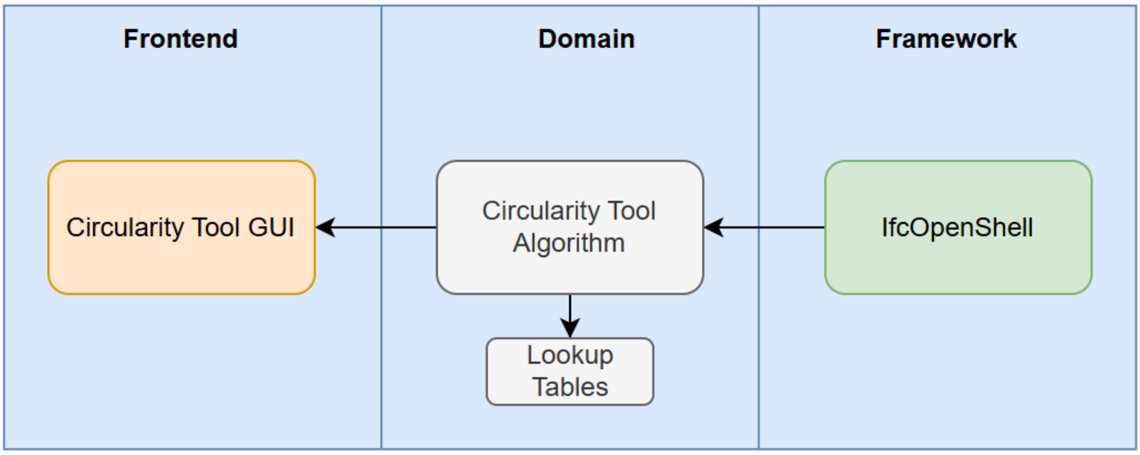


Figure 11 Basic software structure of the tool

The tool itself works as follows:

1. The user sees the welcome screen where an IFC file can be selected:

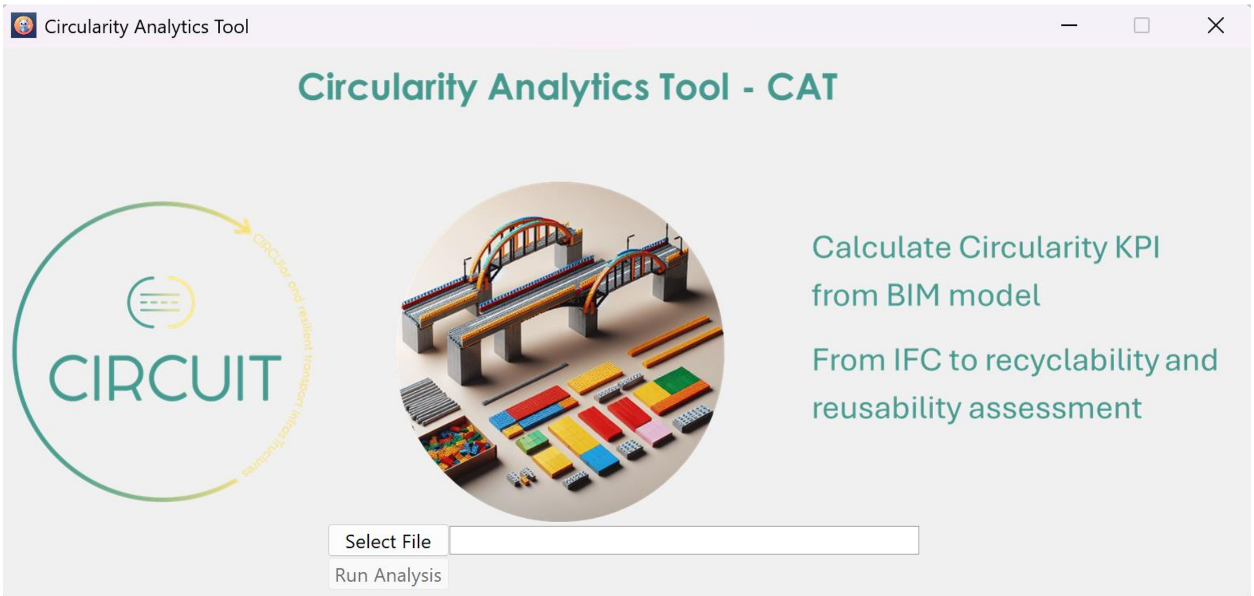


Figure 12 Welcome screen of the CAT Tool

2. User selects an option "Run Analysis",
3. If the IFC file contains the information about the bridge type, proceed with the analysis,
4. Otherwise, ask user to provide the information about the bridge type:

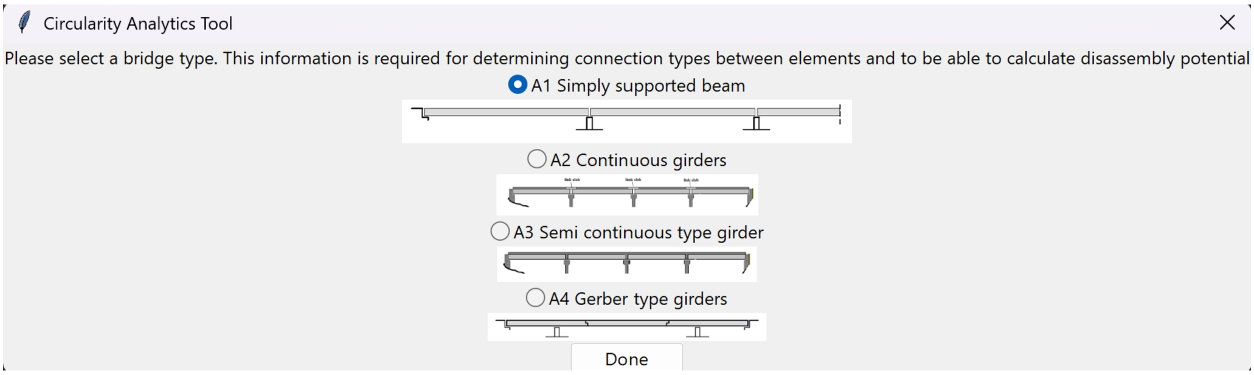


Figure 13 A bridge type selection process

5. Ask user about the superstructure type:

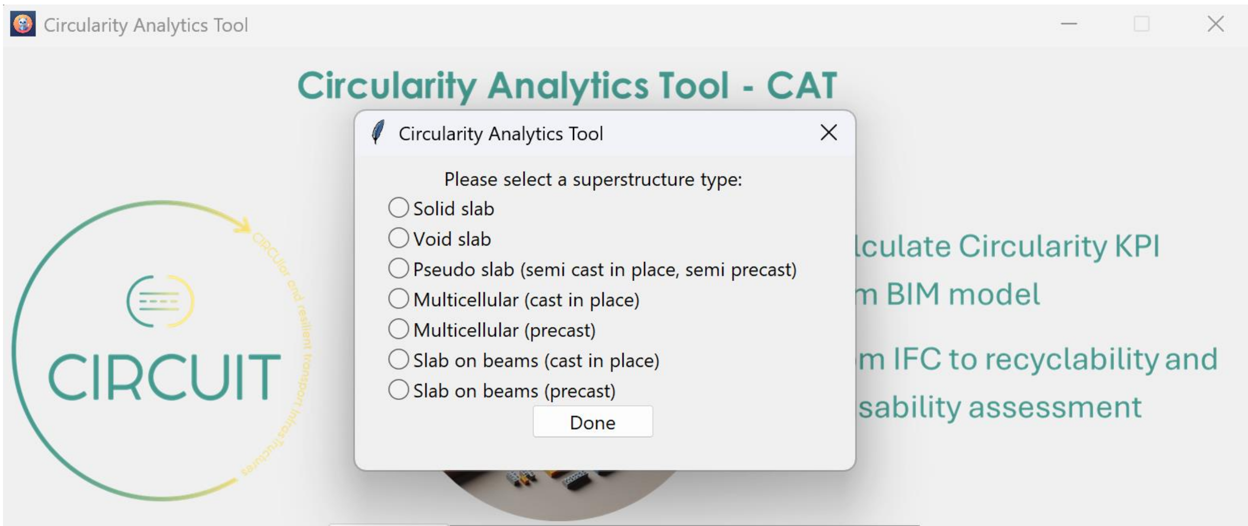


Figure 14 Superstructure type selection process

6. After the analysis is completed, display the circularity score for the bridge, as well as the percentages of reusable and recyclable volume:

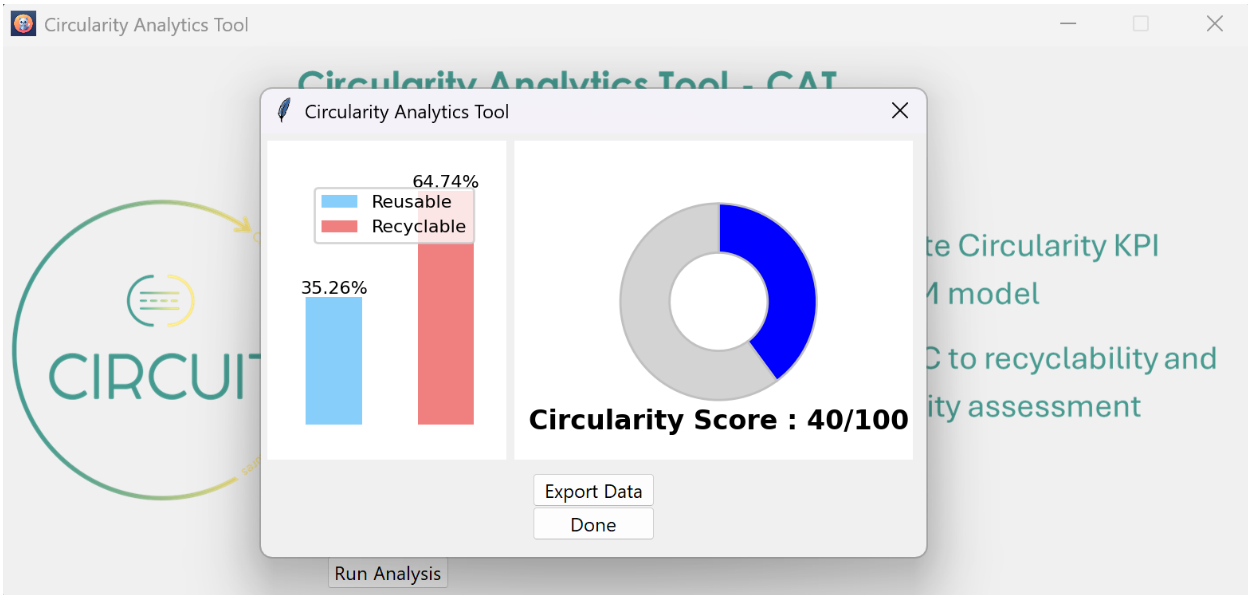


Figure 15 Example of the results

7. The user has an option to export the detailed results for each element using "Export Data" option. A CSV file is generated, containing the information and properties of each element. An example of the export is shown in the Figure 16.

GUID	Name	Element Type	Predefined Type	Volume	Material	Dissasembly Potential	Prefabrication Level	Damage Level	Trasportability	Reusability	Recyclability
1KkR4Gwfv2UeHP	POT-S6L	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
3t8iNvBhL6KhgS4	POT-U12L	IfcBearing	POT	0.038	StainlessSteel	0.65	1	1	0.1	0.69	0.46
33S7KBT7H9CRlR	Girder-Span9L	IfcBeam	BEAM	5.595	HA-25/B/20/IIa	0.57	0	1	0.1	0.42	0.29
3iW_q3OhjAQBVp	POT-S9R	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
1cGbKv4a97sua1I	Walls-U12L	IfcWall	RETAININGWALL	216.169	HA-25/B/20/IIa	0.2	0	1	0.1	0.33	0.29
3paDGXm4r8_g2Y	POT-S7L	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
37LD7LPxX2VuviR	Beam-Span9R	IfcBeam	BEAM	27.203	HP-25/B/20/IIa	0.3	1	1	0.1	0.6	0.29
3Fzd$MUo5F$Q1j	Girder-Span11R	IfcBeam	BEAM	11.872	HA-25/B/20/IIa	0.57	0	1	0.1	0.42	0.29
3fWofJsUDCoOG1	POT-S11L	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
1_IlWDhif7khNyM	POT-S6R	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
3j18VKQsn95RaS(	PierCap-S2R	IfcBeam	PIERCAP	41.632	HA-25/B/20/IIa	0.2	0	1	0.1	0.33	0.29
1OnYvLmS59sv4N	Pier-S5L	IfcColumn	PIERSTEM	30.521	HA-25/B/20/IIa	0.08	0	1	0.1	0.29	0.29
1CpwWOV5X1bvJ	F-S8R	IfcFooting	PAD_FOOTING	33.8	HA-25/B/20/IIa	0.08	0	1	0.1	0.29	0.29
3oa6YhI2bBSPbh3	POT-S6L	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
2Hmi_R4Br3ZRw4	POT-S10R	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
32OfBw41n6aOea	Girder-Span4L	IfcBeam	BEAM	5.595	HA-25/B/20/IIa	0.57	0	1	0.1	0.42	0.29
0JJviQVcn3qeahU	POT-S5R	IfcBearing	POT	0.051	StainlessSteel	0.65	1	1	0.1	0.69	0.46
1OlZag2zH78OhA(	POT-U12R	IfcBearing	POT	0.038	StainlessSteel	0.65	1	1	0.1	0.69	0.46
3Zf3NJQvP7XhYYe	Walls-U1R	IfcWall	RETAININGWALL	131.423	HA-25/B/20/IIa	0.2	0	1	0.1	0.33	0.29
3_pfACF$9A_gsR3	Beam-Span10R	IfcBeam	BEAM	27.203	HP-25/B/20/IIa	0.3	1	1	0.1	0.6	0.29

Figure 16 Example of a CAT Tool data export

4 CONCLUSIONS AND NEXT STEPS

An Asset Management System (AMS) is a structured and methodical framework for managing a network of assets. It encompasses activities such as optimizing maintenance and improvement decisions to maximize benefits while minimizing life-cycle costs (LCC). At the core of an AMS is a database built on data gathered from structures birth certificates, regular inspections and maintenance activities. The system's reliability depends on the quality and accuracy of inventory and condition data collected during field inspections. Key information, including asset identifiers (e.g., name or ID), location, and construction date, is recorded as the foundation of the system. Additional data, such as drawings, maintenance records, and surveys, are reviewed to complement this foundation.

Integrating circularity into the AMS enhances its value by incorporating principles of resource efficiency and sustainability. Circularity assessment focuses on evaluating how effectively materials and components within assets are reused, recycled, or repurposed throughout their life cycle. By leveraging the existing AMS database, managers can systematically assess the potential for material recovery and the environmental impact of asset maintenance and replacement decisions.

The importance of circularity assessment being grounded in the AMS lies in its reliance on accurate, structured data already captured in the system. Information on asset composition, condition, and lifecycle stages provides the necessary foundation for identifying opportunities to minimize waste and maximize the reuse of resources. For example, the data on maintenance records and material specifications can help pinpoint components that are suitable for recovery or require sustainable disposal methods.

Integrating circularity into the AMS ensures that asset management not only prioritizes performance and cost efficiency but also aligns with sustainability goals. This approach empowers managers to make informed, future-ready decisions that balance structural integrity, cost-effectiveness, and environmental responsibility. By embedding circularity within the AMS framework, organizations can transition to more sustainable asset management practices while maintaining a robust decision-making process. The developed methodology is designed as an addition to the existing asset management system. The tool is designed so that the circularity calculation begins with the basic system settings, utilizing the existing classification system for assets and their elements. I

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