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ACCOMPANYING MEASURE FOR DISSEMINATION, VALORISATION AND COLLABORATIVE EXPLOITATION OF CIRCULARITY OF CONSTRUCTIONAL STEEL PRODUCTS

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Environmental assessment of constructional steel reuse: Methodology report

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Executive summary

This report presents the methodology to declare environmental benefits of reused elements in the scope of RFCS project ADVANCE “Accompanying measure for dissemination, valorisation and collaborative exploitation of circularity of constructional steel products”. Our goal is to clarify the calculation method used for Environmental Product Declarations according to EN 15804 + A2 and to analyse alternative metrics for the assessment of circularity of constructional steel products.

The European steel sector has played an important role in the development of LCA assessment methods and standards over many years. Life Cycle Inventory data published by steel industry is based on production of steel from iron ore and steel scrap. This inventory covers material mining and manufacture but also benefits and loads of recycling steel from products at the end of their life. Deconstruction and reuse offer alternative circular path to this well-established recycling process and in the case of steel, it will be always assessed together with scrap recycling, because almost all the material not suitable for reuse can be recycled. Several studies shown that a design approach featuring reused steel allows for considerable savings in energy and carbon reduction with respect to a new one.

In this report we describe a simple methodology to account reuse, in addition to recycling, in LCA calculations for constructional steel. The method is an extension of the Wordsteel Association’s methodology, and it is compatible with the CEN/TC 350 standards and PEF Circular Footprint Formula. We demonstrate this methodology in several calculation examples, where the different choices of recycling, reusing and disposal are selected. The method is suitable for individual projects such as buildings specifically designed to be reused. However, it can also highlight the benefits of product categories with substantial rate of reuse, for instance in the Environmental Product Declarations.

The report will cover the following issues:

- Lifecycle assessment methodology according to CEN/TC350 and CEN/TC135 standards for constructional steel products.
- Overview of possible circularity metrics to quantify the benefits of steel reuse.

Contents

1. Introduction

Steel is used in many, different construction products and systems. However, the main generic product groups are primary structural steelwork, rebar and light gauge steel products including studs and sheeting, decking and cladding products. Whereas all constructional steel is currently highly recycled and could potentially be reused, structural steelwork, including beams and columns, offers potential for reuse due to its size, robustness and durability. Quantifying and allocating the burdens and benefits of reusing constructional steel and designing buildings for reuse has a significant influence on their sustainability credentials or impacts. The importance of such impacts in the development of design solutions has increased in the recent years. The environmental benefits of reusing building components are clear, but the robust method to quantify those benefits for constructional steel is missing.

The challenge of quantifying and declaring the environmental benefits of reusing and recycling structural steel is a controversial and contested subject within the LCA community. A few approaches have been proposed, ranging from ignoring the savings due to reusing materials from demolished buildings to allocating benefits equally across all life cycles [1][2]. At the heart of this methodological debate is the incompatibility between life cycles of the different products made from steel and their scope of assessment. Steel (as a material) theoretically has an infinite life, through multiple recycling loops, whereas building assessments are generally limited in scope to the predicted design life of the building. Structural steel (as a product) also has the potential to be reused over several building life cycles. This yields some methodological challenges on which there is a lack of consensus; most notably, on how the initial and long-term environmental burdens and benefits are quantified and allocated over time. At the same time, declaration of environmental impacts beyond the system boundary became mandatory in several countries, creating additional difficulties in allocations of burdens and benefits. For instance, it is specifically required to calculate impacts of reusable components in the Finnish guidance for the whole life carbon assessment of buildings [3] and will become mandatory part of the Climate Declaration for the construction and renovation permits since 2025.

The way allocations are done determines how different design solutions regarding end-of-life deconstruction and future reuse are perceived, an important driver of decisions especially in the early design phases [4]. Hence, besides the scholarly discussion within LCA circles, the allocation decisions have a broad implication on how society perceives the sustainability of reused or reusable building solution. For structural steel, the basis of the response of the industry to climate challenge is expected to be based on zero waste and 4R (reuse, remanufacture, recycle and recover) approaches, together with innovations to decrease CO_2 emissions per tonne of steel [5].

This report proposes a methodology to quantify and allocate the environmental benefits of structural steel reuse and recycling based on the most up-to-date LCA standards and guidance, namely the PEF methodology developed by EU DG Environment for building the single market for green products and standards developed under CEN/TC 350 mandate [6],

Structural steel is manufactured by both the primary steelmaking process of converting molten pig iron into steel in blast oxygen furnaces (BOS) and the secondary production route utilizing a high-current electric arcs to melt steel scrap into liquid steel in electric arc furnaces (EAF). Following building demolition, structural steel is almost entirely recovered.

Therefore, the recent focus of improving structural steel circularity is exploring new ways in which the construction systems and elements can be designed for deconstruction and reuse rather than recycling by re-melting [9]-[11]. The environmental benefits and desirability of reusing more structural steel are undisputed and the discussion gravitates on how to overcome the barriers of reusing, how to stimulate reuse by the LCA and how important part reuse will play in the transformation of the industry towards cleaner production.

In the next sections, we give the background of how recycling and reuse are defined within the European regulatory context and how we use the two concepts for constructional steel within this report and we discuss the methodologies in life-cycle assessment (LCA) to define system boundaries based on the production and removal from service of constructional steel and steel based products in buildings (Section 2), we compare the choices to integrate reuse of constructional steel in other methodologies (Section 3) and we highlight the effect of these choices on declaring of environmental impacts for reused and reusable steel construction products on the calculated case study (Section 4). We conclude that the described LCA method follows the CEN standards and is generally compatible with the other methods, but offers flexibility, simplicity, and transparency in handling the multiple routes of recycling, remanufacturing, and reuse of constructional steel.

The Network for Reuse and Recycling European Union Social Enterprises defines reuse as “an action or operation by which components or whole products are used again for the same purpose for which they were conceived.” [12]. The European Waste Framework Directive adapted this definition in 2008 with the specification that reuse applies to products or components that are not waste [13]. In this report, the ‘same purpose’ means for instance structural steel reused as structural steel. The product groups commonly used in buildings are schematically presented in Figure 1 with their approximate lifetime. The boundaries between product groups that change at different rates highlight the shearing layers, where maximum flexibility is required to change the building.

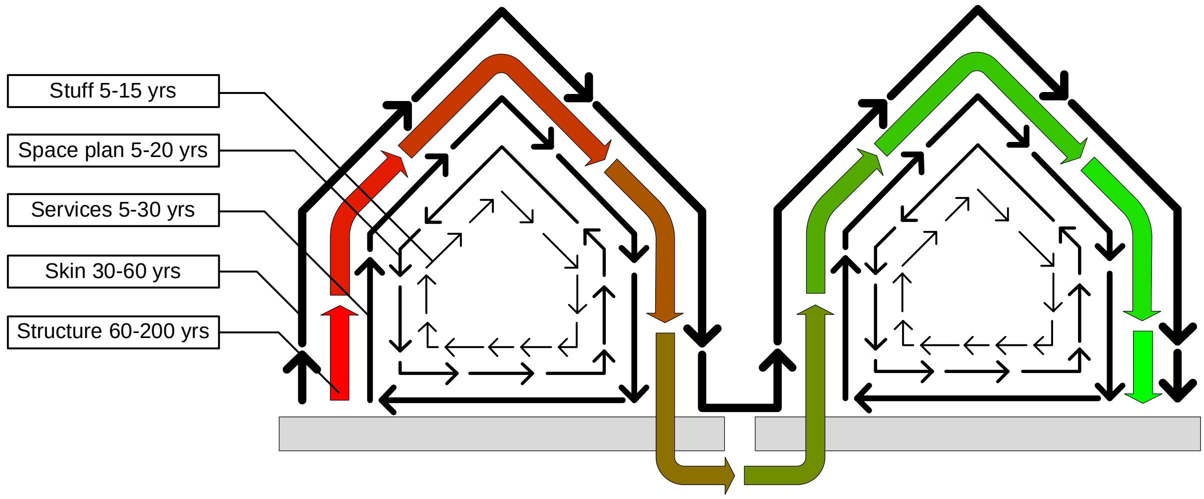

Figure 1 Shearing layers in the context of structural steel reuse based on Brand [14]

According to the RREUSE [12], reuse covers activities in two categories (see Table 1): activities allowing the product to continue its lifecycle as conceived and activities where the product is altered.

Table 1 Reuse activities according to RREUSE [12]

Reuse of product as conceived	Reuse of product with alterations
Refurbish/reconditioning (returning product/component to satisfactory working condition)	Remanufacture (returning product/component to OEM performance specification)
Repair (correction of a specified fault in a product/component)	Upgrade (upgrade a product/component to a better performance compared to the original performance)
Resell/remarket (cleaning likely to be the maximum work carried out)	

The distinction in the two categories is important because of the waste management and product marketing legislation. For instance, the essential characteristics in the product's Declaration of Performance for CE marking can be carried over to the certification of constructional steelwork if the product is not altered [15][16]. Moreover, if the product is reused as conceived, it does not become a waste according to the Waste Framework Directive [13]. In the scope of quantification of environmental benefits, the LCA system end-of-life boundary has to be set for the products in the second category, while the activities in the first group can be seen as the extension of product's lifecycle, especially in the case where the product is reused in its original configuration in situ.

2. Life cycle assessment methodology

Lifecycle assessment (LCA) provides data describing some of the environmental impacts caused by the manufacture, use, recycling, and ultimate disposal of material over its entire life cycle. Conducting an LCA helps to understand the phases where the most adverse effects are created in the building or product’s lifecycle and facilitates decision-making towards an ecological optimization of the products manufacture, use and end-of-life treatment.

The goal of an LCA can be to compare impacts that are occurring at different life cycle stages, or to compare different production, use or end of life scenarios for a product or a building. In this report we focus on structural steel products, their different production, design, manufacturing, and recovery scenarios at the end of their service life. The calculations extend from cradle to cradle, meaning from the extraction of the raw materials for steel making up to disposal, recycling, or reuse. We are focusing on the typical end-of-life scenarios of today, but also on potential end-of-life scenarios as they are influenced by the design of steel products and buildings.

The results of LCA calculations are typically divided into several stages as illustrated in the Figure 2 where the lifecycle stages are: Product stage (A in Figure 2) divided into modules A1 to A5, Use stage (B in Figure 2) and End-of-life stage (C in Figure 2). The impacts of possible future recycling and reuse (D in Figure 2) are always declared separately because they do not appear in the studied lifecycle.

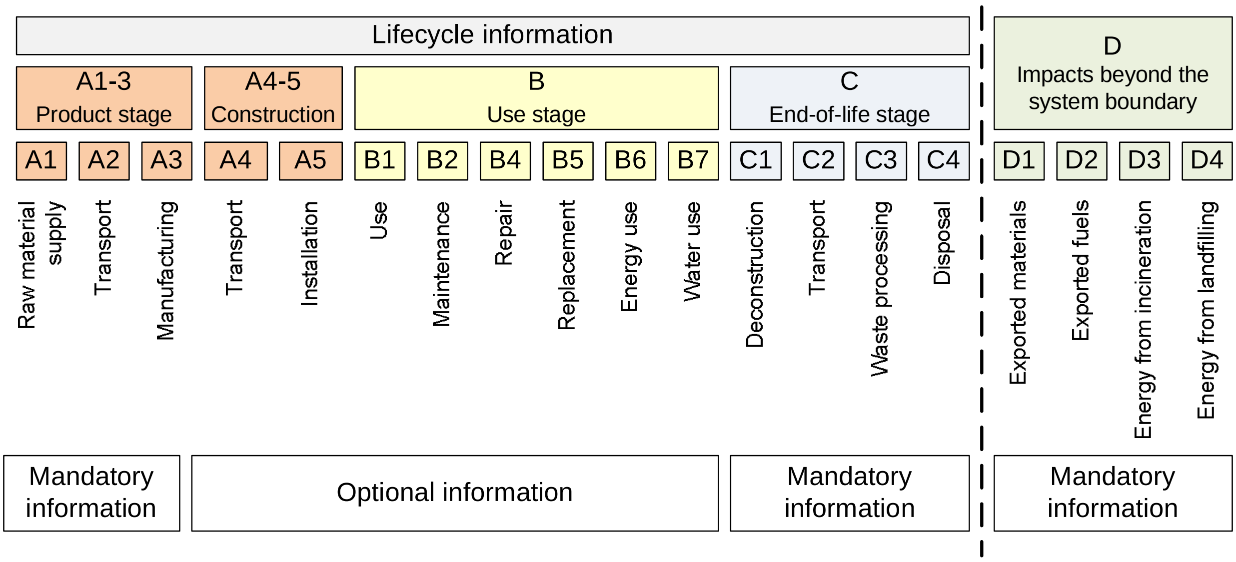

Figure 2 Lifecycle stages and modules according to CEN/TC350

Declaring these impacts beyond the system boundary (D in Figure 2) is nowadays mandatory for the Environmental Products Declarations in EU [17] and is becoming mandatory for the whole buildings in several Member States; for instance in Finland it is part of the “carbon handprint” [3] and will be required for all building projects since 2025. These impacts show the future improvement or deterioration of the materials recoverability, and therefore the knowledge of the current Product stage impacts (A) is essential for their calculation at least until the point of the functional equivalence. The point of functional equivalence is typically different for reuse of a steel product and for recycling of steel.

Depending on the scope of the LCA study, the functional unit may be one kilogram of steel, one meter of long product (e.g. rolled steel section), one square meter of flat product (e.g. steel plate), the whole steel product (e.g. a steel column) or the entire steelwork (e.g. steel frame of hall building). The functional unit used in our examples is one kilogram of constructional steel product placed in a building, however the methodology described in this report is directly applicable to other functional units related to the product. The assessment of the entire building is not covered by the presented methodology, but it is assumed that the same principles would be applicable.

A problem in the lifecycle assessment of the buildings made of reused or reusable products is the definition of system boundaries. Upstream processes (mining, etc.) are providing life cycle data to the current assessment (e.g. A in Figure 2) and they are typically well known and accurately defined at the time of the building's design or building product's use, while downstream processes (e.g. C in Figure 2) often rely on generic data. This will minimise the down-stream of the old building's life and allow allocating most of the impacts to the upstream processes of the new building.

The lifecycle of the building component does not necessarily need to be equivalent to the lifecycle of the building. It is usually shorter since internal building components may be regularly replaced (see Figure 1). However, reuse leads to situations when the component is used in several buildings and its lifecycle, in the repeated use phases, extends the lifecycle of one building. In such cases, it is advisable to define system boundaries of a component assessment equal to those of the building assessment for each reuse cycle separately to ensure the compatibility between both calculations.

In the scope of a single lifecycle assessment, we can have several different situations dealing with reused steel components:

<u>(a) Reuse today</u>, when the product is reused in the current lifecycle and enters the system as a secondary raw material. The benefit of reuse is reflected in the lower environmental impacts in the product stage (A in Figure 2). It should be noted that if the product cannot be reused after the current lifecycle, module D will show environmental burden.

<u>(b) Design for future deconstruction and reuse</u>. This scenario may create a slightly higher impact in the initial product stage but shows greater benefit in following lifecycles (D in Figure 2).

(c) <u>Combination of both scenarios</u> with the benefits mostly reflected in the module A. Impacts beyond the system boundary depend on its future reusability. If it is expected to improve, module D will show benefits, if it deteriorates, module D will show burden.

2.1 Impacts of today reuse

EN 15804 [17] is not providing specific rules how to allocate LCA impacts of reuse of construction products in Modules A1 to A3. However, new Construction Products Regulation (CPR) [18] is taking a position that should be used, when and how LCA impacts of reused products are allocated to Module A3. The CPR text is aligned with the principles and definitions of EU Waste Framework Directive [13] as well as with the principle included also in EN 15804 [16] and EN 15978 [15]. This means that the life cycle in which a product has been manufactured will end at the point when the product has been dismantled from the construction works and it is reused directly (Module C2) or has undergone processes for preparation for reuse and by which it ceases to be waste. These processes include checking, cleaning, and repairing, by which products or components of products are prepared so that they can be reused in general for construction purposes without any other pre-processing (Module C3). This is the case e.g., when an audit before deconstruction is done [19].

If a product that intends to be reused in the next life cycle is not valid for reuse in the specific intended use without further processing, the impacts of these processes shall be addressed to Module A3. The new CPR [18] recognises two different cases when the product needs to be transformed in a way that it fulfils the requirements of the relevant harmonised product standard:

- intended use requires transformation to modify product's non-essential characteristics (e.g., cutting to the new size, decorative repainting) or,
- intended use requires remanufacturing to ensure or modify product's essential characteristics for structural use ensuring functional and technical performance of a product (e.g., by including relevant testing of technical characteristics, and also galvanisation and repainting for proper surface treatments)."

2.2 Loads and benefits of future reuse

The loads and benefits of future reuse are part of mandatory module D of LCA calculation. Their calculation shall follow the allocation procedure of reuse, recycling, and recovery of materials in Section 6.4.3.3 of EN 15804 [17]. Formula D.6 "*specific loads and benefits per unit of analysis for module D related to the export of secondary materials*" in the informative Annex D of the standard describes the practical application of this procedure.

In module D, the net impacts are calculated (1) by adding all output flows of a secondary material and subtracting all input flows of this secondary material from sub-modules, modules and from the total product system thus arriving at net output flows of secondary material from this system, (2) by adding the impacts connected to the recycling or recovery processes from beyond the system boundary up to the point of functional equivalence where the secondary material substitutes primary production and subtracting the impacts resulting from the substituted production of the product from primary sources and (3) by applying a justified value-correction factor to reflect the difference in functional equivalence where the output flow does not reach the functional equivalence of the substituting process.

Additionally, the material losses downstream of the steel recycling chain shall be considered according to the Worldsteel Association's methodology [20].

This can be expressed by extended formula D.6 from Annex D of EN 15804 proposed in PROGRESS project methodology [8]:

$$e_{moduleD1} = \sum_i \left(M_{MR,out,i} - M_{MR,in,i}\right)\left(E_{MRafterEoW,out,i} - E_{VMSub,out,i}\frac{Q_{R,out,i}}{Q_{Sub.i}}\right)Y_i \quad (1)$$

with the following parameters:

$M_{MR,out}$ amount of material exiting the system that will be recovered in a subsequent system. This amount is equal to the output flow of "materials to recycling [kg]" reported for modules A, B and C;

$M_{MR,in}$ amount of input material to the product system that has been recovered from a previous system (determined at the system boundary) and is to be used as input in the current system;

$E_{MRafterEoW,out}$	specific emissions and resources consumed per unit of analysis arising from material recovery processes of the current system;
$E_{VMSub,out}$	specific emissions and resources consumed per unit of analysis arising from acquisition and pre-processing of the primary material, or average input material if primary material is not used, from the cradle to the point of functional equivalence where it would substitute secondary material that would be used in a subsequent system;
$Q_{R,out}$	quality of the outgoing recovered material, i.e., quality of the recycled material at the point of substitution;
Q_{Sub}	quality of the substituted material, i.e., quality of primary material or quality of the average input material if primary material is not used.

Impacts of reuse and recycling (or different kinds of recycling) of the same material shall be calculated separately with different index i. The reason is that reuse and recycling have different points of functional equivalence and different specific emissions and resources. For instance, the value of $e_{moduleD1}$ of the product with 100% recycled material input, which is 100% reused at the end of life, will not be zero. In most of the cases, it will be negative, because the net impact of reuse is higher than the net impact of recycling.

The results of $e_{moduleD1}$ calculation can be presented separately, for example $e_{moduleD1.1}$ for recycling and $e_{moduleD1.2}$ for reuse. In such case, the selected allocation procedure has to be reported, because it directly affects how the loads and benefits of $e_{moduleD1}$ are divided between $e_{moduleD1.1}$ and $e_{moduleD1.2}$ (see Section 2.2.1 and 2.2.4)

2.2.1 Calculation of net flows of secondary materials

Impacts beyond the product's system boundary are net impacts, and therefore can be both positive (burden) or negative (credits), depending on the balance between the production route of the component and its future recovery scenario. Net flows M_{net} are calculated by subtracting from the output material flows at the end-of-life of the product (i.e. recovered steel) all content of secondary material of the product at fabrication, as in Equation (2). In this equation, the amount of recovered steel used in the manufacturing of the product is the input flow $M_{MR,in}$, while the amount of steel to be recovered at the end-of-life of the product is the output flow to the LCA system $M_{MR,out}$.

$$M_{net} = M_{MR,out} - M_{MR,in} \qquad (2)$$

All relevant secondary material flows should be considered resulting either in benefits (negative $e_{moduleD1}$) or loads (positive $e_{moduleD1}$) of the assessed system. For example, negative net flow of recycled material that is going to be landfilled at its end of life cannot be neglected, because it creates burden in the subsequent system.

2.2.2 Substituted emissions and resources

Net impacts (specific emissions and resources consumed per unit of analysis) associated with the material flows are calculated by adding impacts arising from the material recovery E_{MR} and subtracting the impacts arising from the acquisition and pre-processing of primary or secondary material E_{VM}. This material impact is calculated from the cradle to the point of functional equivalence, where it can be substituted by secondary material from recovery (i.e., E_{MR}). Functional equivalency can be established for a constituent product, component, or assembly. Then the lifecycle impacts (LCI) beyond the system boundary e can be expressed as in Equation (3):

$$e = M_{MR,out}\left(E_{MR,out} - E_{VM,out}\right) - M_{MR,in}\left(E_{MR,in} - E_{VM,in}\right) \quad (3)$$

Steel scrap can be infinitely recycled, and therefore closed-loop allocation procedure according to ISO 14044 [21] and World Steel Association methodology [20] can be used for the recycling flow. This procedure assumes that the use of secondary material displaces the use of virgin (primary) material.

On the other hand, fabricated components can be reused only for a limited number of cycles, and therefore the product system involving reuse is open-loop. Such system can be still assessed using closed-loop allocation procedure according to ISO 14044 [21] provided that no changes occur in the inherent properties of the material. In the following sections, we will demonstrate that both, closed-loop and open-loop allocation procedures can be used in the assessment of reusable constructional steelwork and will lead to the same outcome.

2.2.3 Closed-loop allocation procedure

Closed-loop product system or open-loop product system without inherent material changes can avoid allocation of secondary material over several lifecycles by assuming that the secondary material substitutes virgin (primary) material in the product [21] until the point of their functional equivalence. In this procedure, reported in detail in the PROGRESS guide [22], the material amounts $M_{MR,in}$, and $M_{MR,out}$ are the amounts of secondary materials entering and exiting the lifecycle of the particular product under assessment (M_{in}, and M_{out} in Figure 3). Therefore, total amount of input material and output material cannot be higher than the amount of the material contained in the product. Reuse and recycling flows can be fully separated and the value of $E_{VMSub,out}$ for recycling and for reuse refers to virgin (primary) material.

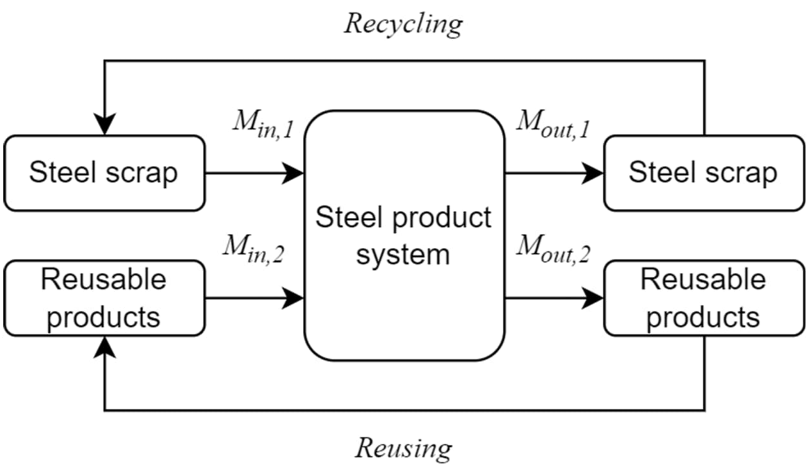

Figure 3 Closed-loop allocation of material flows

2.2.4 Open-loop allocation procedure

Open-loop allocation procedure for reused steel is widely used in the current steel Environmental Product Declarations (EPDs) [22]. It assumes open-loop system with limited number reuse cycles embedded in the closed-loop recycling system. The reusable product carries load of the scrap used in its original production and benefit of the scrap generated after its decommissioning. On the other hand, the substituted impacts $E_{VMSub,out}$ cannot be related to virgin (primary) production and shall be determined from the avoided product's production substituted in the following lifecycle.

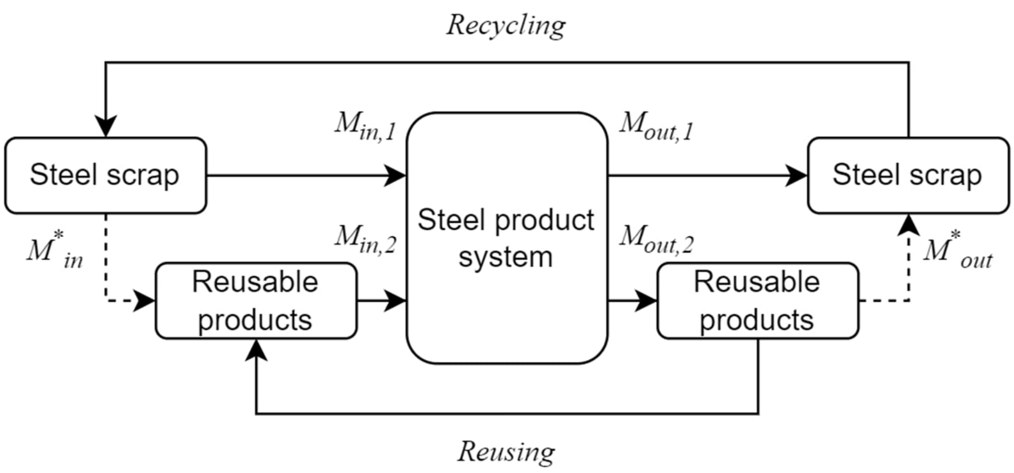

Figure 4 Open-loop allocation of material flows

The amount of steel scrap used in the first production of the reusable product M^*_{in} and the amount of steel scrap generated after decommissioning this product M^*_{out} are added to the amounts of steel scrap entering and exiting the system directly (see Equations (4) and (5)).

$$M_{MR,in,1} = M_{in,1} + M_{in,2} \cdot \Delta M^* \tag{4}$$

$$M_{MR,out,1} = M_{out,1} + M_{out,2} \cdot \Delta M^* \tag{5}$$

where ΔM^* is calculated from the initial and final flows M^*_{in} and M^*_{out} and a total mass of the product M according to Equation (6).

$$\Delta M^* = \frac{M^*_{out} - M^*_{in}}{M} \tag{6}$$

At the same time, the impact of material substituted by reuse $E_{VM,2}$ is lower, because it does not contain the benefits of closed-loop recycling. It is calculated according to the Equation (7).

$$E_{VM,2,open-loop} = E_{VM,2} - \left(E_{VM,1} - E_{MR,1}\right) \Delta M^* \tag{7}$$

This procedure generates the same module D ($e_{moduleD1}$) as closed-loop allocation, but part of the impacts of the reused product flow are allocated to the recycling flow. For better understanding of the differences between those two procedures, see the examples in Sections 2.3.1 and 2.3.2.

2.2.5 Material losses downstream in the recycling chain

The net amount of substituted primary material (virgin steel) can be different from the amount of recovered secondary material (steel scrap), and therefore the net flow may be reduced by the yield factor Y representing the efficiency of the recovery process. This factor can be used to modify net flows of secondary materials as in the Equation (8) or their net impacts according to the Equation (9). The second option is used in the World Steel Association's methodology as $ScrapLCI$ [20].

$$M_{net} = M_{MR,out} \cdot Y - M_{MR,in} \cdot Y \tag{8}$$

$$SecondaryMaterialLCI = Y\left(E_{MR,in} - E_{VM,in}\right) \tag{9}$$

Both approaches lead to the same expression of the impacts in the module D1 (see Equation (10)).

$$e = M_{MR,out} \cdot Y\left(E_{MR,out} - E_{VM,out}\right) - M_{MR,in} \cdot Y\left(E_{MR,in} - E_{VM,in}\right) \tag{10}$$

2.2.6 Quality aspects

If the product is going to be downcycled or has a different quality than the substituted material, the impact of substituted primary production may be modified by quality factors of the secondary and virgin material Q_{MR} and Q_{VM} respectively. This is not the case in steel recycling because steel produced from recycled scrap has equivalent qualities to steel produced from virgin materials, but it might affect the declaration of impacts of steel reuse. The extended Equation (10) is presented here as Equation (11). The allocation principle for a single recovery route, recycling, is illustrated in Figure 5.

$$e = M_{MR,out} \cdot Y\left(E_{MR,out} - E_{VM,out}\frac{Q_{MR,out}}{Q_{VM,out}}\right) - M_{MR,in} \cdot Y\left(E_{MR,in} - E_{VM,in}\frac{Q_{MR,in}}{Q_{VM,in}}\right) \tag{11}$$

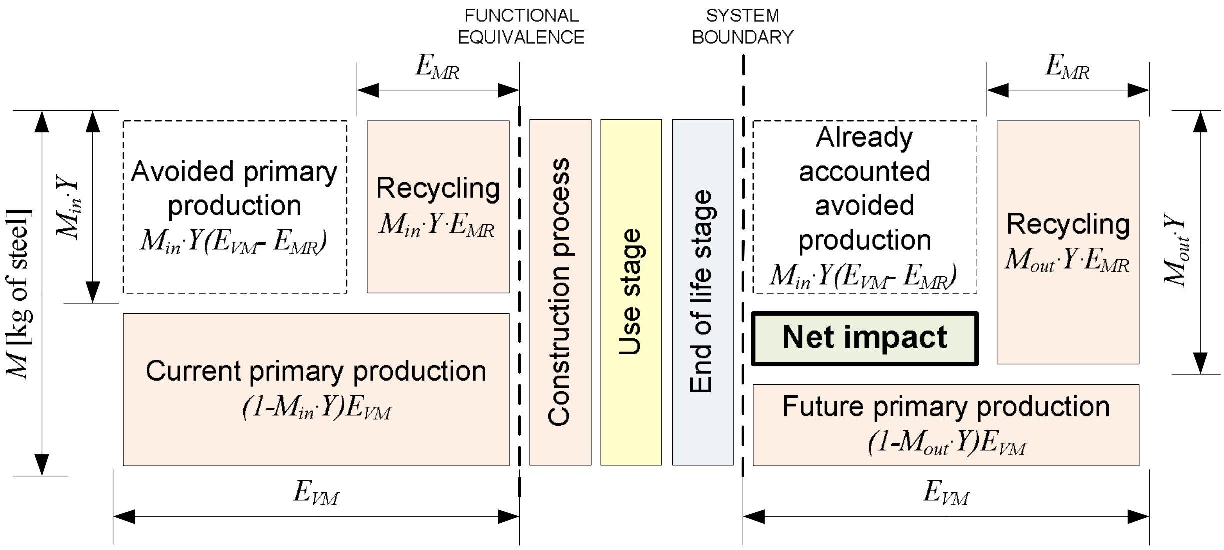

Figure 5 Allocation of net impact of recycling beyond the system boundary

If the unit impacts of the primary production and recovery process are the same at the beginning and end of product's life ($E_{MR} = E_{MR,in} = E_{MR,out}$ and $E_{VM} = E_{VM,in} = E_{VM,out}$), Equation (11) can be simplified to Equation (12). This expression takes the same format as the standard calculation from EN 15804 [17] in Equation (1).

$$e = \left(M_{MR,out} - M_{MR,in}\right) \cdot Y \cdot \left(E_{MR,out} - E_{VM,Out}\frac{Q_{MR}}{Q_{VM}}\right) \quad (12)$$

When the input flow of the existing product is more environmentally efficient than the recovery at the end-of-life stage, Equations (11) and (12) produce positive number. This means that the impact e is overall burden. On the contrary, if the existing product has low recovered material content and it is recovered very efficiently at the end-of-life, the impact e is benefit.

2.3 Calculated examples

The following examples are demonstrating the calculation principle in such situations where multiple recovery processes (e.g., recovery and reuse) shall be evaluated for the same product. The scenarios and emissions related to different materials are simplified in the examples, because they are not intended to highlight benefits of specific materials, but rather different situations in which the methodology can be used. The functional unit of the calculation is 100 kg of products made of different materials and product types (steel column, timber wall, concrete slab).

2.3.1 Example 1a: Steel (closed-loop allocation)

This example shows the calculation of 100 kg steel column fabricated from 90 kg hot-rolled section (50 kg of steel scrap used in production) and 10 kg reused endplates and fittings. Material losses in the reuse or recycling process are neglected. It is estimated that 60 kg of the product can be further reused. Then 10 kg of the material will be lost or disposed at the end of life, and the remaining 30 kg will be sent for recycling. The material flows parameters are presented in Table 2.

Table 2. Material amounts in recycling and reuse of steel column

	1: Steel recycling	**2: Steel reuse**
Material flow	Steel scrap	Steel section and plates
Amounts of input material	$M_{MR,in,1} = 50\ kg$	$M_{MR,in,2} = 10\ kg$
Amount of material exiting the system	$M_{MR,out,1} = 30\ kg$	$M_{MR,out,2} = 60\ kg$

The net flow of recycled material is then $M_{MR,out,1} - M_{MR,in,1} = -20\ kg$ and for reused material $M_{MR,out,2} - M_{MR,in,2} = 50\ kg$. Negative flow will result in environmental burden and positive flow will result in benefit as will be explained in this example.

The unit impacts of the substituted material are based on the primary production, recycling or reuse up until the gate of the factory ($e_{moduleA1-3}$). The impact category selected for the calculation is GWP. Specific emissions of the substituted primary production per unit of analysis are 2.0 kgCO$_2$e/kg (steel slab) and 2.5 kgCO$_2$e/kg (steel section and plates), specific emissions of recycling are 0.5

$kgCO_2e/kg$ and emissions related to reuse are 0.1 $kgCO_2e/kg$ (see Table 3). The quality factors $Q_{R,out,i}$ and $Q_{Sub,i}$ are assumed to be 1.0 for simplicity.

Table 3. Specific emissions in recycling and reuse of steel column

	1: Steel recycling	**2: Steel reuse**
Substituted product	Steel slab	Steel section and plates
Specific emissions of the recovery process	$E_{MRafterEoW,out,1} = 0.5\ kgCO_2e/kg$	$E_{MRafterEoW,out,2} = 0.1\ kgCO_2e/kg$
Specific emissions of the substituted primary production	$E_{VMSub,out,1} = 2.0\ kgCO_2e/kg$	$E_{VMSub,out,2} = 2.5\ kgCO_2e/kg$

In combination with the material flows described in Table 2, the final loads and benefits related to export of secondary materials shall be calculated as:

$$\begin{aligned} e_{moduleD1} &= \sum_i (M_{MR,out,i} - M_{MR,in,i}) \left(E_{MRafterEoW,out,i} - E_{VMSub,out,i} \frac{Q_{R,out,i}}{Q_{Sub,i}}\right) \\ &= (M_{MR,out,1} - M_{MR,in,1}) \left(E_{MRafterEoW,out,1} - E_{VMSub,out,1} \frac{Q_{R,out,1}}{Q_{Sub,1}}\right) \\ &+ (M_{MR,out,2} - M_{MR,in,2}) \left(E_{MRafterEoW,out,2} - E_{VMSub,out,2} \frac{Q_{R,out,2}}{Q_{Sub,2}}\right) \\ &= (30 - 50)\left(0.5 - 2.0\frac{1}{1}\right) + (60 - 10)\left(0.1 - 2.5\frac{1}{1}\right) \\ &= -20 \cdot (-1.5) + 50 \cdot (-2.4) = 30 - 120 = -90\ kgCO_2e \end{aligned} \tag{13}$$

2.3.2 Example 1b: Steel (open-loop allocation)

The steel column from the previous example will be assessed using open-loop allocation procedure. This procedure requires additional parameters related to the first and last lifecycles of the reusable part of the product. We will therefore assume that 5 kg of scrap was originally used to produce the new column ($M_{in}^* = 5\ kg$) and 95 kg of steel will be recycled after its last use ($M_{out}^* = 95\ kg$). The material flows parameters are presented in Table 4.

$$\Delta M^* = \frac{M_{out}^* - M_{in}^*}{M} = \frac{95\ kg - 5\ kg}{100\ kg} = 0{,}9 \tag{14}$$

Then the corrected input and output flows of the steel scrap are:

$$M_{MR,in,1} = M_{in,1} + M_{in,2} \cdot \Delta M^* = 50 + 10 \cdot 0{,}9 = 59\ kg \tag{15}$$

$$M_{MR,out,1} = M_{out,1} + M_{out,2} \cdot \Delta M^* = 30 + 60 \cdot 0{,}9 = 84\ kg \tag{16}$$

Table 4. Material amounts in recycling and reuse of steel column

	1: Steel recycling	**2: Steel reuse**
Material flow	Steel scrap	Steel section and plates
Amounts of input material	$M_{MR,in,1}$ = 59 kg	$M_{MR,in,2}$ = 10 kg
Amount of material exiting the system	$M_{MR,out,1}$ = 84 kg	$M_{MR,out,2}$ = 60 kg

The net flow of recycled material is then $M_{MR,out,1} - M_{MR,in,1} = 25\,kg$ and for reused material $M_{MR,out,2} - M_{MR,in,2} = 50\,kg$. Both flows are positive and will result in benefit.

The unit impact of the substituted reused product is based on the production of the actual product, recycling or reuse up until the gate of the factory ($e_{moduleA1-3}$) and is calculated according to the Equation (17).

$$E_{VMSub,out,2} = E_{VM,2} - \left(E_{VMSub,out,1} - E_{MRafterEoW,out,1}\right)\Delta M^* \\ = 2{,}5 - (2{,}0 - 0{,}5) \cdot 0{,}9 = 1{,}15\ kgCO_2e/kg \qquad (17)$$

Table 5. Specific emissions in recycling and reuse of steel column

	1: Steel recycling	**2: Steel reuse**
Substituted product	Steel slab	Steel section and plates
Specific emissions of the recovery process	$E_{MRafterEoW,out,1}$ = 0.5 $kgCO_2e/kg$	$E_{MRafterEoW,out,2}$ = 0.1 $kgCO_2e/kg$
Specific emissions of the substituted primary production	$E_{VMSub,out,1}$ = 2.0 $kgCO_2e/kg$	$E_{VMSub,out,2}$ = 1,15 $kgCO_2e/kg$

In combination with the material flows described in Table 4, the final loads and benefits related to export of secondary materials shall be calculated as:

$$\begin{aligned} e_{moduleD1} &= \sum_i \left(M_{MR,out,i} - M_{MR,in,i}\right)\left(E_{MRafterEoW,out,i} - E_{VMSub,out,i}\frac{Q_{R,out,i}}{Q_{Sub,i}}\right) \\ &= \left(M_{MR,out,1} - M_{MR,in,1}\right)\left(E_{MRafterEoW,out,1} - E_{VMSub,out,1}\frac{Q_{R,out,1}}{Q_{Sub,1}}\right) \\ &+ \left(M_{MR,out,2} - M_{MR,in,2}\right)\left(E_{MRafterEoW,out,2} - E_{VMSub,out,2}\frac{Q_{R,out,2}}{Q_{Sub,2}}\right) \\ &= (84 - 59)\left(0.5 - 2.0\frac{1}{1}\right) + (60 - 10)\left(0.1 - 1.15\frac{1}{1}\right) \\ &= 25 \cdot (-1.5) + 50 \cdot (-1{,}05) = -37{,}5 - 52{,}5 = -90\ kgCO_2e \end{aligned} \qquad (18)$$

2.3.3 Example 2: Timber

This example shows the calculation of 100 kg CLT wall panel from sawn timber. It is assumed that half of the panel will be cut and reused at the end of life and 80% of the remaining material (40 kg) will be recycled as chips in the particleboard. The material flows parameters are presented in Table 6.

Table 6. Material amounts in recycling and reuse of CLT board

	1: Timber recycling	**2: Timber reuse**
Material flow	Wood waste	CLT board
Amounts of input material	$M_{MR,in,1} = 0\ kg$	$M_{MR,in,2} = 0\ kg$
Amount of material exiting the system	$M_{MR,out,1} = 40\ kg$	$M_{MR,out,2} = 50\ kg$

Specific emissions of the substituted production of CLT board and wood chips are 0.1 $kgCO_2e/kg$, specific emissions of recycling are 0.2 $kgCO_2e/kg$ and emissions related to reuse are 0.1 $kgCO_2e/kg$ (see Table 7).

Table 7. Specific emissions in recycling and reuse of CLT board

	1: Timber recycling	**2: Timber reuse**
Substituted product	Wood chips	CLT wall panel
Specific emissions of the recovery process	$E_{MRafterEoW,out,1} = 0.1\ kgCO_2e/kg$	$E_{MRafterEoW,out,2} = 0.1\ kgCO_2e/kg$
	$E_{MRseq} = -1.5\ kgCO_2e/kg$	
Specific emissions of the substituted primary production	$E_{VMSub,out,1} = 0.2\ kgCO_2e/kg$	$E_{VMSub,out,2} = 0.3\ kgCO_2e/kg$
	$E_{VMseq} = -1.5\ kgCO_2e/kg$	

For the primary product or fuel that these outputs substitute, the sequestered carbon -1.5 $kgCO_2e/kg$, as a removal of CO_2 is included as the avoided impact, however, the sequestration is typically cancelled out in the calculation of $e_{moduleD1}$.

In combination with the material flows described in Table 6, the final loads and benefits related to export of secondary materials shall be calculated as:

$$
\begin{aligned}
e_{moduleD1} &= \sum_i \left(M_{MR,out,i} - M_{MR,in,i}\right)\left(E_{MRafterEoW,out,i} - E_{VMSub,out,i}\frac{Q_{R,out,i}}{Q_{Sub,i}}\right) \\
&= \left(M_{MR,out,1} - M_{MR,in,1}\right)\left(E_{MRafterEoW,out,1} - E_{VMSub,out,1}\frac{Q_{R,out,1}}{Q_{Sub,1}}\right) \\
&+ \left(M_{MR,out,2} - M_{MR,in,2}\right)\left(E_{MRafterEoW,out,2} - E_{VMSub,out,2}\frac{Q_{R,out,2}}{Q_{Sub,2}}\right) \\
&= (40-0)\left(0.1 - 0.2\frac{1}{1}\right) + (50-0)\left(0.1 - 0.3\frac{1}{1}\right) \\
&= 40 \cdot (-0.1) + 50 \cdot (-0.2) = -4 - 10 = -14\ kgCO_2e
\end{aligned} \tag{19}
$$

and including sequestered carbon:

$$
\begin{aligned}
e_{moduleD1} &= (40-0)\left(-1.4 + 1.3\frac{1}{1}\right) + (50-0)\left(-1.4 + 1.2\frac{1}{1}\right) \\
&= 40 \cdot (-0.1) + 50 \cdot (-0.2) = -4 - 10 = -14\ kgCO_2e
\end{aligned} \tag{20}
$$

2.3.4 Example 3: Reinforced concrete

This example shows 100 kg in-situ concrete containing 4 kg of steel rebar. Half of the element is cut and reused at the end of life, and from the remaining material 40 kg of crushed concrete is recycled as road base and 2 kg of steel scrap is collected for recycling. Rebar is assumed to be 75% recycled content (3 kg).

Table 8. Material amounts in recycling and reuse.

	1: Concrete recycling	**2: Concrete reuse**	**3: Steel recycling**
Material flow	Crushed concrete	Reinforced concrete slab	Steel scrap
Amounts of input material	$M_{MR,in,1} = 0\ kg$	$M_{MR,in,2} = 0\ kg$	$M_{MR,in,3} = 3\ kg$
Amount of material exiting the system	$M_{MR,out,1} = 40\ kg$	$M_{MR,out,2} = 50\ kg$	$M_{MR,out,3} = 2\ kg$

Specific emissions of concrete recycling and reuse are assumed to be similar (0.001 $kgCO_2e/kg$) and emissions associated to the recycling of the steel rebar, 0.5 $kgCO_2e/kg$, are obtained from the first example. The emissions of the substituted material are 0.005 $kgCO_2e/kg$ for stone and gravel, 0.2 $kgCO_2e/kg$ for reinforced concrete (including rebar) and 2 $kgCO_2e/kg$ for steel.

Table 9. Specific emissions in recycling and reuse.

	1: Concrete recycling	**2: Concrete reuse**	**3: Steel recycling**
Substituted product	Gravel and stone	Reinforced concrete slab	Steel slab
Specific emissions of the recovery process	$E_{MRafterEoW,out,1} = 0.001\ kgCO_2e/kg$	$E_{MRafterEoW,out,2} = 0.001\ kgCO_2e/kg$	$E_{MRafterEoW,out,3} = 0.5\ kgCO_2e/kg$
Specific emissions of the substituted primary production	$E_{VMSub,out,1} = 0.005\ kgCO_2e/kg$	$E_{VMSub,out,2} = 0.2\ kgCO_2e/kg$	$E_{VMSub,out,3} = 2\ kgCO_2e/kg$

In combination with the material flows described in Table 8, the final loads and benefits related to export of secondary materials shall be calculated as:

$$\begin{aligned}
e_{moduleD1} &= \sum_i \left(M_{MR,out,i} - M_{MR,in,i}\right)\left(E_{MRafterEoW,out,i} - E_{VMSub,out,i}\frac{Q_{R,out,i}}{Q_{Sub,i}}\right) \\
&= \left(M_{MR,out,1} - M_{MR,in,1}\right)\left(E_{MRafterEoW,out,1} - E_{VMSub,out,1}\frac{Q_{R,out,1}}{Q_{Sub,1}}\right) \\
&+ \left(M_{MR,out,2} - M_{MR,in,2}\right)\left(E_{MRafterEoW,out,2} - E_{VMSub,out,2}\frac{Q_{R,out,2}}{Q_{Sub,2}}\right) \\
&+ \left(M_{MR,out,3} - M_{MR,in,3}\right)\left(E_{MRafterEoW,out,3} - E_{VMSub,out,3}\frac{Q_{R,out,3}}{Q_{Sub,3}}\right) \\
&= (40-0)\left(0.001 - 0.005\frac{1}{1}\right) + (50-0)\left(0.001 - 0.2\frac{1}{1}\right) \\
&+ (2-3)\left(0.5 - 2\frac{1}{1}\right) = 40\cdot(-0.004) + 50\cdot(-0.199) - 1\cdot(-1.5) \\
&= -0.16 - 9.95 + 1.5 = -8.61\ kgCO_2e
\end{aligned} \tag{21}$$

2.4 Recommendations for the development of EPDs

The publication of Annex D of EN 15804 [17] according to the CEN mandate [23] to harmonize the calculation with PEF methodology [6] clarified the most important aspects of the declaration of loads and benefits of steel recycling and reuse. However, there is still some space for different interpretation of the standard rules. This may lead to different impacts of similar materials in different Environmental Product Declarations (EPDs). Our goal is to improve this situation and provide such recommendations that would harmonize the calculation methodology across the steel sector with respect to the existing practices in other materials.

- Module D is compulsory and shall be declared even if it is positive (creates loads). In the situations, when secondary materials are entering and/or exiting the system in different amounts, the value of module D will not be zero.

- The preferrable system for the LCA assessment shall be one service life of one product from the point when it is produced from primary or secondary materials, or reused until the point when it is disposed, sent for recycling, or reused again. For reusable product, this will lead to one EPD of new product and another EPD of reused product, both with possible alternative end-of-life scenarios.

- The scenarios outlined for the end-of-life phase (module C) have repercussions on the benefits and loads beyond the system boundary (module D). However, in Environmental Product Declarations (EPDs), these scenarios might not align with the specific construction projects under evaluation (e.g., buildings, constructions, civil engineering works), necessitating potential adaptations. In such instances, EPDs should offer diverse scenarios, enabling Life Cycle Assessment (LCA) practitioners to craft end-of-life scenarios modified to the unique focus of their assessments. For instance, when considering steel, EPDs should declare scenarios like 100% recycling, 100% reusing, or 100% landfilling. Similarly, for other materials such as wood, scenario options might encompass 100% incineration with energy recovery, 100% reuse, 100% recycling/downcycling, and 100% landfilling. This flexibility empowers practitioners to construct end-of-life scenarios that better correspond to the specific characteristics of the construction works they are analysing.

- Several modifications distinguish between EN 15804+A1 [24] and EN 15804+A2 [17], encompassing alterations in impact categories, including the introduction of new ones. Particularly, the Global Warming Potential (GWP) has undergone subdivision into three distinct impact categories: Climate Change Fossil, Climate Change Biogenic Removal and Emissions, and Climate Change Land Use and Land Use Change. The cumulative impact of these categories is represented by Climate Change Total. EPDs published before July 2022 in accordance with EN 15804+A1 remain valid for a duration of 5 years. Given the coexistence of EPDs following both amendments during this transitional period, where compatibility issues may arise in LCA assessments, new EPDs aligned with EN 15804+A2 should explicitly declare, in their annex, the environmental indicators in accordance with EN 15804+A1. This proactive step facilitates LCA practitioners in resolving compatibility challenges and ensures a smooth transition in the assessment of environmental impacts.

3. Alternative circularity assessment methods

3.1 LCA-based assessment

3.1.1 World Steel Association LCA methodology

The World Steel Association introduced the lifecycle inventory (LCI) model in 2011 [26] with a functional unit of 1 kg of steel product at the factory gate. Their method calculates the impacts from raw materials (cradle) to the gate of the steelworks with the benefits of end-of-life recycling. The calculation of the benefits or burdens generated from end-of-life recycling LCI_D is shown in Equation (6) where the lifecycle impacts of primary production and recycling are X_{pr} and X_{re} respectively, input flow is the amount of scrap in the steelmaking process S and output flow is the recovery rate RR of the scrap. The expression has the same form as Equation (12).

$$LCI_D = -M_{net} \cdot ScrapLCI \cdot Y = -(RR - S) \cdot \left(X_{pr} - X_{re}\right) \cdot Y \qquad (6)$$

where M_{net} is the net scrap flow $RR - S$ and $ScrapLCI$ is the lifecycle impact associated with 1 kg of scrap $X_{pr} - X_{re}$. These benefits or burdens are fully aggregated with the basic LCI results in a so-called 0-100 end-of-life approach. The efficiency Y of secondary electric arc furnace (EAF) production in World Steel Association's model is 1/1.092 [26].

3.1.2 PEF-CFF formula

The multi-criteria assessment methodology called Product Environmental Footprint (PEF) was developed by the European Commission's Joint Research Centre (JRC) [47]. It presents a general assessment of material and energy efficiency of materials that can be reused, recycled, disposed, or recovered as energy. The calculation of environmental impacts for different product categories under the so-called Product Environmental Footprint Category Rules (PEFCR) is described in the PEFCR guidance [6] as Circular Footprint Formula (CFF). One example of the PEFCR rules were developed by Eurometaux [27] for metal sheets. The formula, or its modular version (CFF-M), calculates the whole lifecycle impacts including the end-of-life recovery. The part related to the burdens and benefits beyond the system boundaries presented in Equation (7) has a form similar to the Equation (11). As it can be seen from the structure of Equation (7), different impacts can be considered in the production and recycling of materials used for the current product and in its end-of-life stage. Moreover, impacts of the substituted virgin material E_V can be further reduced by the ratio of secondary and primary material quality factors entering the system Q_{Sin}/Q_P and exiting the system Q_{Sout}/Q_P.

$$e = R_2 \left(E_{recEoL} - E_V^* \frac{Q_{Sout}}{Q_P}\right) - R_1 \left(E_{rec} - E_V \frac{Q_{Sin}}{Q_P}\right) \qquad (7)$$

where R_1 and R_2 are the amounts of the recovered material in the production inputs and the material that will be recovered. The specific emissions and consumed resources in Equation (7) are arising from the recovery of materials used in the manufacturing of the analysed product E_{rec} or from their recovery at the product's end of life E_{recEoL}. They are subtracted from the specific emissions and consumed resources arising from the acquisition and pre-processing of virgin material in today's production or at the product's end of life, E_V and E_V^* respectively.

The results can be aggregated with the rest of the calculated lifecycle impacts by the allocation factor A, which considers the difference between the supply and demand of secondary materials. In practice, the term $e(1-A)$ is added to the impacts calculated in the remaining product's lifecycle stages. For the recycling of metal sheets, it is recommended that $A = 0.2$, and therefore 80% of the impact e is added to the impacts calculated within the system boundaries. The formula can consider multiple recycling or reusing technologies if the flows and impacts are calculated according to Equation (7) from the flows and impacts of each individual (i-th) recovery process.

$$R = \sum R_i \quad \text{and} \quad E = \sum \frac{E_i R_i}{R_i} \tag{8}$$

3.1.3 Comparison of the existing LCA-based methods

Two of the existing methods, CEN/TC350 and PEF CFF-M, can calculate several simultaneous secondary material flows, and therefore may be considered for the assessment of the reuse and recycling of the constructional steelwork. Unfortunately, neither of them considers the efficiency of steel recycling in the format used by World Steel Association. The calculation of this effect is proposed by CEN/TC135 in prEN 17662 [29]. CEN/TC 350 method is simpler but cannot distinguish between different unit impacts at the beginning and end of the product's life. On the other hand, the PEF CFF-M formula requires complex calculations of total flows and average unit impacts. The comparison of variables used in all three methods is in Table 10.

Table 10 Comparison of the existing methods to calculate impact beyond the system boundaries

	World Steel Association	**PEF**	**CEN/TC 350**
Input flow of secondary material	S	R_1	$M_{MR,in}$
Output flow of secondary material	RR	R_2	$M_{MR,out}$
Unit impact of the recovery process (e.g. recycling or reuse)	X_{re}	E_{rec} E_{recEoL}	$E_{MRafterEoW,out}$
Unit impact of the substituted primary production	X_{pr}	E_V E_V^*	$E_{VMSub,out}$
Efficiency of the recovery process	Y	-	-
Quality of the secondary material	-	Q_{Sin} Q_{Sout}	$Q_{R,out}$
Quality of the primary material	-	Q_P	Q_{Sub}
Allocation of impacts between supplier and user	100%	$1-A$	-

3.2 Circularity in construction indicators

3.2.1 Background

The European Commission has communicated to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions the importance to adopt the circular economy.

“The transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized, is an essential contribution to the EU’s efforts to develop a sustainable, low carbon, resource efficient and competitive economy. Such transition is the opportunity to transform our economy and generate new and sustainable competitive advantages for Europe.

The circular economy will boost Europe’s resource productivity, achieve sustainable management and efficient use of natural resources, reduce dependence on nonrenewable resources and critical raw materials, generate co-benefits and cost savings, and create jobs. Construction has been identified as a priority sector for the implementation of the circular economy [30]”

The Transition to a Circular Economy framework is provided in the “Circular Economy Action Plan” [30](March 2020). Construction Industry is identified as key value chain within the Transition to a Circular Economy. This document also identifies the lack of sustainability and circularity assessment tools while identifies some specific tools:

“EU initiatives and legislation already address to a certain extent sustainability aspects of products, either on a mandatory or voluntary basis. Notably, the Ecodesign Directive, successfully regulates energy efficiency and some circularity features of energy-related products.

At the same time, instruments such as the EU Ecolabel or the EU green public procurement (GPP) criteria are broader in scope but have reduced impact due to the limitations of voluntary approaches. In fact, there is no comprehensive set of requirements to ensure that all products placed on the EU market become increasingly sustainable and stand the test of circularity”.

At EU level there is a general agreement on Construction Circularity objectives as reflected in:“Circular Economy - Principles for Building Design” [31]:

The document that supports Level(S) Macro-objective 2: “Resource efficient and circular material life cycles” introduces the following objectives for the circular economy in construction:

- **Durability:** building and elemental service life planning, encouraging a medium to long term focus on the design life of major building elements, as well as their associated maintenance and replacement cycles;
- **Adaptability:** to extend the service life of the building as a whole, either by facilitating the continuation of the intended use or through possible future changes in use – with a focus on replacement and refurbishment;
- **Reduce waste and facilitate high-quality waste management:** facilitate the future circular use of building elements, components and parts, with a focus on producing less waste and on the potential for the reuse, or high-quality recycling of major building elements following deconstruction. This includes efforts along the value chain to promote: the reuse or recycling of resources, (i.e. materials) in a way that most of the material’s value is retained and

recovered at the end of a building's life span and the component design and the use of different construction methods to influence the recovery for reuse or recycling to avoid down-cycling.

Level(s) Macro-Objective 2: Resource efficient and circular material life cycles provide a set of indicators to evaluate the alignment of buildings to the three circular economy objectives.

In addition, The Council of the European Union in "Circular Economy in the Construction Sector - Council Conclusions (adopted 28 November 2019)" [32]:

"STRESSES the importance of the integration of circularity principles, life cycle thinking and modular design into construction by further elaborating and promoting the use by the Member States of tools, such as Level(s), Green Public Procurement criteria for construction works, and the EU Construction and Demolition Waste Management Protocol where feasible, and providing guidelines for waste audits before demolition and renovation works of buildings;"

In the next section, an overview of the available circularity indicators implemented at the UE level is provided, including critical review of the available tool including gaps, shortcomings, and recommendations.

3.2.2 CEN TC 350 Indicators

CEN TC 350 "Sustainability of Construction Works" has recently started to work in Circular Economy. To do so, the CEN TC 350/SC1 "CIRCULAR ECONOMY IN THE CONSTRUCTION SECTOR" has been recently created. The purpose of this subcommittee is to develop deliverables enabling the transition from a linear to a circular economy of the construction sector to support a climate neutral and resource efficient sector. Currently 5 Task Groups are working in the 5 Work Instruction to develop a set of standards including circularity assessment or design for circularity among others.

Nowadays a set of Circularity Indicators can be found in the CEN TC 350 standards. Most these indicators can be found in the EN 15804 and EN 15978

3.2.2.1 EN 15804 Indicators:

- EN 15804:2012+A2:2019 provides a set of indicators in section "7.2 Declaration of environmental indicators derived from LCA". Under "7.2.3 Indicators describing environmental impacts based on Life Cycle Impact Assessment (LCIA)" table 3. The following three core indicators can be considered related to Circular Economy.

Table 11. Core Indicators related to circularity from EN 15804 Table 3.

Impact category	Indicator	Unit (expressed per functional unit or per declared unit)
Depletion of abiotic resources - minerals and metals [c d]	Abiotic depletion potential for non-fossil resources (ADP-minerals&metals)	kg Sb eq.
Depletion of abiotic resources - fossil fuels [c]	Abiotic depletion for fossil resources potential (ADP-fossil)	MJ, net calorific value
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived

However, these indicators are linked to disclaimer 2 in Table 5 — Classification of disclaimers to the declaration of core and additional environmental impact indicators; *"the results of this environmental impact indicator shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator".*

If material flows are meant to be central to the Transition to a Circular Economy assessment, then, the corresponding LCI are to be evaluated. As example the Module A1 to A3 and D values for the above-mentioned indicators are provided below:

Table 12.Circularity core indicators values from existing EPD´s.

Indicator	Primary Steel [33]		Secondary Steel [34]		Re-used Steel [35]	
	A1-A3	D	A1-A3	D	A1-A3	D
Depletion of abiotic resources-minerals and metals (kgSb-Eq.)	$8.08\ 10^{-5}$	$4.27\ 10^{-5}$	$4.86\ 10^{-4}$	$8.05\ 10^{-4}$	$4.75\ 10^{-5}$	0
Abiotic depletion potential for fossil resources (MJ)	$2.35\ 10^{4}$	$-1.43\ 10^{4}$	$4.25\ 10^{3}$	$2.86\ 10^{3}$	818	0
Water Deprivation potential (m^3 world eq. deprived)	N/A	N/A	N/A	N/A	6.33	0
GWP ($kgCO_2e$)	2600	-1800	370	324	46.6	0

Only one the EPD provides the Water Deprivation Potential, while the three of them provide values for the net use of fresh water (see Table 14). In general, resource efficiency related core indicators are not easy to interpret and involve the use of non-robust processes.

"7.2.4 Indicators describing resource use and environmental information based on Life Cycle Inventory (LCI)" provides a set of indicators related to resource use. Under section 7.2.4.2 "Indicators describing resource use" Table 6 presents indicators describing resource use which shall be included in each module declared in the EPD.

Table 13 EN 15804 Table 6 ""Indicators describing resource use".

Parameter	**Unit(expressed per functional unit or per declared unit)**
Use of renewable primary energy excluding renewable primary energy resources used as raw materials	MJ, net calorific value
Use of renewable primary energy resources used as raw materials	MJ, net calorific value
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value
Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	MJ, net calorific value
Use of non-renewable primary energy resources used as raw materials	MJ, net calorific value
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ, net calorific value
Use of non-renewable secondary fuels	MJ, net calorific value
Net use of fresh water	m^3

This set of indicators have been identified by TC 350 SC1 TG5 "Design for Circularity" as potential Circularity Indicator. As example the Module A1 to A3 and D values for the above-mentioned indicators are provided in Table 14.

Table 14 Indicators describing resource use from existing EPD´s.

Indicator	Primary Steel [33]		Secondary Steel [34]		Re-used Steel [35]	
	A1-A3	D	A1-A3	D	A1-A3	D
Total use of renewable primary energy resources (MJ)	7.87 10^2	-1.48 10^2	7.53 10^3	-1.04 10^3	77.2	0
Total use of non-renewable primary energy resources (MJ)	1.15 10^4	-3.76 10^3	0	0	818	0
Use of renewable secondary fuels (MJ)	0	0	0	0	0	0
Use of non-renewable secondary fuels (MJ)	0	0	0	0	0	0
Use of secondary material (kg)	42	0	1.16 10^3	0	1000	0
Use of net fresh water (m^3)	5.23	-1.41	0.61	1.09	0.17	0

The set of indicators in Table 13 from existing EPD´s are provided in Table 14. Here we find a clear methodological shortcoming. When use of secondary materials is considered, due to the lower efficiency of recycling processes, in which more than 1000 kg of scrap are needed to produce 1000 kg of steel, then the use of secondary materials in recycling is higher than in re-use, where 1000 kg result into 1000 kg of steel. This shortcoming should be overcome by adding a quality recycling factor as in Level(S) 2.4. In addition, the direct use of this indicators favours low efficiency recycling processes.

Use of net fresh water also shows the advantage of re-use when compared to recycling or primary materials.

Under section 7.2.4.3 “Environmental information describing waste categories” Table 15 presents indicators describing waste categories derived from LCI. They shall be included in each module declared in the EPD.

Table 15. EN 15804 “Environmental information describing waste categories” Table 7

Parameter	Unit(expressed per functional unit or per declared unit)
Hazardous waste disposed	kg
Non-hazardous waste disposed	kg
Radioactive waste disposed	kg

Table 16. Environmental information describing waste categories from existing EPD´s

Indicator	Primary Steel [33]		Secondary Steel [34]		Re-used Steel [35]	
	A1-A3	D	A1-A3	D	A1-A3	D
Hazardous waste disposed (kg)	$1.01\ 10^{-5}$	$-8.98\ 10^{-6}$	$1.52\ 10^{-6}$	$-8.06\ 10^{-7}$	30	0
Non-hazardous waste disposed (kg)	-27.58	-28.2	3.02	-27.8	10	0
Radioactive waste disposed (kg)	0.1	0.289	$5.46\ 10^{-2}$	$-6.09\ 10^{-3}$	0	0

Under section “7.2.4.4 Environmental information describing output flows”, Table 17 presents indicators describing output flows derived from LCI. They shall be included in each module declared in the EPD. These indicators are also part of the additional information for scenarios at end-of-life in section 7.3.4, Table 15 of EN 15804, where the information is extended including the resulted separated and mixed streams.

Table 17. EN 15804 Table 15, End of Life.

Table [A2] 8 [A2] — [A2] *deleted text* [A2] Environmental information describing output flows

[A2] Indicator [A2]	Unit (expressed per functional unit or per declared unit)
Components for re-use	kg
Materials for recycling	kg
Materials for energy recovery	kg
Exported energy	MJ per energy carrier

Table 18. Environmental information describing output flows from Existing EPD´s.

Indicator	Primary Steel [33]		Secondary Steel [34]		Re-used Steel [35]	
	A1-A3	D	A1-A3	D	A1-A3	D
Components for re-use (kg)	0	0	110	0	0	0
Materials for recycling (kg)	980	0	880	0	0	0

Table 17 parameters are the values used to model the E.o.L life scenarios (Module D) and should be considered as the defaults values unless other specific scenario is to be considered, for example as the results of the implementation of designed for re-use construction techniques.

Additionally, under section “7.3 Scenarios and additional technical information” a set of indicators may be included in the EPD´s corresponding to the following Life Cycle Stages:

In 7.3.2.2 A5, Installation in the building indicators are provided in table 11 of EN 15804 (Table 19).

Table 19. EN 15804 Table 11 Additional Technical information: Installation of the product in the building indicators

A2 Scenario information A2	Unit (expressed per functional unit or per declared unit)
Ancillary materials for installation (specified by material);	kg or other units as appropriate
Water use	m^3
Other resource use	kg
Quantitative description of energy type (regional mix) and consumption during the installation process	kWh or MJ

A2 Scenario information A2	Unit (expressed per functional unit or per declared unit)
Waste materials on the building site before waste processing, generated by the product's installation (specified by type)	kg
Output materials (specified by type) as result of waste processing at the building site e.g. of collection for recycling, for energy recovery, disposal (specified by route)	kg
Direct emissions to ambient air, soil and water	kg

In Section "7.3.3 B1-B7 use stage" two tables with addition indicators are provided.

In 7.3.3.1 B1-B5 use stage indicators related to the building fabric for products requiring maintenance, repair, replacement, refurbishment: Table 12 of EN 15804 (Table 20).

Table 20. Table 12 of EN 15804: B1-B5 use stage indicators

A2 Scenario information A2	Unit (expressed per functional unit or per declared unit)
B2 Maintenance	
Ancillary materials for maintenance, e.g. cleaning agent, specify materials	kg / cycle,
Waste material resulting from maintenance (specify materials)	kg
Net fresh water consumption during maintenance	m^3
Energy input during maintenance, e.g. vacuum cleaning, energy carrier type, e.g. electricity, and amount, if applicable and relevant	kWh
B3 Repair	
Waste material resulting from repair, (specify materials)	kg
Net fresh water consumption during repair	m^3
Energy input during repair, e.g. crane activity, energy carrier type, e.g. electricity, and amount	kWh / RSL, kWh / cycle
B4 Replacement	
Energy input during replacement e.g. crane activity, energy carrier type, e.g. electricity and amount if applicable and relevant	kWh
Exchange of worn parts during the product's life cycle, e.g. zinc galvanised steel sheet, specify materials	kg
B5 Refurbishment	
Energy input during refurbishment e.g. crane activity, energy carrier type, e.g. electricity, and amount if applicable and relevant	kWh
Material input for refurbishment, e.g. bricks, including ancillary materials for the refurbishment process e.g. lubricant, (specify materials)	kg or kg / cycle
Waste material resulting from refurbishment (specify materials)	kg

In 7.3.3.3 B6, use of energy and B7, use of water B1-B5 use stage indicators related to the building fabric for products requiring maintenance, repair, replacement, refurbishment: Table 14 of EN 15804 (Table 21).

Table 21. EN 15804 Table 14: B6, use of energy and B7, use of water

A2 Scenario information A2	Unit (expressed per functional unit or per declared unit)
Ancillary materials specified by material	kg or units as appropriate
Net fresh water consumption	m^3
Type of energy carrier, e.g. electricity, natural gas, district heating	kWh
Power output of equipment	kW
Characteristic performance, e.g. energy efficiency, emissions, variation of performance with capacity utilisation etc.	units as appropriate
Further assumptions for scenario development, e.g. frequency and period of use, number of occupants	units as appropriate

Additional Technical Information is not currently being provided in EPD´s for structural products.

Under section "7.3.4 End-of-life additional technical information is provided in the EPD about end-of-life processes, for all construction products to specify the end-of-life scenarios used or to support development of the end-of-life scenarios at the building level. Scenarios shall only model processes e.g. recycling systems that have been proven to be economically and technically viable.

Table 22 End-of-life additional technical; Table 15 in EN 15804

Processes	Unit (expressed per functional unit or per declared unit of components products or materials and by type of material)
Collection process specified by type	kg collected separately
	kg collected with mixed construction waste
Recovery system specified by type	kg for re-use
	kg for recycling
	kg for energy recovery
Disposal specified by type	kg product or material for final deposition
Assumptions for scenario development, e.g. transportation	units as appropriate

Table 15 of EN 15804 (Table 22) provides the necessary information to conduct EN 15978 Annex Ca and Level(s) 2.4 Assessment.

EN 15804 also includes a set of indicators to evaluate product lifespan and durability. The set of indicators is provided under section "7.3.3.2 Reference service life".

Table 23. EN 15804 Table13 Reference Service Life.

A2 RSL information A2	Unit (expressed per functional unit or per declared unit)
Reference Service Life	Years
Declared product properties (at the gate) and finishes, etc.	Units as appropriate
Design application parameters (if instructed by the manufacturer), including the references to the appropriate practices and application codes	Units as appropriate
An assumed quality of work, when installed in accordance with the manufacturer's instructions	Units as appropriate
Outdoor environment, (for outdoor applications), e.g. weathering, pollutants, UV and wind exposure, building orientation, shading, temperature	Units as appropriate
Indoor environment (for indoor applications), e.g. temperature, moisture, chemical exposure	Units as appropriate
Usage conditions, e.g. frequency of use, mechanical exposure	Units as appropriate
Maintenance e.g. required frequency, type and quality and replacement of components	Units as appropriate

The description of the RSL may be based on data collected as average data or at the beginning or end of the service life. The reference in-use conditions for achieving the declared technical and functional performance and the declared RSL shall include the RSL data as described in Table 13 of EN 15804 (Table 23). This information should be used to elaborate the Level(s) 2.1 Indicator.

3.2.2.2 EN 15978 Circularity Indicators:

Module D

EN 15978, currently a draft to be sent to vote relies in EN 15804. EN 15978 implements EN 15804 at building level. Some important differences are found.

prEN 15978 has been aligned with EN 15643 regarding modules A0, B8 and D1 and D2. Therefore, Module D1. As a consequence, in section 7.4 System boundary, Module is divided in Module D1 and Module D2.

“Module D shall be included in the assessment to provide supplementary information on the benefits and loads beyond the system boundary relating to the recovery and repurposing of resources that exit the system boundary. This includes secondary materials, products (module D1) or fuels being reused, recycled, or used for energy recovery and/or other recovery as well as exported energy and other utilities (module D2).”

In addition Section “7.4.7 Boundary for the benefits and loads beyond the system boundary (Module D)” of EN 15978, module D1 is divided in three sub-modules:

- Reuse, (sub-module D1.1),
- Recycling, (sub-module D1.2),
- Energy recovery (sub-module D1.3)

Module D is considered in EN 15978 as “design for deconstruction and circularity” indicator. From NOTE 1*:*

“Module D acknowledges the concept of “design for deconstruction and circularity” to promote reuse and recycling, see Annex C. Module D provides information to help with transparency on the benefits and loads of processes beyond the system boundary of the object of assessment”.

Module D (According to sub-clause 6.4.3.3 in EN 15804+A2) applies when material flow exits the system boundary and has an economic value, has reached the end-of-waste stage, and substitutes another product, then the impacts shall be calculated and based on:

- Representative current practice based on existing technology as a default scenario;
- Additional scenarios for likely future practices may be developed. These shall be based on robust forecasts/future pathways for energy & fuel types, processing and/or manufacturing technologies, upcoming products, etc., and reported separately.

In Note “ is stated that re-use and recycling must be considered as separate scenarios resulting in different benefits and loads.

“NOTE 2: Reuse and recycling result to different benefits and loads and therefore should be treated as different scenarios.”

Net flows are used to for Module D1. Net flows shall be calculated per secondary material type and shall result from the difference between the quantity of the secondary i.e., previously used material exiting the system minus the quantity of the secondary material entering the system.

While net flows are necessary for Life Cycle Assessment, where module D would lead to negative carbon footprint values for secondary materials, what is not desirable nor realistic, when assessing material flows, Module D fails to reflect multicycle materials benefits.

However, the EN 15978 is open to *“Additional scenarios considering the total material flows exiting the system, rather than the net flows i.e. virgin only, may be developed. These need to be clearly indicated and reported separately as additional information”.*

Associated net impacts and consider the substitution of secondary materials, items and fuels.

“Net impacts refer to deducting any loads occurring from the processing of the reused/recycled secondary item(s), materials or fuels, to make them usable in the new system, from the benefit (avoided impacts) occurring from the substitution of an equivalent average product.”

The information in Module D shall contain the predetermined indicators as listed in Clause 10 and may include as well optional technical information.

Clause 10 of EN 15978 includes the above mentioned list of indicators in Table 11, Table 13, Table 15 and Table 17 are also part EN 15708, however the specific indicators for each stage are not included.

Instead of the additional technical information, “Annex C (Normative) Synergies between circularity and the environmental performance of buildings”, former Annex F “Design for Circularity (Informative)” is included.

ANNEX C: “Annex C (Normative): Synergies between circularity and the environmental performance of buildings”

Annex C covers the objective of design for circularity is to design buildings in a way that they leave behind as many reusable and recyclable building components and materials as possible and as little unusable waste as possible at the end of their life cycle.

Annex C covers:

- Selective demolition of buildings
- Resource mapping of buildings
- Classification of the reuse and recycling potential of the building components.

And excludes:

- Reducing the quantity of material use or increasing the recycled content of materials used in a building,
- Construction site waste management and logistics
- Potential to reutilise parts of the building as a new building (in-situ or ex-situ)
- Management support for design for disassembly
- Health effects due to emissions during demolition (e.g., dust, noise)
- Resource use and impacts measured by LCA related indicators for module C and D.

Trade-offs between improved ease of recovery and environmental performance can be quantified making a life cycle assessment for the building.

The scenarios described in 8.9 of the EN 15978 apply accordingly to assessment of design for circularity and assumes full removal of the building (by demolition /deconstruction /disassembly), and the final waste treatment (landfilling or waste incineration), recycling or reuse or energy recovery of products and materials according to the current end of life management practices in the building’s country. Baseline scenarios shall model processes that are available and have been proven to be economically and technically viable. Services not available in the region must be clearly marked as “future prospects”.

Annex C indicators apply for the undesirable case of demolishing a building and renovation, refurbishment, repair and repurpose are discarded.

For the implementation of the Annex C Indicators, it is recommended to use the same level of detail for the building constituency as for the life cycle assessment. The indicators are based on the bill of materials of the building, usually derived from the LCA tool, which serves as the starting point for the building material passport. It must include at least the description of each building component, the element to which it belongs and the amount of the building component in this element. The amount shall be measured in mass (kg) or volume (m3) or in both.

Scoring figures according to Level(s) indicator 2.4 “design for deconstruction” are compatible with this standard and shall be used to compare buildings at any stage, based on the stages of the waste framework directive in L.2.2 Step 5.

Two indicators are included in Annex C: “Easy of Disassembly” and “C.9 Reuse and recycling potential of dismantled building products and components”

Ease of disassembly

Easy of disassembly aims to quantify the building components according to their disassembly potential at the building site analysing each building component according to the end of life (as in 8.9). In addition, the building components may be assessed using a “future prospects” scenario. The disassembly potential(s) shall be inserted in the building material passport containing at minimum the following assignments of disassembly potentials as specified in Table C.1 using standardized system.

Table 24. EN 15978 Annex C Table C.1.

Table C.1 Assignment of disassembly potential to component layers

Description of disassembly	amount (kg)	disassembly potential (baseline scenario as in 8.9)	disassembly potential (future prospects as in 8.9)
Building component can be disassembled without damaging the shape and material structure	X	A++ (classification chosen)	A+++
Building component can be disassembled with minor damage to the shape and material structure	X	A+	A++
Building component / material can be disassembled clean (without impurities from adjacent layers), but the shape and material structure are damaged or destroyed	X	A	A+
Building component / material cannot be separated clean (without impurities from adjacent layers)	X	B	A

Additionally, aggregated list of specific components/materials with the same disassembly potential (on functional or building level) and respective share of building components or materials classified as A++, A+ or A may be calculated.

The result shall be a bill of materials and components enhanced by the disassembly potential of each material/component.

- Share of building components / materials classified as A++;
- Share of building components / materials classified as A+;
- Share of building components / materials classified as A;
- Share of building components / materials classified in other classes.

C.9 Reuse and recycling potential of dismantled building products and components

The indicator aims to classify the building components according to their potential for reuse, recycling or recovery according to the end of life (EoL) scenario represented by the baseline scenario as in 8.9; The following E.o.L scenarioas are considered and described.

- Reuse.
- Recycling.
- Other material recovery.
- Energy recovery.
- Incineration without energy recovery.
- Landfill.

The allocation of the building components to the fitting end of life scenarios depends on the disassembly potential (C.8) and of the associated impurities (Materials, usually originating from adjacent layers that can prevent or impede the intended waste treatment or preparation for reuse, recycling or energy recovery).

The result shall be a bill of materials and components differentiated by each material/component and their end-of-life scenario or an aggregated list of specific components/materials with the same end of life potential:

- Share of building components / materials classified as A++;
- Share of building components / materials classified as A+;
- Share of building components / materials classified as A;
- Share of building components / materials classified in other classes.

For values aggregation, 2.4 Level(s) indicator 2.4 “design for deconstruction” shall be used to compare buildings at any stage, based on the stages of the waste framework directive in L.2.2 Step 5.

3.2.2.3 EN 17680 Sustainability of construction works — Evaluation of the potential for sustainable refurbishment of buildings:

EN 17680 aims to support the strategic decision process on how to refurbish existing building(s) in a sustainable way, taking into consideration that not all buildings should be refurbished if the existing conditions of a building do not permit. A starting point for decisions on (further) handling of existing buildings is a comprehensive analysis.

“Annex A (informative) Example of classification of indicators in performance and performance classes, from 0 – 3”. Provides indicators for evaluation on the potential including criteria for adaptability in table A3 (Table 25). The table provides 13 different indicators and 4 classes depending on the level of compliance with set indicators. The standard also provides a reference value for the overall adaptability assessment; Class 0, Class 1, Class 2 and Class 3.

Table 25. Informative Adaptability Criteria in EN 17680

Table A.3 Example of criteria for adaptability performance and performance classes

Indicator	Class 0	Class 1	Class 2	Class 3
Net floor to ceiling height (Indicator 1)	x > 4,0 m. (or that the over or underlying floor is a technical mezzanine)	3,5 m < x ≤ 4,0 m	3,0 m < x ≤3,5 m	x ≤ 3 m
Load bearing capacity floors (Indicator 2)	x >5 kN/m^2	4 kN/m^2 - 5 kN/m^2	3 kN/m^2 - 3,9 kN/m^2	< 3 kN/m^2
Vertical space for installations (Indicator 3)	Large and/or several shafts providing large space for expansion and/or new vertical transmissions (alternatively technical towers	Shafts size and/or several shafts providing possibility for expansion and /or vertical shafts	Shafts size and/or several shafts providing a limited / remote for expansion and /or vertical shafts	Small shafts and / or number of shafts providing a very little space for expansion and /or new vertical shafts. No residual capacity
Create openings in structural element. (Indicator 4)	Well adapted for creating new openings (eg. in situ slabs)	Adapted for creating new openings in some areas (eg. prestressed concrete elements)	Restricted opportunity for creating new openings in some areas (eg. prestressed concrete elements)	Not / very restricted opportunity for creating new openings (eg. prestressed concrete elements)
Amount of space on each floor (Indicator 5)	x > xx m^2	xx m^2 < x ≤ yy m^2	yy m^2 < x ≤ zz^2 m^2	x≤ zz m^2
Possibility to open space (not communication routes).[a] (Indicator 6)	x > xx m^2	xx m^2 < x ≤ yy m^2	yy m^2 < x ≤ zz m^2	x ≤ zz m^2
With of communication routes (corridors within the functional range) (Indicator 7)	x > xx m	xx m < x ≤ yy m	yy m < x ≤ zz m	x ≤ zz m
Interior walls (Indicator 8)	No load bearing interior walls, light system walls without bindings to technical installations.	Limited extent of load bearing internal walls in one direction	Heavy inner walls with partial load bearing	Heavy and load bearing inner walls in both directions
Building width (Indicator 9)	x ≤ xx m	xx m < x ≤ yy m	yy m < x ≤ zz m	x ≤ zz m

Elevators (Indicator 10)	Elevators of good size that are wheelchair accessible, take beds, equipment, and personnel. Separation of patients and goods. Number of lifts is sufficient.	Elevators with acceptable size, wheelchair accessible, space for necessary equipment. To a degree separation of people and goods. Acceptable capacity / number of lifts	Small / narrow that do meet the needs of necessary equipment. Under capacity / few lifts	No elevators
Elasticity (Indicator 11)	The building's location on the site and the site's size makes excellent opportunities for horizontal extension (additions).	The building's location on the site and the site's size suggests some possibilities for horizontal extension (additions).	The building's location on the site and the site's size implies few opportunities for horizontal extension (additions).	The building's location on the site and the site's size makes no possibilities for horizontal expansion (additions).
Site (Indicator 12)	No limitations in regulations or ground conditions	Limitation in height of buildings. No limitations in ground conditions,	Consideration zone due to heritage neighborhood and/or with limitations in ground conditions	Heritage Listing with strong restrictions and/or limitations in ground conditions
Vertical and foundations load bearing capacity (Indicator 13)	Remaining load bearing capacity. Most likely possibilities for the equipment of two or more floors.	Most likely some residual load bearing capacity with the possibility of extension of one floor.	Difficult to assess the remaining load bearing capacity, but probably limited possibilities for increased load or equipment.	Impossible to increase the application of loads associated with equipment.

The EN 17680 includes an overall assessment of adaptability, that can be considered a reference for the definition of adaptability targets for example in the Taxonomy.

Table 26: Overall Adaptability Assessment Criteria.

Group of indicators	Class 0	Class 1	Class 2	Class 3
Adaptability	Fulfilling class 0 for all adaptability indicators	Fulfilling 7-8 of class 0 of all adaptability indicators	Fulfilling 4-6 of class 0 of all adaptability indicators	No flexibility, generality or elasticity

3.2.3 Level(s):

The Macro-objective 2: “Resource efficient and circular material life cycles” includes a set of indicators to assess the circularity of buildings[1]. The set of indicators can be applied a three different levels; “Conceptual Design”, “Detailed Design and Construction” and “As-built and in-use”.

[1] https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/412/documents visited 02-24

Level	Activities related to the use of indicator 2.2
1. Conceptual design (choice of construction/demoliton methods and waste management planning)	✓ In the conceptual design, information is provided to prompt discussion and decision making for the project about aspects that will directly or indirectly shape the outline Waste Management Plan (WMP) and thus the quantities of CDW generated and their possible reuse, recycling and recovery.
2. Detailed design and construction (based on pre-demolition audit and/or draft Bill of Quantities)	✓ During the detailed design and prior to construction/demolition activity, estimates of CDW can be compiled in an inventory following the Level(s) excel template, which in turn will inform a more detailed WMP for the project.
3. As-built and in-use (based on invoices, delivery notes and site records)	✓ During and after the construction/demolition activity, actual data can validate performance when compared to estimates and project targets, both for quantities and outcomes for different types of CDW.

Level(s) Macro-objective 2 Indicators have been developed to quantify the Circular Economy Objectives defined in Circular Economy - Principles for Building Design.

3.2.3.1 Level(s) 2.1 Bill of Quantities, materials and lifespans.

Levels 2 and 3 of this indicator estimate and measure the mass of construction products and materials necessary to complete defined parts of the building (all of which are grouped under shell, core or external aspects of the building). For each entry, the mass is disaggregated into different material fractions (concrete/brick/tile, wood, glass, plastic, bituminous mixtures, metals, insulation materials, gypsum, mixed and EEE). If optional cost data is entered, the costs of each entry will be measured. If optional lifespans are entered for each entry, the masses and costs of materials over the building lifetime can be measured, assuming a like-for-like replacement.

Data is reported in tonnes and % of total mass, with further splits by: material type (i.e. concrete, wood, metals etc.), and building aspect (i.e. shell, core or external).

Where optional cost data is entered, this is reported in units of thousand Euros (‘000 €) and is broadly split into shell, core and external aspects of the building. To allow for better comparability, the cost data are also normalised to €/t and €/m2.

The same units apply whether the BoQ is for construction only or for the duration of the projected building lifetime (i.e. including scheduled repair and replacement).

The indicator is generally focused on the A5 stage (construction & installation) of the building life cycle. If lifespans for different building elements and materials are factored into a “lifetime BoQ”, module B (use stage) impacts also become relevant for any replacement materials bought in and module C (end-of-life) impacts for the materials that are disposed of.

The scope includes data for all construction products and materials that are purchased to construct or renovate the building. The relationship between the inputs to indicator 2.1 and other indicators is illustrated below.

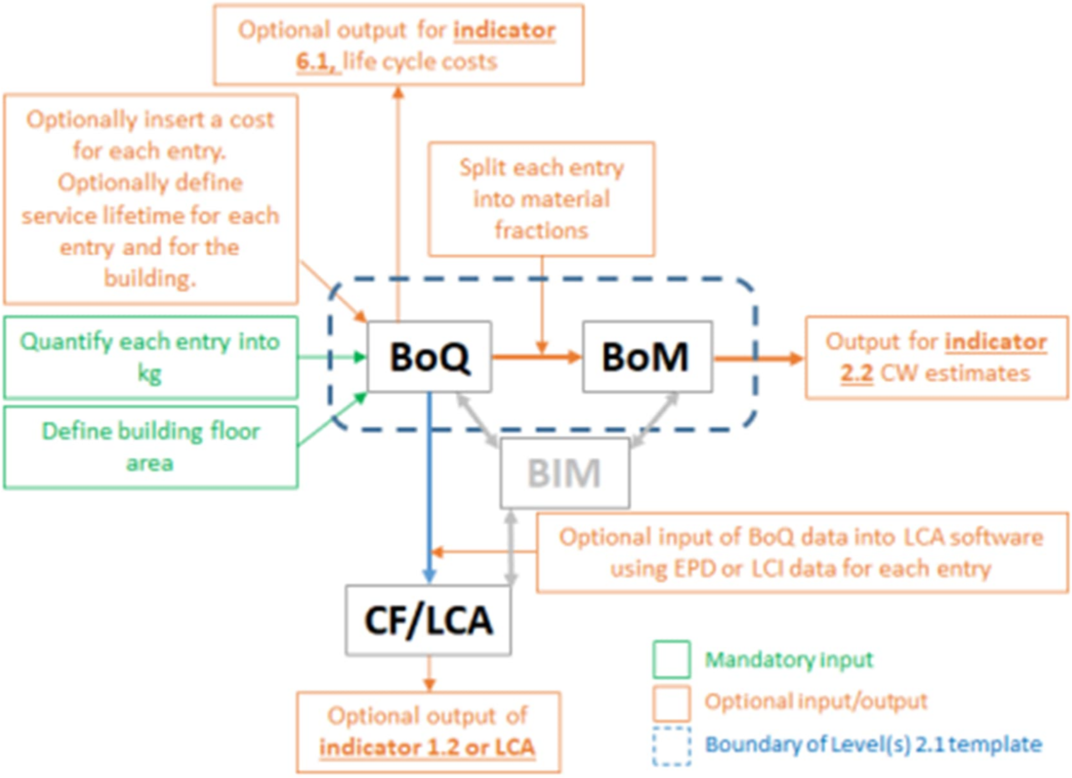

Figure 6. Illustration of inputs and outputs of indicator 2.1 and potential relationship with BIM

When correctly filled out, the data from indicator 2.1 will be suitable to use as a basis for making estimates of construction waste (CW) from the building project (relevant to indicator 2.2), provide material costs for indicator 6.1 (life cycle costs) and provide a basis for conducting a life cycle assessment (LCA) or carbon footprint (CF) in line with indicator 1.2.

In cases where users are already using BIM, it may be more appropriate for them to continue using BIM software for data compilation and manipulation regarding the BoQ, BoM and associated costs and service life estimates.

The calculation used for Levels 2 and 3 is based on the excel-based Level(s) reporting template for BoQ [36]. Data in green cells must be entered and data in yellow cells is optional. In cases where the user intends to estimate CW, the user must define the split by % mass into one of 10 material fractions that are compatible with indicator 2.2. (Construction and Demolition Waste, CDW). When considering the optional service life data for each entry in the BoQ, the user is recommended to follow the rules in section 9.3.3 of EN 15978, ISO 15686-8, tools such as BCIS, DGNB or ETool, specific standards for specific elements (e.g. EN 15459 for heating systems) know-how gained from experience with such elements in similar buildings and circumstances. EN 15804 also includes a set of indicators to evaluate product lifespan and durability. The set of indicators is provided under subclause “7.3.3.2 Reference service life” in Table 13 of EN 15804 (Table 23). In addition, some references are provided in Table 3 for different construction products.

3.2.3.2 Level(s) 2.2 Construction and Demolition Waste (CDW) and materials.

Levels 2 and 3 of this indicator estimate and measure the overall quantity of waste generated by construction, renovation and demolition activities (in kg). This quantity is disaggregated into the main types of CDW as per the European List of Waste entries. Final outcomes for each waste type (e.g., recycling, landfill etc.) are also recommended (Level 2) and later recorded during the project (Level 3). Data is reported in kg and shall later be normalised to the useful internal floor area of the building in question (kg/m2)

The indicator is generally focussed on the A5 stage (construction process) of the building life cycle for new construction projects and on stages B4 and B5 for renovation projects.

This indicator is directly related with EN 15804 sub-clause "7.3 Scenarios and additional technical information" particularly in:

- "7.3.2.2 A5, Installation in the building" indicators are provided in table 11 of EN 15804.
- "7.3.3 B1-B7 use stage" indicator tables 12 and 14 of EN 15804.

The scope includes data for all building elements, materials and wastes generated by construction, renovation and/or demolition activities. Data may include Waste Electronic and Electrical Equipment (WEEE)1 and excavation waste (EW), although these are reported separately from CDW. Indicator 2.2 reports on all final outcomes for CDW.

The calculation used for Levels 2 and 3 is based on the European list of waste codes and consists of either an estimation (Level 2) or the recording (Level 3) of the different flows of waste by category and their ultimate destination. The Level(s) excel reporting templates for CDW generally follow the EU CDW management guidelines for waste audits, published in 2018 in 15 EU languages [37].

3.2.3.3 Level(s) 2.3 Design for adaptability and renovation

The indicator [36] provides a semi-quantitative assessment of the extent to which the design of a building could facilitate future adaptation to changing occupier needs and market conditions. It therefore provides a proxy for the capacity of a building to continue fulfilling its function and to extend the useful service life into the future.

The indicator measures the design and servicing aspects of particular relevance, identified based on market research and experience. The aspects assessed differ depending on whether it is an office or residential building. For offices, the design and servicing aspects focus on flexibility within the office market, as well as flexibility to change use within the property market. For residential properties, the checklist focuses on the potential to adapt to changing family and personal circumstances over time, as well as the flexibility to support a change of use within the property market.

The common unit of measurement is a dimensionless scoring of the adaptability of a building. The score represents the sum of the weighted scores for each of the adaptability aspects that have been incorporated into the building design. The assessment boundary is the building and the relevant spatial and structural design features that it incorporates.

The aspects that may contribute to the design for adaptability score mainly comprise a building's structural engineering, internal layouts and technical services.

The calculation method is provided as a bespoke part of Level(s). A transitional calculation method is provided for use, which is partly based on the building flexibility calculator provided by BREEAM Netherlands and the Dutch Real Estate Norm (REN). The German Green Building Council's (DGNB) flexibility and adaptability criterion ECO2.1 may also be used to allocate a score. The method additionally makes reference to the principles and design aspects that are included in EN 15643-3, EN 16309 and ISO 20887.

A detailed description of the weighed scores is provided in “Table 7. Office building scoring and weighting system for adaptability design aspects. However, there is no reference scoring for residential buildings. Instead, DGNB and The Lifetime Homes criteria scores are referred as a reference.

No target scores are provided, although references maybe found in the DGNB scoring system for example or EN 17860.

3.2.3.4 Level(s) 2.4 Design for deconstruction:

The indicator provides a quantitative assessment of the extent to which the design of a building could facilitate the future reuse, recycling or recovery of building elements, components and constituent parts and materials. It therefore provides a proxy for:

- The contribution of the building to the circular economy, and
- The practical potential to access the material value reported under Module D of indicator 1.2 of the Level(s) framework.

The indicator considers the ease of disassembly for a minimum scope of building elements, as well as the ease of reuse and recycling for these elements and their associated parts and materials.

The common unit of measurement is a dimensionless scoring of the circularity potential of a building. The assessment boundary is the building and its complete bill of quantities and materials, if they are addressed in the design assessment by a Level(s) user.

The building’s bill of quantities and materials, in so far as they are encompassed by the design assessment and the minimum scope of building elements that is identified in the instructions for level 2 and 3. The scope for building elements and materials is effectively the same as Level(s) indicator 2.1.

A bespoke calculation method has been developed for Level(s) that is broadly related to the principles of the German Green Building Council’s (DGNB) ease of recovery and recycling criterion TEC1.6. The method results in a score between 0 and 100 for the applicable building elements and components, with 100 being the best design that allows for full reuse of the elements and components. The score can be weighted by mass or by value of the applicable components and elements. The instructions for each level and guidance additionally make reference to the principles and design aspects that are included in ISO 20887.

3.2.4 Circular Buildings Tool-Kit Indicators:

Arup and the Ellen Macarthur Foundation have developed the “Circular Buildings Toolkit” [38] providing a framework to evaluate the circularity of Buildings. Through this tool, the principles of the circular economy have been translated into a prioritised set of strategies and actions relevant for real estate projects.

The framework is aligned with the EU Taxonomy EU Level(s), World Green Building Council and the Green Building Councils.

3.2.4.1 Strategies, Actions and Key Performance Indicators:

Starting from circular economy principles translation to the real estate projects 10 strategies and 46 actions than can be split. For each of the 10 strategies, indicators are allocated.

Table 27

Strategy	Key Performance Indicator
1. Refuse unnecessary new construction	**Reuse of existing usable surface**: Share of reused floor area as percentage of total project gross floor area [%]
2. Increase building utilisation	**Total building utilisation:** Cumulative hours of occupancy, defined as total hours*person spent in the building on a weekly basis, and normalized per square metre [hrs/m2]
3. Design for Longevity	**Value retention and recovery over whole life cycle:** A good indicator to assess value retention is Life Cycle Cost (according to EU Level(s) Indicator 6.1 Life Cycle Costs), accounting for real functional service lives of the building and of each individual component, as well as assessing potential returns due to sell-back schemes and high residual value of components.
4. Design for Adaptability	**Adaptability potential:** Adaptability Score, defined as per EU Level(s) Indicator 2.3. Adaptability, Table 6. (quantitative rating resulting from a qualitative assessment)
5. Design for Disassembly	**Disassembly and recovery potential:** Ease of Recovery + Ease of Reuse and Recycling Scoring, defined as per EU Level(s) Indicator 2.4 Design for Deconstruction (Assessment methodology based on DGNB TEC1.6 Ease of recovery & recycling)
6. Refuse unnecessary components	**Conceptual material efficiency:** To account for material use reductions not achieved through technical optimisations, but rather conceptual decisions, a material use intensity factor per functional unit over building life cycle is introduced. The functional unit is to be set depending on the building typology, for example, total material use intensity per workstation/hotel bed/resident, etc.
7. Increase material efficiency	**Material use efficiency:** Total material use intensity by area, and over whole building life cycle, accounting for all building materials [kg/m2/yr]
8. Reduce the use of virgin and non-renewable materials	A good overall indicator for material input use and output potential is the **Material Circularity Indicator (MCI)** from the Ellen MacArthur Foundation.
9. Reduce the use of carbon-intensive materials	**Whole life cycle GHG emissions:** Carbon emissions intensity measured over the whole building life-cycle, as defined under Level(s) Indicator 1.2 Life-cycle Global Warming Potential. [kgCO2eq/m2/year]
10. Design out hazardous/pollutant materials	**Environmental cost:** Whole life cycle environmental impact cost per floor area, and over the whole life cycle period as defined, as defined by the Dutch MPG methodology [€/m2/year]

3.2.4.2 Ellen Macarthur Foundation Circularity Indicator.

One way to determine the success of a CE strategy at the product level is to use the Material Circularity Indicator (MCI). This indicator helps to measure which linear flow has been minimised and which restorative flow maximised for its component materials, and how long and intensively a product is used compared to a similar industry-average product.

To determine circularity, the MCI analyses a combination of product characteristics (Figure 7):

- use of virgin materials – the fraction of virgin materials used in the product;
- use of re-used materials and recycled content in the product;
- the efficiency of recycling;
- the mass of unrecoverable waste that goes to landfill or incineration;
- a utility factor that accounts for the duration and intensity of the product’s use.

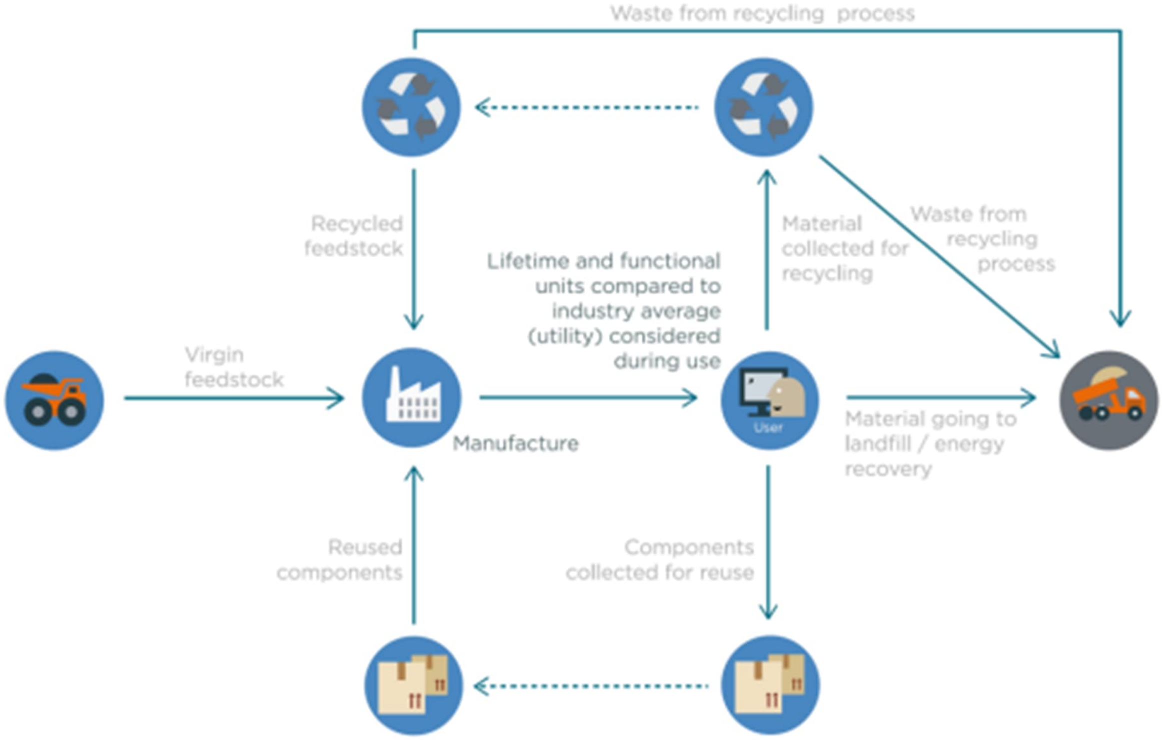

Figure 7. Material Flows for MCI calculation

From this information, the MCI generates a score between 0 and 1. For example: A product that utilises 100% virgin materials is given a MCI close to 0, which means the product is ‘linear’. On the other hand, a product that uses a large amount of recycled materials, has an extended lifespan and a high recycling efficiency will yield MCI values closer to 1.

3.2.5 Taxonomy Indicators

The Taxonomy second delegated act was approved in principle on 13 June 2023 and adopted on 27 June 2023. They will apply as of January 2024 including the “Transition to a Circular Economy” is one of the Environmental Objectives under the EU Taxonomy.

The taxonomy includes two different levels of compliance for the “Transition to a Circular Economy”; significant contribution” which technical screening criteria criteria apply to those projects that decide to comply by meeting substantial contribution to “Transition to a Circular Economy”, and the “do not significantly harm” criteria all projects complying with the Taxonomy must meet.

3.2.5.1 Significant Contribution to “Transition to a Circular Economy” Technical Screening Criteria 1:

“All generated construction and demolition waste is treated in accordance with Union waste legislation and with the full checklist of the EU Construction and Demolition Waste Management Protocol, in particular by setting sorting systems and pre-demolition audits

The preparing for re-use or recycling of the non-hazardous construction and demolition waste generated on the construction site is at least 90% (by mass in kilogrammes), excluding backfilling. This excludes naturally occurring material referred to in category 17 05 04 in the European List of Waste established by Decision 2000/532/EC. The operator of the activity demonstrates compliance with the 90% threshold by reporting on the Level(s) indicator 2.2 using the Level 2 reporting format for different waste streams”

3.2.5.2 Significant Contribution to “Transition to a Circular Economy” Technical Screening Criteria 2:

The life-cycle Global Warming Potential (GWP) of the building resulting from the construction has been calculated for each stage in the life cycle and is disclosed to investors and clients on demand.

3.2.5.3 Significant Contribution to “Transition to a Circular Economy” Technical Screening Criteria 3:

Construction designs and techniques support circularity via the incorporation of concepts for design for adaptability and deconstruction as outlined in Level(s) indicators 2.3 and 2.4 respectively. Compliance with this requirement is demonstrated by reporting on the Level(s) indicators 2.3 and 2.4 at Level 2

3.2.5.4 Significant Contribution to “Transition to a Circular Economy” Technical Screening Criteria 4:

The use of primary raw material in the construction of the building is minimised through the use of secondary raw materials. The operator of the activity ensures that the three heaviest material categories used to construct the building, measured by mass in kilogrammes, comply with the following maximum total amounts of primary raw material used:

(a) for the combined total of concrete83, natural or agglomerated stone, a maximum of 70% of the material come from primary raw material;

(b) for the combined total of brick, tile, ceramic, a maximum of 70% of the material come from primary raw material;

(c) for bio-based materials, a maximum of 80% of the total material come from primary raw material;

(d) for the combined total of glass, mineral insulation, a maximum of 70% of the total material come from primary raw material;

(e) for non-biobased plastic, a maximum of 50% of the total material come from primary raw material;

(f) for metals, a maximum of 30% of the total material come from primary raw material;

(g) for gypsum, a maximum of 65% of the material come from primary raw material.

The thresholds are calculated by subtracting the secondary raw material from the total amount of each material category used in the works measured by mass in kilogrammes. Where the information on the recycled content of a construction product is not available, it is to be counted as comprising 100% primary raw material.

In order to respect the Waste Hierarchy and thereby favour re-use over recycling, re-used construction products, including those containing non-waste materials reprocessed on site, are to be counted as comprising zero primary raw material. Compliance with this criterion is demonstrated by reporting in accordance with the Level(s) indicator 2.1

3.2.5.5 Significant Contribution to “Transition to a Circular Economy” Technical Screening Criteria 5:

The circularity assessment is so that considers that 30% use of recycled aggregates in concrete is more circular than using 65% recycled or re-used steel, what is not correct maintenance, recovery, and reuse, for example using EN ISO 22057:2022 to provide

Environmental Product Declarations. The information is stored in a digital format and is made available to investors and clients on demand. In addition, the operator ensures the long-term preservation of this information beyond the useful life of the building by using the information managing systems provided by national tools, such as cadastre or public register.

3.2.5.6 Do not Significant Harm Criteria 1 for “Transition to a Circular Economy”:

At least 70 % (by weight) of the non-hazardous construction and demolition waste (excluding naturally occurring material referred to in category 17 05 04 in the European List of Waste established by Decision 2000/532/EC) generated on the construction site is prepared for reuse, recycling and other material recovery, including backfilling operations using waste to substitute other materials, in accordance with the waste hierarchy and the EU Construction and Demolition Waste Management Protocol. Operators limit waste generation in processes related to construction and demolition, in accordance with the EU Construction and Demolition Waste Management Protocol and taking into account best available techniques and using selective demolition to enable removal and safe handling of hazardous substances and facilitate reuse and high-quality recycling by selective removal of materials, using available sorting systems for construction and demolition waste.
.

3.2.5.7 Do not Significant Harm Criteria 1 for “Transition to a Circular Economy”:

Building designs and construction techniques support circularity and in particular demonstrate, with reference to ISO 20887 (288) or other standards for assessing the disassembly or adaptability of buildings, how they are designed to be more resource efficient, adaptable, flexible and dismantlable to enable reuse and recycling.

3.2.6 Circularity Indicators Critical Review:

3.2.6.1 EN Circularity Indicators Critical Review:

Circularity Indicators are found in different standards; however, some shortcomings and lack of consistence can be found when indicators are considered as a whole.

EN 15804

The EN 15804 indicators are list of parameters that enables the implementation of the EN 15978 indicators as well as other indicators such as Level(S) 2.1, 2.2 and 2.4, while Level(s) 2.3 is mainly dependent on building lay-out and construction techniques.

While energy flows are properly accounted, materials flow are not adequately addressed as the abiotic resources depletion indicators referred and Kg of antimony does not provide an intuitive and simple way to compare different materials, products and processes. In fact, the lack of robustness of the these core indicators is highlighted in the EN 15804.

EN 15804 provides LCA Modules in an aggregated and modular way so that it is possible to conduct a cradle-to-cradle analysis, necessary to assessment circularity and solve the sustainability and circularity trade-offs that may appear.

EN 15804 provides the necessary inputs for:

- LCA including potential A to D aggregations.
- Level(s) 2.1 Bill of Quantities, materials and lifespans.
- Level(s) 2.2 Construction and Demolition Waste (CDW) and materials.
- Level(s) 2.4 Design for deconstruction user manual.
- Taxonomy “Transition to a Circular Economy” Technical Screening Criteria.

Attending to the new requirements and definition in EN 15804 it seems that EPD´s should be adapted to the new D1 and D2 and D1.1, D1.2 and D1.3 Module D splits as well as Module B8 (other operational processes)

EN 15978

LCA assessment at the building level, relies on Module D as circularity indicator, however it yet lacks a consistent Cradle to Cradle Assessment as module D is always provided as a separate value. Despite the CEN mandates ask for a End of Life formulate to be developed integrating Modules A, C and D and PEF is asked to be considered as the reference. The formula is not developed. This is a shortcoming particularly when there are notes in the EN 15978 highlighting that circularity implementation will involve circularity and sustainability trade-off that must be addressed through LCA.

The circularity assessment is addressed through Module D and Annex C. The limitations of Module D to reflect the benefits of re-use or recycling if fully accounted have been introduced in the present document; 100% accounting provides a non-realistic assessment.

In addition, the net values used in Module D are useful to model GWP avoiding negative values but is not efficient to provide information on materials flows through different cycles. Although the standard is open to other assessments in gross values, and these should be necessary for the accurate assessment of mass flow through multiple cycles.

Annex C limits the circularity assessment to “Easy of disassembly” and “Reuse and recycling potential of dismantled building products and components”, however the same indicators state in C.4 subclause NOTE 1: Before a building has to be demolished all other measures (such as renovation, refurbishment, repair and repurpose) are taken to extend the useful life. Thus, the indicators at hand mainly apply for the undesirable case of demolishing a building. Design for adaptability seems to be a necessary indicator to be included.

In this direction, the EN 15804 additional information to proceed with the assessment of the Taxonomy Technical Screening Criteria is not included in the EN 15978. As an example, there is clear relation between the indicators provided on EN 15804 sub-clause 7.3.4 E.o.L additional technical information table 15 are in fact very close to EN 15978 “Reuse and recycling potential of dismantled building products and components”

In general the implementation of the additional information subclauses in EN 15804 will lead to Level(s) indicators in EN 15978 and the inclusion of Level(s) Macro-Objective 2 indicators in future EN 15978 should be considered.

EN 17680

The adaptability indicators on EN 17680 are aligned with other adaptability indicators that can be found in the Level(s) indicator, DGNB and others. Despite reference values for scoring are only part of an informative annex, Annex A, and reference values are lacking for some of the indicators in table A.3, the Classification in A.4, provides a good reference to set adaptability targets for example in the Taxonomy. In addition, the overall requirements for adaptability are to be refined as some criteria find a strong reluctance with the CEN members.

3.2.6.2 Level(s) Indicators Critical Review:

Level(s) provide a set of indicators that allows to evaluate the three main objectives in circularity of buildings. Indicators do not show overlap or inconsistences and rely on recognized standards and certifications. Despite the methodology is not perfect, is easily understandable and the assessments are comparable and practical. It includes some necessary tools as a weight the different end of life scenarios following the EU Waste Hierarchy.

Some shortcomings are found for example in Level(s) 2.1 as the reference lifespans standards are to be developed withing CEN and for example the assessment criteria for many type of buildings in Level(2.3) Design for adaptability are not developed, but referenced through other certification systems.

The main shortcoming is related to the lack of an integrated concept to provide an overall understanding of the methodology and set targets and thresholds. As an example, the Taxonomy fails to allocate a threshold value to for both 2.3 and 2.4 Level(S) requirements. Indicator 2.1 is only evaluated based on secondary material use, what is not part of the indicator. What the indicator contains is a bill of materials with lifespan and some references to materials efficiency that also refer to need to solve trade-offs when assessing resources efficiency.

The methodology is constrained by the lack of circularity assessment tools (cradle to cradle) and the Module D net value assessment. Level(s) 1.2 Indicator is limited to GWP and does not follow a cradle-to-cradle approach. This is fact a EN 15978 shortcoming.

On the one hand, this shortcoming does not allow to conduct any cradle-to-cradle assessment in which, durability, use of secondary materials and EoL value of buildings are integrated.

On the other hand, it is not possible to compare and design requirements; durability, adaptability and recycling potentials overlap, and it may not be necessary to set requirements for the three indicators but for example define subset of indicators (durability and adaptability criteria or durability and design for deconstruction). As indicated in 9R´s and EN 15978 Annex C Clause C.4 Note, adaptability or life extension are preferred to deconstruction.

3.2.6.3 Ellen Macarthur Foundation Tool-Kit Indicators Critical Review:

The Ellen Macarthur Foundation and ARUP have developed a toolkit that includes Level(s) indicators. It includes materials and use efficiency indicators that open allow to quantify the use and functionality of a building as circular indicator and it also economic indicators.

One of the most interesting parameters is Ellen Macarthur Material Circularity indicator. This indicator considers:

- mass flows throughout the life cycle.
- The utility or function of the product, via timespan of usage (including durability of products, repair/maintenance, and shared consumption business models) and intensity of usage.
- Rates and flows at the EoL that are going to landfill (or energy recovery), collected for recycling, and collected for reuse.
- Rates and flows of recyclable materials.
- Composting and energy recovery from biological materials

The input data used for the MCI respond to variables that can be categorized in to following life cycle stages:

- A1: production of raw materials
- B: use phase of the product
- C3: recycling and C4: disposal

In recent Master Thesis [39], integrated in the efforts of the ECO-platform task force on circular economy the MCI and the NCI [40] developed by Enel X and ICMQ are identified as the best indicators to be included in EPD´s.

NCI index is not being considered here as it does not aim to transition to a circular economy; it only considers renewable and secondary resources and does not consider the EU waste hierarchy and the 9 R´s.

The MCI provides a more balanced cradle to cradle assessment. Some examples are provided by Infrabuild [41]

- Structural Steel products (primary route and 316 kg of scrap) with an MCI score of 0.379, these products are shown to be considerably better than fully linear, reflecting the high recyclability potential at end of life.
- Merchant Bar products (secondary route 1200 kg if scrap), their MCI score of 0.823 indicates that these products are well on the way becoming fully circular, reflecting their extremely high recycled steel content as well as their recyclability potential at end of life.

The indicator yet provides a higher relevance to the use of secondary materials than to EoL value, what is a shortcoming as we are assessing the Transition to a Circular Economy and the use of secondary materials is to be accounted only in the cases in which there is a mismatch between the secondary resources availability and its demand. In addition, the indicator does not reflect waste hierarchy nor process efficiency. As an example the high use of secondary materials, results of a non-particularly efficient process is not reflected (1200 kg of scrap are needed for the secondary steel and the GWP of both primary and secondary processes is high (3700 and 1500 kgCO_2/t , when 2.500 and 500 kgCO_2/t should be considered as a reference)

3.2.6.4 Taxonomy Indicators Critical Review:

Technical screening criteria number 3 “Construction designs and techniques support circularity via the incorporation of concepts for design for adaptability and deconstruction as outlined in Level(s) indicators 2.3 and 2.4” compliance is not linked to any target. The provided references are only assessment methods. Therefore, there is not any threshold to comply despite design for adaptability and deconstruction are the most relevant aspect for the “transition to a circular economy”.

Technical screening criteria number 4 refer to maximum primary resources use, what is the same, minimum recycled content. The way this technical screening criteria is defined does not contribute to the transition to a circular economy and disincentives the use of circular materials:

- The set criteria do not consider the EU waste Hierarchy to construction and do not set any different between high quality recycling and downcycling. In addition, more stringent requirements are set to consolidated circular economies that have already implemented high quality recycling than for example to the waste streams than have been listed by the CEAP as a priority.
- Minimum recycled content is considered in the “Circular Economy Action Plan” for certain materials to prevent a mismatch between supply and demand in those cases in which the use of secondary materials may find reluctance. Consolidated circular economies as it is the case of metals should not be subjected to minimal content. Particularly in the case of steel, the most recycled material, scrap is used and for steel production and scrap is a valuable material that find not reluctance to its use.
- The approach is not consistent with the taxonomy for steel manufacturing criteria where circular economy criteria are lacking at level of Substantial Contribution and at DNSH level. It is not correct to introduce them ‘indirectly’ as the PSF 1.0 did not agree/conclude on such criteria for steel manufacturing.
- The category metals is too wide as it comprises different materials (e.g. steel, aluminium and cooper). Even for these different materials is necessary to set subdivisions that represent the different products and technologies.
- The high share of recycled content necessary to meet “substantial contribution to the transition to a circular economy” for metals (70% of secondary materials twice than the values set for other construction materials) constrains the use of metals, regardless of metals are

the most representative example of circular economy in construction. The target will in fact prevents the use of some specific metallic construction products. The availability and current State of Art secondary material based metallic construction products must be considered and an agreed position with the main stakeholders representing metals in construction is needed. The way the technical screening criteria 4 is defined will not contribute to “the transition to a circular economy” but will limit the use of metals and will create a market distortion.

- In case of being mandatory setting a maximum primary resources use, the values set for renovation of existing building (65% maximum primary materials and 35% minimum secondary material content) is more accurate, even this value should be agreed with the relevant stakeholders.
- As the material assessment is E.o.L central it does not set any secondary material threshold to cement.
- The circularity assessment is so that considers that 30% use of recycled aggregates in concrete is more circular than using 65% recycled or re-used steel, what is not correct.

For Technical screening criteria 2 “The life-cycle Global Warming Potential (GWP):

- When assessing the circular economy, the use of PEF Circularity Footprint Formula should be considered as indicated in the “COMMISSION RECOMMENDATION of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations”

3.2.6.5 Recommendations for the Transition to a Circular Economy Standardization:

The main objective for Construction Works is the Transition to a Circular Economy.

The translation of Circular Economy principles for construction works has been done by the JRC and there is an agreement on these three principles: Durability, Adaptability and Reduce waste and facilitate high quality management.

Level(S) has developed a set of indicators to evaluate these three principles.

The existing standards provide parameters and indicators to evaluate environmental impact.

As circularity is considered part of sustainability in construction works, some of these parameters and indicators reflect circularity.

The way these parameters reflect circularity of materials, products and buildings is not robust. This is recognized in the EN 15804 body.

Main shortcomings:

- Lack of robustness on material flows indicators. Although is clear that it is necessary to evaluate and standardize material flows to compare different streams, depletion of abiotic resources indicators need to be improved. Material flows must reflect the material relevance and impact as well as the recycling quality and efficiency and the EU Waste Hierarchy.
- There is need to develop a agree on a cradle-to-cradle assessment or Circular Footprint formula in which the impacts in which different stages have to be aggregated and weighted.

This will allow to solve the potential trade-offs between actions and compare different E.o.L options.

- There is a need to evaluate circular materials in multiple cycles, therefore an alternative cradle to cradle assessment not based in net flows and reflecting the EU Waste hierarchy.
- Responsibly sourced materials need also to be considered with secondary materials when assessing circularity. In any case, secondary materials contribution to Circular Economy, must be carefully considered. The Circular Economy Action Plan only considers setting secondary materials requirements only in the case that there is a mismatch between secondary material availability and re-use.
- In addition, not considering the EU Waste Hierarchy will allocate the same value to mixed low value streams and high-quality recycling, what provides unfair and unrealistic outcomes. As an example, the EU Taxonomy considers complaint with Transition to a Circular Economy the use of 30% recycled aggregates, but not a 65% re-used metallic structure. In general, the direct use of secondary material use not subjected to any efficiency of resources use or impact assessment leads to wrong assessments.
- All indicators in use should be refined (Level(s) indicators as an example) and integrated in the CEN standards.
- Some obvious gaps must be addressed and the exclusion of design for adaptability from EN 15978, when the text recognizes that other E.o.L options are preferred.
- The definition of a circularity index reflecting efficiency of resources, E.o.L and time boundaries is necessary, however current indicators (MCI or NCI) allocate too much weight to the use of secondary materials.
- It is recommended to work on the existing parameters and mass and energy balances currently being used in LCA. Materials and energy flows are central to LCA. LCA relies on the previous energy and mass balances. In a later step, these flows a translated into impacts using LCI´s.
- LCI´s for mass balances need to be upgraded.
- When any assessment methodology is being developed, it will be necessary to consider the existence reference thresholds and reference values coming from different actions and research projects. Indicators that cannot be translated into targets are not useful as seen in the Taxonomy.

3.2.7 DGNB System for Deconstruction

The German Sustainable Building Council (DGNB) has several criteria catalogues for assessing the sustainability of buildings. The DGNB Criteria for New Buildings (Figure 8 left) [42] and the DGNB Criteria for Deconstruction (Figure 8 right) [43] are of interest for deconstruction. Both systems are explained in this report.

Figure 8: DGNB Criteria Catalogue

3.2.7.1 DGNB Criteria Set New Construction Buildings

The DGNB Criteria for New Buildings assesses sustainability based on six qualities: ecological quality, economic quality, socio-cultural and functional quality, technical quality, and process quality (see Figure 9). Points are awarded for meeting the requirements, leading to bronze, silver, gold, and platinum certificates.

Chapter TEC 1.6 assesses the circular design. The aim of this criterion is to use natural resources sparingly, to make efficient use of assets already created, to use few primary resources for the construction and maintenance of buildings, to focus on the loss-free recycling of materials and to reduce the amounts of materials used. The aim is to contribute to overall sustainability: Decent work and economic growth; Industry, innovation, and infrastructure; Sustainable cities and communities; Climate action; and Sustainable consumption and production.

The criterion distinguishes whether a previous deconstruction can be attributed to the project. The assessment of the criterion includes the site and inventory analysis and previous (partial) deconstruction, the circular construction design phase, and the execution and documentation of the circular construction.

Figure 9: Basic structure of the DGNB System New Buildings

3.2.7.2 DGNB Criteria Set Deconstruction

The DGNB system for deconstruction refers to five equally weighted qualities: ecology, economy, socio-cultural and functional aspects, technology, and processes (see Figure 10). Again, points are awarded for meeting criteria, which can lead to silver, gold, or platinum certification.

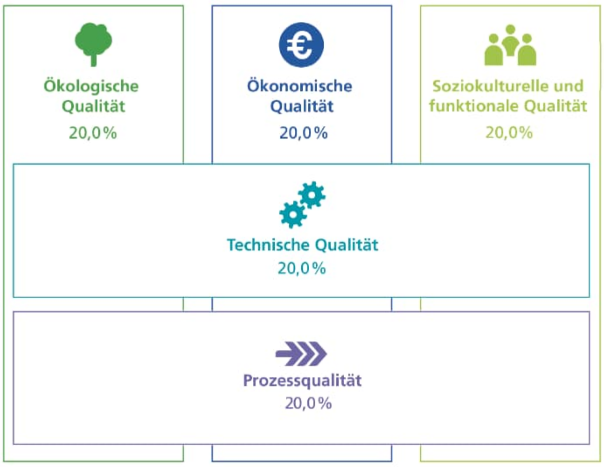

Figure 10: Basic structure of the DGNB System Deconstruction

<u>Ecological quality</u>

The two ecological quality criteria enable transparency of material flows and minimisation of hazardous deconstruction materials to reduce the associated risks to people and the environment.

The first criterion, ENV1-R - Material Flow Balance, focuses on creating transparency in the material flows of the deconstruction process. By reducing transport distances for recycling and disposal, the environmental impact in terms of emissions and consumption of resources should also be minimised. In assessing this criterion, the transparent listing of all dismantling masses and transport distances in accordance with GewAbfV § 8 Para. 1 is of particular importance.

The second criterion ENV2-R - Remediation of Hazardous Materials deals with the prevention of risks to people and the environment from hazardous building materials and contaminated deconstruction waste. This criterion considers the three protection goals of user protection, occupational safety and minimisation of contaminated waste. The criterion is constantly adapted to current developments, such as the scarcity of landfill sites. The minimum requirement for assessment is the systematic identification and documentation of hazardous substances.

Economical quality

The two economic quality criteria are used to assess financial risks and ensure that costs remain stable. At the same time, they are intended to raise awareness of the value of available resources.

The first criterion, ECO1-R - Risk Assessment and Cost Certainty, is designed to provide a realistic assessment of the economic risks of dismantling in order to increase cost certainty throughout the process. The aim is to create transparency in terms of data quality and remaining risks, as well as clearly regulated supplementary management. Factors such as the level of detail in the cost estimate, transparent presentation of uncertainties and explanation of economic risks, and transparent follow-up management play an important role in the assessment.

The second criterion, ECO2-R - Values of Expandable Resources, is about increasing the appreciation of potential expandable resources, for example through the inventory measure, in order to increase awareness and transparency regarding possible project-related waste of resources. The assessment includes raising awareness of existing resources among those involved in the dismantling process, increasing the value of resources by evaluating the inventory and market assessment, as well as evaluating the search for buyers and their acceptance for actual reuse.

Socio-cultural quality

The socio-cultural and functional quality is used to proactively organise information in the environment and improve internal project communication to avoid potentially dangerous situations on the site.

The first criterion SOC1-R - Project Communication aims to raise awareness of the importance of acceptance of the decommissioning process by those directly or indirectly affected, in order to prevent potential conflicts during the decommissioning process. The assessment rewards proactive information to the public and assessment of internal project communication. (Points: 100 without bonuses, max. 110 including bonuses)

The second criterion, SOC2-R - Safety, aims to prevent hazardous situations by taking certain measures, such as assessing expected hazards in advance and monitoring the implementation of safety requirements. The assessment rewards comprehensive hazard assessment and control of site regulations, recognition of training and assessment of the implementation and control of site safety measures.

Technological quality

The two aspects of technical quality are used to create transparency and optimise the efficiency of recycling and disposal routes. In addition, segregation by type is assessed to improve preparation for reuse and recycling.

The first criterion, TEC1-R - Recycling and Disposal, is concerned with the economical use and efficient utilisation of natural resources. The focus is on the circular economy to optimise recycling and disposal routes. The assessment recognises the transparent allocation of dismantling materials to recycling and disposal routes.

The second criterion, TEC2-R - Separation by type and recycling, is aimed at the economical use of natural resources (maximum separation and separation by type), their return to the cycle for maximum reuse and high-quality material recycling. The assessment largely takes into account the documentation of unmixed separation, the processing and recycling of mineral material flows and the recognition of the reuse of building components and building products, which are rewarded accordingly.

Process quality

The purpose of the four process quality criteria is to make deconstruction processes transparent while ensuring quality in the areas of deconstruction planning, tendering and construction.

The objective of the first criterion PRO1-R - Deconstruction Planning is to optimise deconstruction processes through detailed planning, to make them transparent and to raise awareness of the ability to influence deconstruction quality. The assessment considers the need for deconstruction, the evaluation of the environmental analysis and the recycling and disposal concept, the development of a deconstruction and dismantling plan and the recognition of an environmentally and neighbourhood friendly logistics concept for the award.

The second criterion PRO2-R - Tendering aims to integrate the sustainability aspects addressed in the dismantling certification criteria into the tendering process to ensure that the planned measures and requirements are communicated to the relevant stakeholders. The evaluation rewards the setting of quotas in the tender, the assessment of data quality and the integration of planning specifications for sustainability aspects, as well as the implementation of restricted tendering with competitive tendering.

The third criterion, PRO3-R - Quality Assurance and Documentation, focuses on the implementation and verification of sustainability requirements through quality assurance processes. The established approval, acceptance, and change management, with clear processes and responsibilities, and the recognition of detailed documentation of recycling and disposal are positively assessed.

The fourth criterion, PRO4-R - Construction Site and Deconstruction Process, aims to minimise negative environmental impacts during the deconstruction phase by raising environmental awareness among construction site personnel and transparent construction site management. The assessment covers site equipment, prevention of errors and machinery and equipment, training of site personnel, and measures to avoid site-specific risks and their implementation.

4. Case study

The study describes an LCA model of a hypothetical project of single-story industrial hall in Finland introduced in the Deliverable D5.1 of PROGRESS project [8] and adapted to the current standards and methodology presented in this report. The building is made of steel portal frames, secondary structure (purlins, side rails and bracing), and envelope from steel sandwich panels with mineral wool insulation. Although, the most common single-storey steel structure in the Nordic countries has roof truss girders on columns, portal frames offer a competitive alternative to this construction system, especially for shorter spans. Portal frames can be more easily reusable in some situations because they are more resistant to damage during the deconstruction process. Environmental impact assessment is based on life cycle assessment method presented in this report considering system boundaries described in this section.

Portal frames for industrial buildings have been extensively studied because of their widespread use. The improvement of the design methods for portal frames is one of the recurring topics in the field of steel structures. Due to the large number of similar framed structures, the desire to “automate” the design and manufacturing process was popular from the very early stage. As Dowling et al. [44] noted, there are two design tendencies when trying to achieve more economical solutions: (a) to use compact hot-rolled sections and exploit the advantages of plastic design and (b) to use slender built-up sections with the most advantageous distribution of the material but keep the design in the elastic range. The second option usually leads to slender structures, and therefore stability becomes the main concern of the designer.

One of the outcomes of RFCS project PRECASTEEL was a database of optimized constructional steelwork for industrial buildings [44] that can resist up to 1500 N/m^2 of vertical snow load and appropriate horizontal wind load or seismic load with the peak ground acceleration (PGA) up to 0.32 g. The frames (welded-tapered, hot-rolled and truss girders) were optimized to minimize the steel consumption with sufficient structural resistance and stability using advanced 3D finite element models and genetic algorithms as optimization and simulation methods (Figure 11).

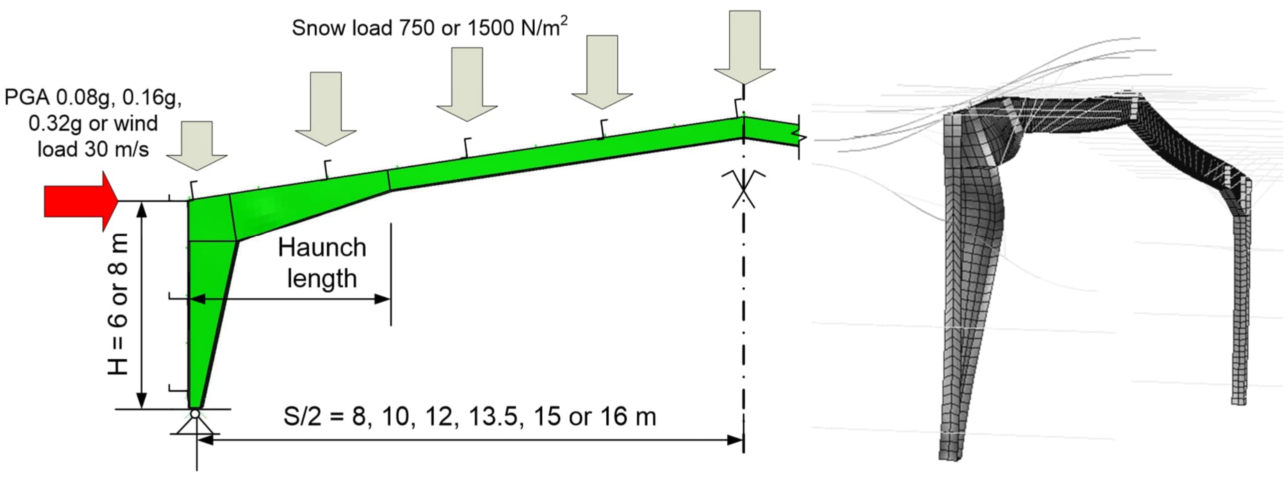

Figure 11 Loads and basic dimensions of the optimized frames (left) and example of the lateral-torsional buckling failure of 3D FEM model used for the optimization of the structural shape (right)

4.1 Basic assumptions

One of the optimized solutions with welded-tapered frames was selected for the purpose of this study. Since the building shall be erected in Finland, heavy snow load (1500 N/m^2) was assumed, but no seismic loading. The span of the frame is 16 m and eaves height is 6 m, which leads to steel consumption of the primary structure under 20 kg/m^2. The total length of the building is 30 m with six identical frames at 5 m spacing.

Life cycle assessment method chosen for the evaluation of the environmental impact follows the rules of ISO 14044 [21] and EN 15978 [17].

The main goal is to show the potential of environmental performance and improvements through comparison of new hall construction (‘new building’) and steelwork with reused steel components (‘reused steel’). The assessment considers global warming potential (GWP) as the indicator of the environmental performance.

System boundaries:

- Functional unit for the industrial building hall is the heated floor area 480 m^2;
- External walls and ground floor slab have U-value 0.16 W/m2K, roof elements 0.09 W/m^{2}K and windows + entrance-door 1.0 W/m^{2}K;
- The area of windows and door is 44 m^2 (20 + 24 m^2);
- The assessment considers the main following building structures: foundation (concrete), ground floor slab (concrete and EPS insulation), steel frame, sandwich panels (steel cassettes with mineral wool), triple glazing windows and entrance door;
- The building assessment includes the following life cycle stages: ‘Product stage’ (A1 - raw materials, A2 - transportation, A3 - production), ‘Construction stage’ (A4 - transportation, A5 - building construction), ‘Use stage’ (B6 - operational energy use), ‘End of life’ (C1 - demolition/deconstruction and C2 - transportation to the salvage yard, in case of reused steel) and impact beyond the system boundary (D - recycling and future reuse);
  GWP’s for building materials based on Environmental Product Declarations (EPD’s) by Ruukki Construction Oy [46], ELCD database [47] and other literature data [8].

4.2 Lifecycle impacts (Module A-C)

4.2.1 Product stage (Module A1-3)

This simplified assessment considers primary structure (Figure 12), secondary structure, foundations, floor slab and envelope. In the “reuse” scenario, it is considered that the building is completely re-assembled, or all its parts are reused with no steel waste materials generated. Use of the building materials for the primary construction is shown in Table 28.

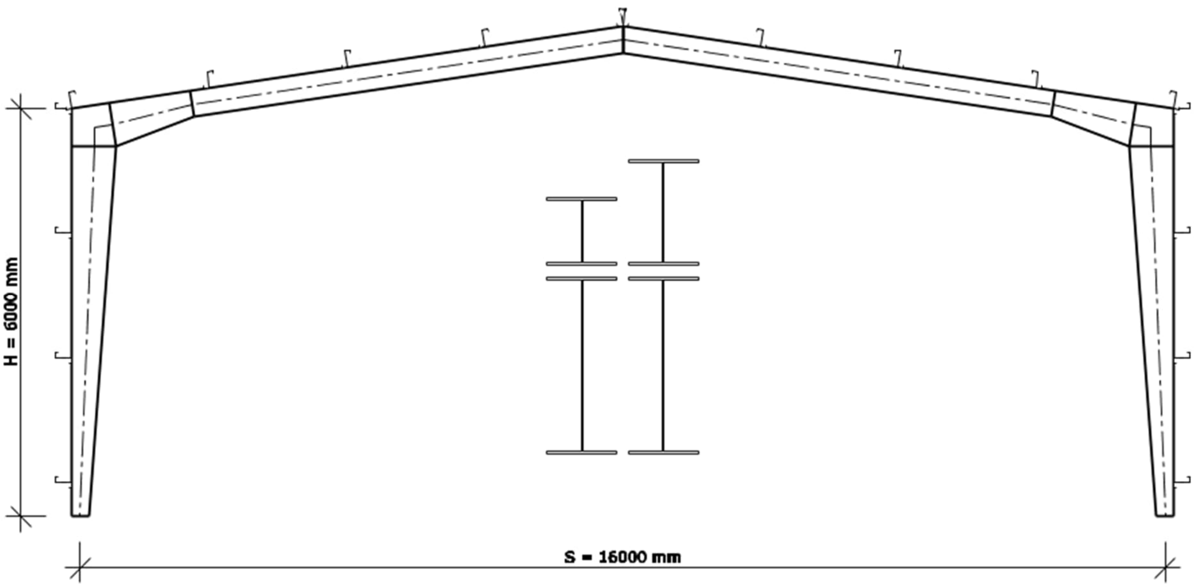

Figure 12 Geometry of the selected portal frame

Product stage for the reused structures include sand blasting and cutting welds (if required) 10 kgCO_2e per tonne of steel and repainting from 260 to 280 kgCO_2e per tonne of steel as in Table 28.

Table 28. Total amount of products and unit GWP for material production (A1-3)

Product	**Total units**	**Unit impact (tCO_2e)**
Primary structure (welded-tapered frames)	8.52 t	2.71 / t
Secondary structure (purlins, rails & bracing)	5.18 t	2.75 / t
Envelope (sandwich panels)	1068 m^2	0.0535 / m^2
Concrete floor and foundations	236 m^3	0.029 / m^3
EPS	3.9 t	3.38 / t
Windows	20 m^2	0.0205 /m^2
Doors	24 m^2	0.0215 / m^2
Reconditioning of the primary structure	8.52 t	0.27 / t
Reconditioning of the secondary structure	5.18 kg	0.29 / t
Reconditioning of the envelope	1068 m^2	0.00032 / m^2

LCA results are calculated for two scenarios: the first use (‘*new steel*’) and 100% reuse of the steel structure of industrial building hall (‘*reused steel*’). The reuse case is reassembled from the re-covered steel from the first scenario. This assessment takes use environmental benefits as (GWP-savings).

Table 29 and Figure 13 show results of the two alternatives studied (‘*new steel*’ and ‘*reused steel*’).

Table 29. LCA results of the production stage (A1-3)

	New steel (tCO_2e)	Reused steel (tCO_2e)
Total impacts of the production stage (A1-3)	180.1	90.7
- Welded-tapered frames	23.0	2.3
- Purlins and rails	14.3	1.5
- Bracing	3.1	3.1
- Envelope	57.1	0.3
- Concrete and EPS	81.6	81.6
- Reconditioning	0	0.4
- Windows	0.4	0.4
- Doors	0.5	0.5

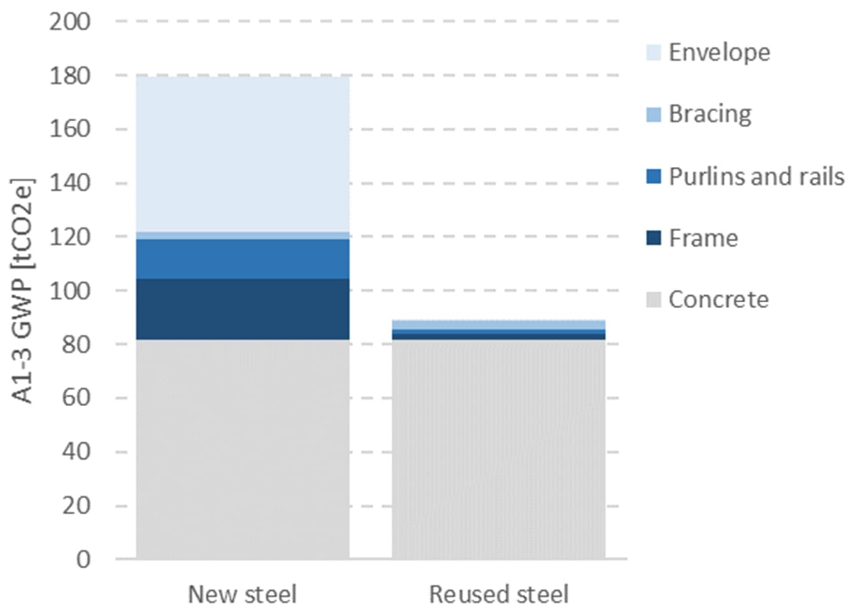

Figure 13 LCA results of the production stage (A1-3)

4.2.2 Construction stage (Module A4-5)

The finished products should be transported to the building site from the factory in Raahe (frame) and Hämeenlinna (purlins, rails, and panels). The distances of 469 km and 107 km used in this study are the weighted average distances to the major cities in Finland from Raahe and Hämeenlinna respectively. Articulated lorry transport (40 t) was assigned to each product from the ELCD database [47], and 0.1638 $kgCO_2e/km$ was used for the return journey of an empty truck. The construction work included excavation of soil for the floor slab and foundations from the ELCD database, concreting and erection of constructional steelwork using 100-tonne crane, forklifts, and man-lifts. Their respective workloads are presented in Table 30.

Table 30. Construction phase workloads

Process	Unit load (min/piece)	Total load (min)
Crane workload		1016
- Columns preparation	3	36
- Columns placing and temporary connection	10	120
- Rafters preparation	2.5	30
- Rafters placing and temporary connection	7.5	90
- Purlins and rails placing	5	250
- Sandwich panels placing	5	490
Forklift workload		945
- Columns unloading	7	84
- Columns placing	5	60
- Rafters unloading	7	84
- Purlins and rails unloading	3	270
- Sandwich panels unloading	3	447
Man-lift workload		830
- Rafters placing and temporary connection	7.5	90
- Purlins and rails placing	5	250
- Sandwich panels placing	5	490

Additional diesel consumption of 2400 kg was estimated for equipment transportation (1 x crane, 2 x forklift and 2 x man-lift) and workers transportation (15 workers, 14 working days). Table 31 and Figure 14 show results of the two alternatives studied (‘New building’ and ‘Reused steel’).

Table 31. LCA results of the construction stage (A4-5)

	New steel (tCO_2e)	Reused steel (tCO_2e)
Total impacts of the construction stage (A4-5)	14.3	14.4
- Transport	2.5	2.6
- On-site energy and fuel	0.9	0.9
- Crane	6.5	6.5
- Forklifts	2.0	2.0
- Man-lifts	1.4	1.4
- Excavator	0.9	0.9

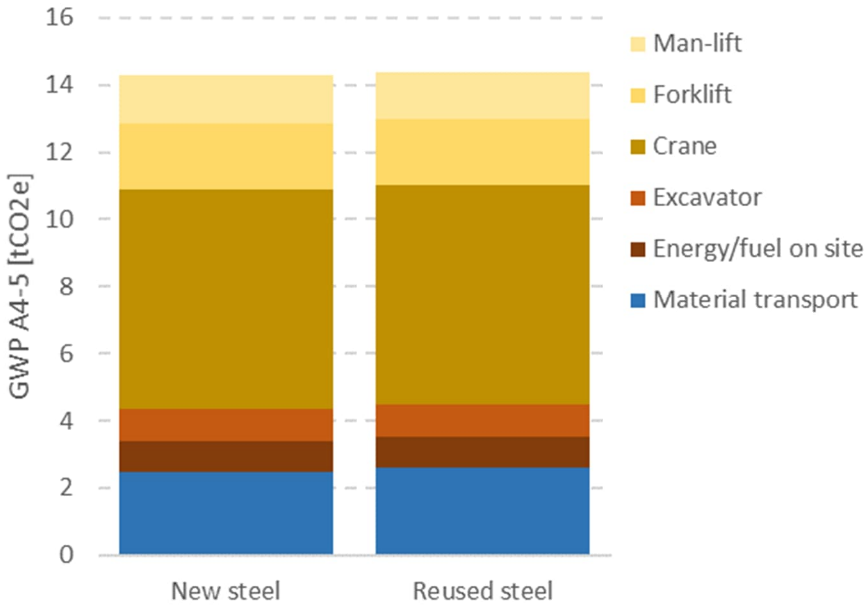

Figure 14 LCA results of the construction stage (A4-5)

4.2.3 Use stage (Module B6)

The use stage covers the building lifetime from the completion of building construction to the point of time when the building is deconstructed/demolished. Lifetime for this assessed building is 27 years (the building service time according to mean service life of industrial halls in Finland). During this lifetime, no maintenance, repair and material replacements and refurbishment are considered.

Operational energy consumption based on energy simulation made by E-pass tool [48]. Assessment considers building location Helsinki and climate condition based on weather data 'Helsinki 1979'. Default value used for the heating of industrial hall was 15 ºC. No mechanical cooling was considered. Building hall was connected to the district heating network. GWP's for the energy consumption based on Finnish average district heat mix [49] and average electricity mix [50] both including delivery losses and in case of electricity, also electricity imports. No heat recovery is considered. Operational energy consumptions and unit GWP values for industrial hall is given in Table 32.

Table 32. Operational energy consumption and unit GWP of the building

Operational energy	**Consumption (MWh/m^2yr)**	**Unit impact (tCO_2/MWh)**
Space heating	0.161	0.173
Hot water	0.014	0.173
Electricity	0.045	0.152

It is assumed that the use stages of new and reused building have identical environmental impact (see Table 33).

Table 33. LCA results of the use stage (B6)

	New steel (tCO_2e)	**Reused steel (tCO_2e)**
Total impacts of the use stage (B6)	481.0	481.0

4.2.4 Demolition/deconstruction stage (Module C1-2)

It is assumed that the deconstruction of the steel frame is the same process as its erection with an additional effort to maintain the integrity of the disconnected components. Such additional effort is in this study modelled as workload multiplier between 1 and 2 depending on the amount of reused steel. Moreover, the transportation (C2) of the recovered building elements to the nearest salvage yard was added to the model. Figure 15 presents LCA the results of the demolition/deconstruction stage.

Table 34. LCA results of the demolition/deconstruction stage (C1-2)

	Demolition (tCO_2e)	**Deconstruction (tCO_2e)**
Total impacts of the demolition/deconstruction	10.8	19.3
- Transport	0.0	0.4
- On-site energy and fuel	0.9	0.9
- Crane	6.5	13.1
- Forklifts	2.0	2.0
- Man-lifts	1.4	2.8

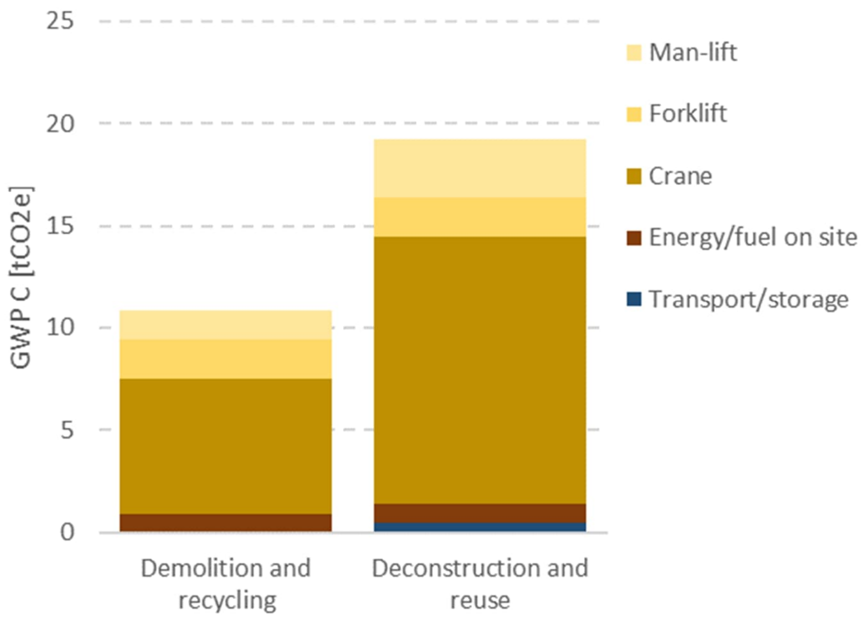

Figure 15 LCA results of the demolition/deconstruction stage (C1-2)

4.3 Loads and benefits beyond the system boundary (Module D)

The environmental impact of the structural steelmaking process (Module A1) is assumed to be 2.44 tCO_2e/t for the primary and secondary structure, scrap content is 20% and end-of-life recycling 90% according to the EPD. Therefore, it can be calculated that the virgin material production generates theoretically 2.99 tCO_2e/t and pure recycling generates 0.94 tCO_2e/t before transport, manufacturing, and galvanizing (in case of purlins and rails). The yield of recycling process is 0.92 t of recycled steel per 1 t of steel scrap is presented in the Table 35. The loads and benefits beyond the system boundary are then calculated for four different scenarios and summarized in Table 36.

Table 35. Loads and benefits of the products' recycling

Product	**Total units**	**Unit impact (tCO_2e)**
Primary structure (welded-tapered frames)	8.52 t	-1.30 / t
Secondary structure (purlins, rails & bracing)	5.18 t	-1.32 / t
Envelope (sandwich panels)	1068 m^2	-0.0124 / m^2

- **<u>New steel – Demolition and recycling:</u>** It is assumed that the new steel is produced from 20% of scrap and then 90% of the steel is recovered for recycling at the end of the life.
- **<u>New steel – Deconstruction and reuse:</u>** It is assumed that the new steel is produced from 20% of scrap, 90% of the steel is reused and 90% of the remaining steel (9% of the total mass) is recovered for recycling at the end of the life.
- **<u>Reused steel – Demolition and recycling:</u>** It is assumed that the building is constructed from 90% of reused elements, the remaining new steel is produced from 20% of scrap and then 90% of the steel is recovered for recycling at the end of the life.
- **<u>Reused steel – Deconstruction and reuse:</u>** It is assumed that the building is constructed from 90% of reused elements, the remaining new steel is produced from 20% of scrap, 90% of the steel is reused and 90% of the remaining steel (9% of the total mass) is recovered for recycling at the end of the life.

Table 36. Material flows in the calculation of Module D

Material source	**New steel**		**Reused steel**	
End-of-life scenario	**Demolition and recycling**	**Deconstruction and reuse**	**Demolition and recycling**	**Deconstruction and reuse**
Input scrap $M_{MR,in,1}$	20%	20%	2%	2%
Input components $M_{MR,in,2}$	0%	0%	90%	90%
Output scrap $M_{MR,out,1}$	90%	9%	90%	9%
Output components $M_{MR,out,2}$	0%	90%	0%	90%

Using the LCI methodology of World Steel Association, it is possible to calculate the theoretical unit impact of steelmaking from the virgin materials $E_{VM,A1}$ and from the scrap $E_{rec,A1}$ as described in Equations (9) and (10).

$E_{VM,A1} = E_{A1}/(1 - M_{MR,in,1}Y) = 2.44/(1 - 0.2 \cdot 0.92) = 2.99\ kgCO_2e/kg$ (9)

$E_{MR,A1} = E_{VM,A1} + E_D/(M_{MR,out,1} - M_{MR,in,1})Y = 2.99 - 1.31/(0.9 - 0.2)0.92 = 0.94\ kgCO_2e/$ (10)

Since the assumed point of functional equivalence is at the end of product phase, the unit impacts of phases A2 and A3 shall be added. The example of structural steel impacts used for the primary structure (frames) is in Equations (11) and (12):

$E_{VMSub,out,1} = E_{VM,A1} + E_{A2} + E_{A3} = 2.99 + 0.01 + 0.25 = 3.26\ kgCO_2e/kg$ (11)

$E_{MRafterEoW,out,1} = E_{MR,A1} + E_{A2} + E_{A3} = 0.94 + 0.01 + 0.25 = 1.21\ kgCO_2e/kg$ (12)

Then for instance for the second scenario, where new steel is going to be reused at the end of building's life, we can calculate Module D of the primary structure using closed-loop formula for reuse according to Equation (13):

$$e_{moduleD1} = \sum_i (M_{MR,out,i} - M_{MR,in,i}) \left(E_{MRafterEoW,out,i} - E_{VMSub,out,i} \frac{Q_{R,out,i}}{Q_{Sub,i}}\right)$$
$$= (M_{MR,out,1} - M_{MR,in,1}) \left(E_{MRafterEoW,out,1} - E_{VMSub,out,1} \frac{Q_{R,out,1}}{Q_{Sub,1}}\right)$$
$$+ (M_{MR,out,2} - M_{MR,in,2}) \left(E_{MRafterEoW,out,2} - E_{VMSub,out,2} \frac{Q_{R,out,2}}{Q_{Sub,2}}\right) \quad (13)$$
$$= (0.09 - 0.2) \cdot (1.21 - 3.26) \cdot 0.92 + (0.9 - 0) \cdot (0 - 3.26) = 0.20 - 2.93$$
$$= -2.73\ kgCO_2e/kg$$

Environmental impacts of the secondary structure and envelope are calculated similarly, and their results are presented in the Table 37. In the case of envelope, EPD for the color-coated products was used with $E_{A1} = 2.89\ kgCO_2e/kg$, $E_{A2} = 0.0139\ kgCO_2e/kg$, $E_{A3} = 0.0116\ kgCO_2e/kg$ and $E_D = -1.32\ kgCO_2e/kg$. It was assumed that 1 m^2 of sandwich panel contains 9.39 kg of steel, and that the core material is not being recycled at all (only reused in relevant scenarios). The total impacts multiplied by the mass or surface area are shown in Figure 16.

Table 37. Loads and benefits beyond the system boundary

Material source	**New steel (tCO_2e)**		**Reused steel (tCO_2e)**	
End-of-life scenario	**Demolition and recycling**	**Deconstruction and reuse**	**Demolition and recycling**	**Deconstruction and reuse**
Primary structure	-1.30 / t	-2.73 / t	1.29 / t	-0.13 / t
Secondary structure	-1.32 / t	-2.74 / t	1.29 / t	-0.13 / t
Envelope (sandwich panels)	-0.0124 / m^2	-0.057 / m^2	0.0434 / m^2	-0.0012 / m^2

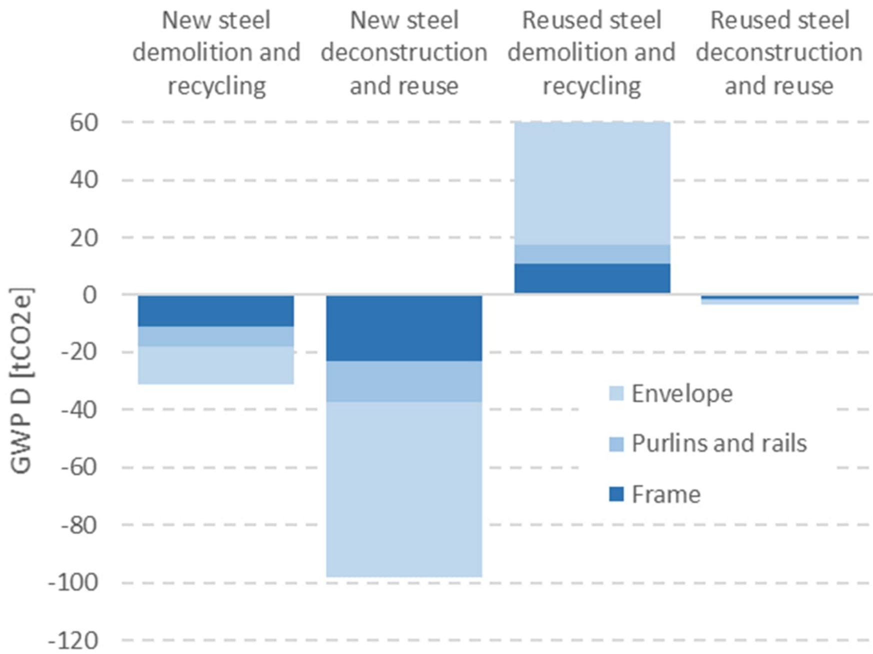

Figure 16 LCA results of the impacts beyond the system boundary (D)

It should be noted that open-loop formula for component reuse can be used as well, but the knowledge of the scrap content in the primary production of the reusable product must be provided. In this example we can assume that the 'new steel' scenario information can serve as estimation of substituted impacts $E_{VMSub,out,2}$ of the reused material with open-loop allocation. Then the corresponding amounts of material must be moved from reuse inputs and outputs in Table 36 to recycling inputs and outputs. The resulting values $e_{moduleD1}$ of this calculation will be identical as with the closed-loop allocation demonstrated in this study.

4.4 Summary

Four scenarios were explored in the example LCA study presented in this report. The scenarios covered situation when the building is constructed from the new or reused components, and when the components are going to be reused or recycled in the future. The differences can be clearly seen as the savings in the production stage (A1-3) when recovered steel is used in the construction, and in the demolition stage (C1-2) with more efforts for deconstruction for the future reuse (see Table 38).

Table 38. Total LCA results of four possible scenarios of an industrial building

Material source	**New steel (tCO_2e)**		**Reused steel (tCO_2e)**	
End-of-life scenario	**Demolition and recycling**	**Deconstruction and reuse**	**Demolition and recycling**	**Deconstruction and reuse**
Lifecycle impacts (A-C)	686.2	694.3	596.9	605.4
- Production stage (A1-3) - Construction stage (A4-5) - Use stage (B6) - Demolition stage (C1-2)	180.1 14.3 481.0 10.8	180.1 14.3 481.0 19.3	90.7 14.4 481.0 10.8	90.7 14.4 481.0 19.3
Loads and benefits beyond the system boundary (D)	-31.1	-98.3	64.0	-3.1

It is recommended that the results from beyond the system boundary (Module D) are not aggregated with the lifecycle impacts (Modules A to C) as demonstrated in Figure 17.

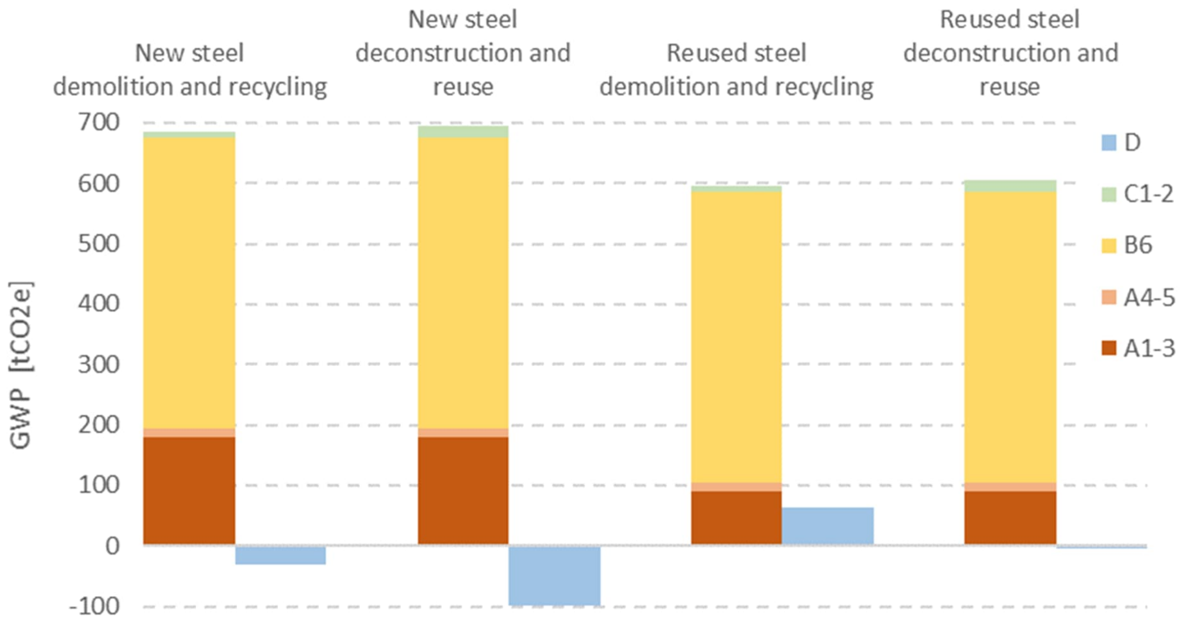

Figure 17 Total LCA results of four possible scenarios of an industrial building

5. Conclusions

This report presents the methodology to declare environmental benefits of reused elements in the scope of RFCS project ADVANCE. The objective of our initiative is to review the legal framework and its application to deconstruction and reuse in the built environment. Different opinions and studies concerning the problem of reuse of steel are presented. We believe that the steel construction industry should be the forerunner in the reuse area because steel is commonly used for connecting building components also from different materials. Thus, the buildings resource efficiency will depend on steel-based innovations to a large extent and the impact of the project can easily extend the scope of steel construction.

The European steel sector has always played an important role in the development of LCA assessment methods and standards over many years. Life Cycle Inventory data published by steel industry is based on production of steel from iron ore and steel scrap. Steel inventory covers material mining and manufacture but also benefits and loads of recycling steel from products at the end of their life. At the same time, after intended life, reusability extends the steel life with less impacts compared to steel recovery through melting process.

Therefore, it is important to strengthen the role of steel reuse and to develop a reliable method of declaring environmental impacts of reused steel in buildings and other products. Less than 10% of currently generated constructional steel waste is being reused but we estimate that is feasible to increase structural steel reuse beyond 30% by 2050. From this point of view a degree of standardization is needed, both in the design for deconstruction and evaluation of reused structures/components.

The life cycle assessment methodology introduced in this report comprises methods for compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle. Assessment is starting with the setting of the goals and scope for the study, making an inventory analysis, impact assessment and finally ends in the results interpretation. The methodology to quantify the environmental benefits of structural steel reuse and recycling is based on the most up to date LCA standards and guidance, and industry practices, namely the standards developed by CEN/TC 350, World Steel Association’s methodology and the PEF methodology developed by EU DG Environment. Our goal was to develop and verify a formula suitable for the assessment of the constructional steel reuse that can be easily extended to other materials.

The case study included in this report describes an LCA model of a single-story industrial hall in Finland made of steel portal frames, secondary structure (purlins, side rails and bracing), and envelope from steel sandwich panels with mineral wool insulation. Life cycle assessment method chosen for the evaluation of the environmental impact follows the rules of ISO 14044 and EN 15978. The main goal is to show the potential of environmental performance and improvements through comparison of new hall construction (‘*new steel*’) and steelwork with reused steel components (‘*reused steel*’) in four scenarios. The scenarios cover situations when the building is constructed from the new or reused components, and when the components are going to be reused or recycled in the future. The differences can be clearly seen as the savings in the production stage (A1-3) when recovered steel is used in the construction, and in the demolition stage (C1-2) with more efforts for deconstruction for the future reuse. The study presents the relevance of including module D in building LCA, discussions about the impact of module D and the impact compared to other Life cycle modules and stages.

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