

# Paving the way towards circularity in the building sector. Empa's Sprint Unit as a beacon of swift and circular construction

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**Abstract.** In order to achieve the CO<sub>2</sub> targets stipulated within the Paris Agreement, future buildings must be constructed in such a way, that their emission profile will be close to zero. In order to achieve this, a radical shift towards a circular construction manner which encompasses topics like material reuse (i.e. design for multiple lifecycles), design-for-disassembly (allowing for maximum recovery of materials and minimization of construction waste) must be promoted against today's, conventional construction practices. Furthermore, the current Covid-19 pandemic has shown that buildings must be constructed in a more flexible manner, in order to be adaptable to changing needs as quickly as possible – including new types of needs. A transition to such a circular construction practice requires also new approaches for Life Cycle Assessment (LCA), taking into account issues such as the circularity or multiple life cycle of materials. Conventional LCA methods fail to deliver trustworthy results as they are designed to assess products and buildings that have only a single life cycle. In this context, a newly constructed unit, set to be the embodiment of the circular construction principle that incorporates all the above-mentioned concepts in the form of a cluster of flexible office spaces, has been integrated into the research building NEST (*Next Evolution in Sustainable Building Technologies*) – a platform located at the Empa campus in Dübendorf (Switzerland), where novel building technologies can be tested and validated under realistic conditions. Its name: *Sprint*. In this paper, the environmental performance of *Sprint* is assessed through LCA, using three different approaches – the EN15804 method, the Product Environmental Footprint method and the Linear Degressive approach – with the latter two approaches considering the circularity of materials, while each one having an own, distinctive allocation rule for the split of the impacts between the current, the previous and the subsequent lifecycles.

**Keywords:** Sprint unit, Life Cycle Assessment, Circular Economy, Sustainability Assessment

## 1. Introduction

Environmental issues associated with the building sector have been researched and well documented over the past years [1]. Context-wise, 60-80% of the global energy consumption & raw material extraction as well as 75% of the global carbon emissions [2] and 40% of waste disposed in landfills is attributed to the building sector [3]. Consequently, the construction industry's "linear" view of the building as a body that discards its own materials after the end-of-life of the building must be modified



and the deployment of so-called circular building systems (i.e. building systems that are designed for disassembly allowing for maximum material recovery and waste minimization after the end of life of the building as well as reuse of building materials and components for multiple life cycles) has to be promoted in order to alleviate the environmental impacts caused by the construction sector [4].

However currently, novel construction processes and products that are in line with circular economy (CE) cannot be easily introduced market. In addition, the Covid-19 pandemic has exposed the necessity for more flexible construction and adaptable buildings in order to accommodate new needs (such as e.g. individual office spaces) as swiftly as possible that were overlooked in the past. To this intend, Empa inaugurated in 2021 the *Sprint* unit, as a further element of the NEST building (NEST stands for Next Evolution in Sustainable Building Technologies) on the Empa campus Dübendorf, Switzerland. The NEST building is a modular research and innovation building of Empa (Swiss Federal Laboratories for material Science and Technology) and is comprised of different working and living units that are plugged into a core frame. In these various units, novel building technologies and materials can be tested and validated under realistic conditions, thus bridging the gap between the lab and the construction site, by accelerating the entry of innovative building systems and materials into the market.

The *Sprint* unit is an outcome of the collaboration between stakeholders from research (Empa), industry (Baubüro in situ AG, Bouygues E&S InTec Schweiz AG, HUSNER AG, Glassolutions) as well as the public sector (City of Dübendorf). It serves as an office unit composed of Covid-19-conform individual office spaces and exhibits in the same time how reclaimed materials and building components obtained from demolished/deconstructed building projects can be re-utilized and go hand-in-hand with appealing architectural design within the shortest possible timeframe that meets users' requirements and complies with the notion of CE. The unit is made out of a prefabricated wooden supporting structure. The wood was reclaimed from demolished buildings and was used in various forms - such as beams - in the *Sprint* unit. Moreover, the *Sprint* unit can be adapted in such a way that two individual offices can be turned into one bigger office area by removing the temporary walls, thereby rendering the *Sprint* unit as an example of flexible construction. There are two variations of temporary walls currently embedded in the unit: (i) one that is built with books and scientific magazines from the Library of Empa and Eawag, as few people visit a library today to read publications as they are available online, and (ii) one that is built by reusing carpet tiles. In both cases, these elements (books/magazines, carpet tiles) are not glued together and therefore can be de-installed with minimum effort in order to create again the big-office space. Finally, the unit has been designed for disassembly, meaning that the unit can be deconstructed easily and all building constituents can be recovered with minimum losses and either reused in other building projects or repurposed to new building products. For the first time, Empa is combining the approach of re-use and the market requirements of "fast and flexible construction", thus demonstrating that such needs in fact can be met together.



**Figure 1.** Temporary walls with books (on the left) and carpet tiles (on the right) in the Sprint unit.  
Images: Martin Zeller

From the point of view sustainability assessment, this transition to a circular construction practice creates the need for novel approaches for Life Cycle Assessment (LCA) that are able to take into account the multiple lifecycles and the circular flows of materials in a fair and transparent manner. Then today, conventional LCA approaches are not delivering credible results in such situations. In fact, they are conceptualized to assess the impacts of building products or buildings of a single life cycle only [5], whereas CE-oriented LCA needs to take into account multiple cycles of materials and products due to the recovery, repair, refurbishing, recycling and/or reuse activities occurring within a circular economy [6], resulting in cascading systems. Main challenge in such cascading systems is the allocation of credits and burdens between the various life cycles that share a specific material and the precariousness surrounding the actual occurrence of the next use-cycles of materials into the distant future, despite the fact that these cycles were planned to occur [7]. Currently, there is no universally accepted allocation approach for such studies [8].

The present study aims therefore to assess the environmental impacts and benefits of the *Sprint* unit, through the use of the LCA methodology by applying three different allocation approaches: (i) the EN15'804 method, which is currently used for the environmental performance of buildings; (ii) the Product Environmental Footprint (PEF) method that considers in the production both in-going (i.e. their recycled content) and out-going secondary materials (i.e. their recycling rates), and allocates the impacts and benefits through a combination of existing methods, while considering the market situation of the material, and (iii) the linearly-degressive approach (LDA) that allocates the impacts of virgin production and end-of-life in a linearly-degressive manner throughout all life cycles. The present manuscript is structured in the following way: Section 2 explains the applied LCA approaches in more details together with the LCA-related elements and assumptions considered, section 3 shows the results of the different LCA approaches and the final section 4 provides besides the conclusions a first list of future work that must be conducted.

## 2. Method and Materials

LCA is a standardised and established framework that assesses quantitatively the environmental impacts and benefits of a product or system over its entire life cycle (i.e. from raw material extraction till the end-of-life of a product) [9]. The application of the framework stretches across multiple organizations – from any sort of private industry to governmental institutions.

### 2.1. Applied LCA approaches

In this study, LCA calculations were performed following the guidelines of several individual LCA approaches – approaches representing the European standard EN15'804, the Product Environmental

Footprint (PEF) of the European Commission and one discussed by various researchers called the linearly-degressive approach (LDA).

- The **European EN15'804 standard** [10] is currently utilized for the systematic environmental assessment of buildings and construction products. The standard uses for the End-of-Life (EoL) allocation the so-called "cut-off" approach, meaning that the impacts associated with virgin production and recycling at the end-of-life (EoL) are assigned completely to the user of the material. Furthermore, net benefits and burdens stemming from reuse and recycling of a specific material or energy recovery can be declared by the producer in a separate section, the so-called module 'D'. Indeed, these activities in module 'D' are occurring outside of the system boundaries, hence their reporting is kept separate from the other stages of the product or system LCA. In contrast with the other standards investigated here, the EN15'804 standard only provides in a descriptive manner the considered EoL approach and thus does not contain any EoL formula. To increase the comparability with other standards, the calculation formulas provided by relevant researchers [11-12] have been used for this study and are provided in table 1.
- The **Product Environmental Footprint** (PEF) of the European Commission comprises the so-called Circular Footprint Formula (CFF) as part of the Guidance document, version 6.3 [13]. The formula in its original form is provided in figure 2. As with the EN15'804 standard, the impacts stemming from the production of virgin material is allocated to the user of the material. A major difference to the EN standard described above lies in the allocation procedure in the area of EoL. This approach takes into account both, ingoing and outgoing secondary materials (i.e.  $E_{\text{recycled}}$  and  $E_{\text{recyclingEoL}}$ ) and allocates the impacts and benefits between the supplier and the user of the recycled materials in a standardized way, based on the market situation of the material, which is represented by the allocation factor 'A'. The allocation factor 'A' ranges in values between 0.2 and 0.8. The high value of 0.8 is given when there is high abundance and low demand of a specific material such as timber. In those situations, the CFF's focus is on rewarding recycled content. On other hand, a low value of 0.2 is given when there is low offer and high demand of materials – the CFF focuses on recycling at the EoL of the product, therefore rewarding the supplier for choosing a recyclable material. When there is balance between the offer and demand of a specific material or the market situation of a material is unknown then the factor 'A' equals to 0.5, rewarding both, the recycled-content and the recyclability at the EoL. Furthermore, the CFF approach allows to quantify the benefits and burdens of all possible EoL scenarios (incineration, recycling, reuse and disposal) including those obtained from an avoided production of another material or potential energy recovery process for both closed-loop (i.e. when a post-consumer product is utilized to supply the material required for the production of the same product) and open-loop systems (i.e. when a post-consumer product is utilized to supply the material required for the production of a different product). To facilitate the comparability between the chosen standards for this study, the CFF has been re-arranged and is provided in table 1 in modular form. Furthermore, the  $E_{\text{recyclingEoL}}$  normally (i.e. in figure 2) contains the impacts of waste processing and transport to waste facility. However, since the focus of the study is to identify the differences in the assessment for the affected life cycle stages, further disaggregation of the formula has been performed by separating the waste transport impacts from the waste processing activity at EoL.

**Material**

$$(1 - R_1)E_v + R_1 \times \left( AE_{recycled} + (1 - A)E_v \times \frac{Q_{sin}}{Q_p} \right) + (1 - A)R_2 \times \left( E_{recyclingEoL} - E_v^* \times \frac{Q_{sout}}{Q_p} \right)$$

**Energy**

$$(1 - B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$$

**Disposal**

$$(1 - R_2 - R_3) \times E_D$$

**Figure 2.** The CFF formula as contained in the guidance document.

- Finally, the **linearly-degressive approach (LDA)** [12] is used by various researchers, but is not yet integrated in any standard, to the best of the authors' knowledge. Compared to the previous examined standards, the allocation of impacts from virgin production and EoL differ significantly. The impact assessment through this method requires first the definition of a specific product cascade system, represented by the 'n' parameter that stands for the number of recycling times (i.e. times that a product has been manufactured from the original virgin material). This method conforms to the so-called 50:50 allocation scheme, meaning that the recycling impact is 50% allocated to the previous lifecycle and 50% to the next one, with the exception of the impacts associated with the initial virgin material and the disposal impacts at EoL. Indeed, both these impacts are allocated in a linearly-degressive way to all product cycles in the cascade system, with the majority of the impact being attributed to the first cycle in the case of the virgin material production (as it can be seen from the factor in front of virgin material production impact  $E_v$  in table 1), and to the last cycle in the case of the disposal at EoL. Furthermore, this method does not take into account any potential burdens or benefits that can be obtained from reuse, recycling or energy recovery as done in the previously mentioned standards.

**Table 1.** Modular representation of CFF, LDA and EN15'804 methods

Stages in CFF and LDA & EN	Methods	Formula for each stage
Virgin production	EN	$(1 - R_1) \times E_v$
	CFF	$(1 - R_1) \times E_v$
	LDA	$\frac{(1-R_1) \times (2 \times n - 1) + (1-R_2)}{n^2} \times E_v$ for all except ( $R_1=R_2=1$ ) $\frac{E_v}{n}$ for $R_1=R_2=1$
Secondary material	EN	$R_1 \times E_{recycled}$
	CFF	$R_1 \times (A \times E_{recycled} + (1 - A) \times E_v \times \frac{Q_{sin}}{Q_p})$
	LDA	$\frac{R_1}{2} \times E_{recycled}$ for all except ( $R_1=R_2=1$ ) $0.5 \times E_{recycled}$ for $R_1=R_2=1$
Waste transport	EN	$R_2 \times E_{freight,w}$ (to waste processing facility) $+(1 - R_2 - R_3) \times E_{freight,D}$ (to landfill)
	CFF	$(1 - A) \times R_2 \times (E_{freight,w} - E_v^* \times \frac{Q_{sout}}{Q_p})$ $+(1 - R_2 - R_3) \times E_{freight,D}$
	LDA	$\frac{R_1}{2} \times E_{freight,w}$ for all except ( $R_1=R_2=1$ ) $0.5 \times E_{freight,w}$ for $R_1=R_2=1$
	EN	$R_2 \times E_{recycling,EoL}$

Waste processing		$+(1 - R_2 - R_3) \times E_D$
	CFF	$(1 - A)R_2 \times (E_{recycling,EoL} - E^*_v \times \frac{Q_{s,out}}{Q_p})$
	LDA	$\frac{+(1 - R_2 - R_3) \times E_D}{\frac{(1-R_1)+(1-R_2) \times (2 \times n - 1)}{n^2}} \times E_D$ for all except ( $R_1=R_2=1$ ) $\frac{E_D}{n}$ for $R_1=R_2=1$
(Recycling) Benefits	EN	$(R_2 - R_1) \times (E_{recycling,EoL} + E_{freight,w} - E^*_v \times \frac{Q_{s,out}}{Q_p})$
	CFF	Reflected in C3-C4
	LDA	Not applicable
<p>A: allocation factor of burdens and credits between supplier and user of recycled materials.</p> <p><math>Q_{s,in}</math>: quality of the ingoing secondary (recycled) at the point of substitution.</p> <p><math>E_{recycled}</math>: Consumed emissions and resources stemming from the recycling process of the recycled or reused material.</p> <p><math>E_D</math>: Consumed emissions and resources stemming from disposal of waste material at the EoL (without energy recovery).</p> <p><math>E_{freight,D}</math>: Transport from building site to disposal site.</p>		
<p><math>R_1</math>: material proportion in the input to the production recycled from a previous system.</p> <p><math>Q_{s,out}</math>: quality of the outgoing secondary (recyclable) material at the point of substitution.</p> <p><math>E_v</math>: consumed emissions and resources consumed stemming from the acquisition and pre-processing of virgin material or component.</p> <p><math>E^*_v</math>: Consumed emissions and resources stemming from the acquisition and pre-processing of virgin material and components that is assumed to be substituted by recyclable materials &amp; components.</p>		
<p><math>R_2</math>: material proportion that will be recycled (or reused) in a subsequent system.</p> <p><math>Q_p</math>: quality of the primary material.</p> <p><math>E_{freight,w}</math>: Transport from building site to waste processing facility.</p> <p><math>E_{recycling,EoL}</math>: Consumed emissions and resources stemming from the recycling process at EoL.</p> <p><math>n</math>: number of recycling times.</p>		

## 2.2. Goal and scope definition

The goal of this study is to assess the environmental impacts and benefits of the Sprint unit using three different LCA approaches (described above) and to compare the results of these different approaches for an objective judgement. For this reason, all inputs and all outputs refer directly to the entire Sprint unit and no other reference unit of measurement has been taken into account.

Furthermore, based on the goal definition, only virgin material production, recycled content and EoL handling stages have been taken into consideration for the assessment of the Sprint unit, as these stages require allocation of burdens and benefits between products in a cascading system. The use stage of the unit, although important, has been excluded from the study as not only it is equal for all three approaches but also refers to inputs (i.e. energy & water consumption, material replacement) that relate directly with the product in question – i.e. the use phase of the Sprint unit – and therefore no allocation of impacts is required. Furthermore, a thorough assessment of such an energy demand is outside the scope of this study, as the main objective is to showcase the application of different LCA approaches and their intricacies regarding allocation of burdens and benefits on a real-life project.

## 2.3. Life Cycle Inventory (LCI)

The LCI modelling enlists all necessary input and output flows of the product system under investigation. In this case it includes, the (few) virgin materials and the reused components used in the Sprint unit along with the product manufacturing process (A3), the transport of the materials from factory to the building site and from building site to the respective handling facilities after the EoL of the unit, the EoL handling of the materials as well as the avoided impact burdens and benefits stemming from the reuse / recycling or energy recovery after the deconstruction and recovery of building components of the Sprint unit. The number of cycles that have to be pre-defined for the application of the LDA, as well as the EoL handling strategy of the different construction products embedded in the unit are displayed in summarized form in Table 2. For the reused materials & components in the unit, it

is assumed that those are in the second lifecycle, while products that have partial recycled content were assumed to be in their first life-cycle.

**Table 2.** EoL handling and number of recycling times for the materials in the Sprint unit.

Cluster of materials	EoL handling	Number of cycles (For LDA)
Wooden materials	Reuse	4
Insulation	Reuse	2
Window Frame, wood	Reuse	2
Window Frame, aluminium	Reuse	2
Window glazing	Reuse	2
Bricks	Reuse	3
Paper (Books)	Reuse	1

#### 2.4. Methodological challenges

To allow for a consistent assessment of the Sprint unit using the three above described LCA approaches, all the foreground data have to be combined with respective background datasets that comply with the different methods previously described. However, the PEF method requires compliant datasets that are currently unavailable. In order to tackle this issue, the background datasets were taken from ecoinvent version 3.7.1 and its recycled-content system model, also called cut-off model. This cut-off approach of the ecoinvent database conforms to the principles of the EN 15'804 standard and can in the same time be adjusted in order to be applicable for the CFF formula. Moreover, the CFF formula can also be rearranged with the purpose of facilitating the comparison between PEF and EN15'804.

The ecoinvent database contains cradle-to-gate datasets (i.e datasets that report the modules of raw materials production, transport from extraction site to factory gate and the manufacturing process jointly), which creates an issue with a correct application of the CFF formula, because in the presence of a recycled content in the material, burdens and benefits associated with the specific recycled content have to be allocated between the previous as well as the subsequent system under study (as shown in table 1). Normally, the datasets chosen to represent the materials of the *Sprint* unit would have to be split first in order to appropriately assess the impact stemming from virgin resources, from recycled content and the avoided impact production – a strategy that has already been implemented in the past [14].

However, in the *Sprint* unit, there are entire construction products that are directly reused and not just materials that have been reclaimed and repurposed into a new product that was then integrated to the unit. Because of this, and considering that the point of substitution (i.e the point where secondary materials substitute primary materials) changes and revolves around products, the assessment of the *Sprint* unit through the CFF has been performed by taking into account the whole datasets of ecoinvent, without splitting them in order to obtain the impacts of raw materials production, transport from extraction site to factory gate and the manufacturing process separately. Even though, the proposed approach may go against what has been proposed in the past, given the fact that the point of substitution is defined by the practitioner, it has been identified by the authors for this case as the best course of action. In this case, the "manufacturing" process would consist of any potential treatment prior to the integration of the reclaimed components into the unit, but this has been excluded from the study due to lack of data. The allocation factor A in this situation was chosen based on the base material of the product (for example, wood cladding is made out of wood which is assigned an allocation factor of 0.8).

#### 2.5. Life Cycle Impact Assessment (LCIA)

In this phase, the inputs and outputs from the LCI are translated to potential environmental impacts, by choosing environmental indicators that are deemed relevant for the study. For the present study, the

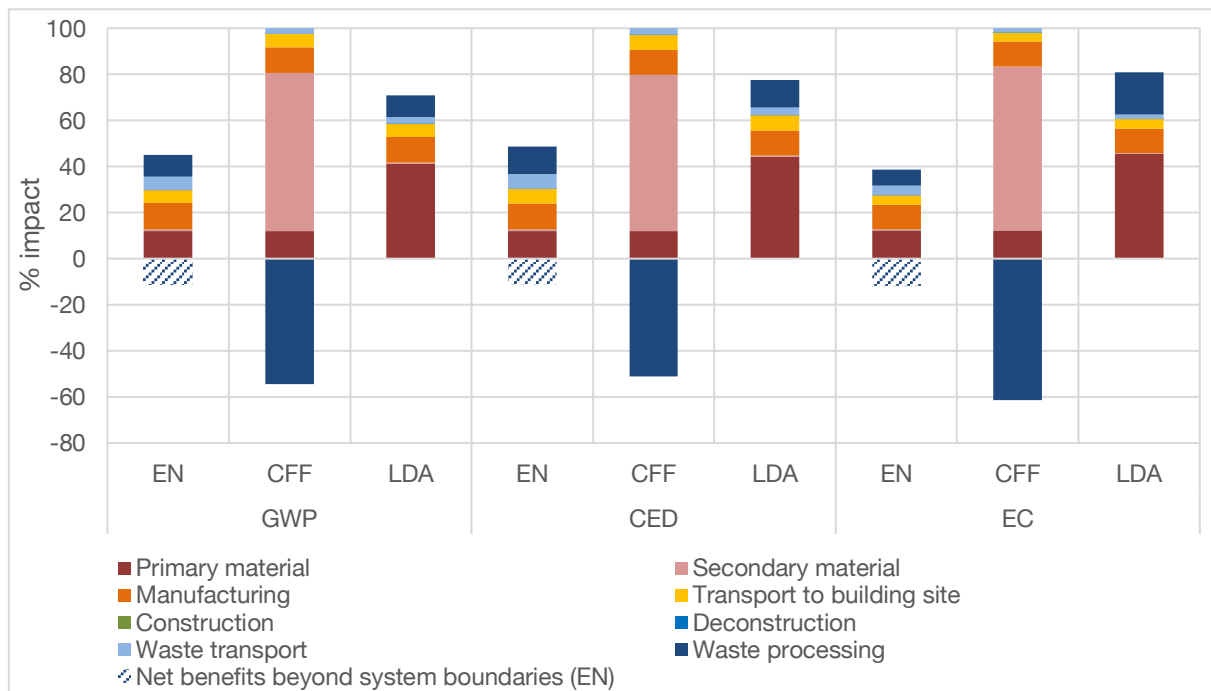
environmental indicators are used according to the guidelines of the Swiss construction industry - indicators that epitomize the most significant environmental issues in our world today – i.e.

- Global Warming Potential (GWP). This impact factor represents the carbon footprint, as it evaluates the total Greenhouse Gas Emissions (GHG) during the entire life-time of a specific product. The impact scores are reported in kg of CO<sub>2</sub> equivalents [15].
- CED (Cumulative Energy Demand). This impact factor represents the energetic footprint, as it assess the total energy (renewable and non-renewable) required for the production of a product throughout its life-time. For this study, only the non-renewable fraction is considered, again according to the Swiss construction industry. The impact scores are reported in MJ energy [16].
- UBP (Ecological Scarcity). The Swiss-based method of ecological scarcity (EC) assesses the total environmental impact in the context of LCA [17].

### 3. Results and discussion

Figure 3 shows in a summarized form the share (%) of impacts per impact factor and lifecycle for each one of the chosen LCA approaches, normalized to the highest overall contributor (in all cases the CFF). The total impacts of the *Sprint* unit through the CFF method are 38'171 kg CO<sub>2</sub>-eq for the GWP, 533'335 MJ-eq for the CED, and 5.55E+07 Eco-points for the EC indicator. The assessment of the unit through the CFF approach results in total higher impacts than the EN15'804 approach (on average 55%) and LDA (on average 29%) for all environmental indicators considered. This occurs because the modelling approach of the CFF regarding the secondary material input accounts part of the recycled materials as if they were coming from virgin production, even though they can be 100% reused. Hence, the secondary material input is the major contributor to the unit's impact, accounting for approximately 68% of its total impact when assessed with the CFF formula. For the EN15'804 and the LDA methods, the impact of secondary material input is negligible for all considered indicators (less than 1%), due to the fact that the reused components bear only the impact of transport from the building site that they were recovered to the new building site.





**Figure 3.** Percentage impact per environmental indicator and lifecycle stage for each one of the chosen LCA approaches normalized to the highest contributor.

The impacts of virgin production in the cases of the CFF and EN15'804 approaches are small (approximately 12%) due to small content of virgin material that was unavoidably used in the unit. However the opposite result occurs for the LDA, where the virgin production impacts consists on average – for all impact indicators – 43% of the total impact. This result is justified, as the impacts stemming from the virgin production of the reused components occurring during the previous lifecycle has to be allocated in a linear-degressive manner to the remaining pre-defined cycles of the component. As it can be seen from table 2, for most of the components, more than two lifecycles have been considered meaning that a significant amount of virgin production occurring in the first life-cycle has to be ascribed to the components in the Sprint unit.

The waste processing impacts are comparable for the EN15'804 and LDA – accounting for roughly 9.5% and 12% of the total impact for the GWP and CED indicator respectively – but not for the CFF approach. The EN15'804 method takes into account only the EoL processing of the reclaimed components (which in all cases is reuse and therefore the impacts again come from transport to the next building site) with the exceptions reported in table 2. The LDA takes into account 50% of the proposed EoL processing but also the impacts from the EoL of the product after the end pre-defined lifecycles – impacts that are allocated again in linear-degressive manner to the unit. For the CFF, the waste processing results in benefits, as this step considers also the environmental benefits obtained from the avoided production of a primary material. The benefits resulting from module 'D' and waste processing are non-negligible in both, the EN15804 and CFF approaches, and demonstrate their positive impacts in the case of the Sprint unit. The LDA has none because the method only considered the impacts of recycling, ignoring potential benefits resulting from reuse/recycling or energy recovery.

#### 4. Conclusion and Outlook

In this study, the innovative Sprint unit constructed mostly out of reused materials and components was assessed by using three different LCA approaches: the EN15'804 standard, the PEF method that utilizes the CFF and the LDA. The results show that in such cases, where reused components or materials that are in the 2nd lifecycle are used for the construction of a building, the EN'15804 standard underestimates

the embodied impacts associated with those materials and is therefore not recommended for such situations.

The LDA seems to provide a more "fair" assessment of the unit because part of the virgin production and EoL impacts are allocated across the different lifecycles, thus showcasing the system's perspective that is required from a CE point of view. However, the application of LDA requires a pre-defined number of future cycles, which is not only difficult to assume but also if it is not correctly evaluated, can imply reductions of the allocated impacts from virgin and EoL to the respective cycles, thus underestimating the potential impacts. Furthermore, it does not consider potential benefits from reuse and/or recycling, or from energy recovery compared to the other two methods.

Also the PEF approach provides a more fair assessment compared to the EN15'804 standard, considering the allocation of impacts and benefits based on the market situation of the materials. However, many parameters are incorporated into the CFF which results in increased complexity. Furthermore, the parameters (such as the A factor and the material quality ratios) are not defined for all materials by the creators of the method, leaving the choice of the assigned values for these parameters directly to the practitioner.

Overall, it seems evident that a transition towards circular economy requires not just engagement from the stakeholders in the building sector but simultaneously requires appropriate LCA methods that take into account the potential multiple lifecycles resulting from reuse, recycling and remanufacturing of materials in such cascading systems. Therefore, further research is required for testing the applicability of existing methods and developing appropriate LCA approaches that incorporate the principles of CE and datasets that are compatible with those approaches.

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