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Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies

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Abstract. Within the ReSOLVE framework, the concept of 'Looping' materials in an efficient way is a crucial theme to ensure environmental sustainability of circular economy. This paper investigates how current calculation practice of building LCA from the EN 15804/15978 standards affects the global warming potential (GWP) of building designs where material loops have been in focus. In this study, we calculate the environmental potentials of circular building design based on two cases; 1) a building constructed from primarily upcycled materials, and 2) a building constructed with principles of design for disassembly (DfD). Results from the two cases point to the significance of the EN standards' allocation approach in which a system's use of recycling/reuse is merited, rather than meriting a system providing recyclable/reusable materials. Hence, the upcycling strategy results in lower GWP, especially from the production stage, whereas the DfD strategy does not realize an environmental advantage within the framework of the EN standards. Results further shows that even though concrete elements are notable components of the DfD building, developing DfD-solutions for these exact elements might not be the preferred focus for optimizing the environmental benefits provided by the building. Instead, DfD focus could be on shorter-lived elements of high benefit potentials.

Keywords: Upcycling, Design for Disassembly, Circular Economy, Buildings, Allocation, LCA

1. Introduction

Circular economy has found a great appeal from business as well as research society as a concept for ensuring efficient use of resources. A comprehensive framework used for classifying circular approaches is presented by the ReSOLVE framework, which covers aspects of Regeneration, Sharing, Optimizing, Looping, Virtualizing, and Exchanging [1]. In the scope of the framework is thus a focus on the efficiency of resource provision (regenerate, loop) as well as a focus on the efficient use of resources (share, optimize, virtualize, exchange).

Life cycle assessment (LCA) has been in use for decades as a tool for documenting the performance of products and services by quantifying the related environmental impacts and resource uses. LCA is thus relevant in evaluating the circular efficiency of resources production and regeneration, because it



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enables pinpointing the preferable circular strategies to reduce environmental impacts [2]. The terminology of LCA reveals how the method already deals with product cycles, and the application potential of LCA for quantifying the looping aspect of the ReSOLVE framework is thus imminent.

Whereas general LCA guidance in accordance with the ISO 14040 series is given in the ILCD guidance [3], current European practice of building LCA is based on the European standards EN15804 and EN15978 [4][5]. These European standards reflect a long-term temporal perspective of buildings by focusing on single building systems - or loops - one at the time.

Central design strategies for looping in circular buildings are found in the concepts of ‘upcycling’ of materials and in the ‘design for disassembly’ (DfD), which represent the concepts of input circularity and output circularity to a building system. Some existing LCA studies deal with building design concepts of upcycling [6][7] and concepts of design for disassembly/reuse [8][9][10] with promising results on eco-efficiency potentials for both strategies. In the literature, however, the two concepts are treated as single cases with suitable allocation practices applied from case to case. Hence, there is a lack of literature showing how the two design concepts perform within the framework of a common allocation approach, such as the one defined in EN 15804/15978.

This paper investigates how current calculation practice of building LCA from the European standards affects the results of building design where circularity and material loops have been in focus. In this study, we calculate the environmental potentials of circular building design based on two cases; 1) a building constructed from recycled/upcycled materials, and 2) a building constructed with principles of design for disassembly (DfD). We discuss the allocation approach and its implications on results, and we point to the factors of the allocation that dis- and/or encourages the different ways of designing buildings with a focus on closing material loops.

2. Method

2.1. LCA modelling details of study

The functional equivalent of the studies are set as 1 m² of residential gross floor area per year.

The process-based LCAs of the two buildings include the following life cycle stages as defined in the EN 15978 standard: A1-A3 production of building materials, B4 replacement of building materials during use stage, C3-C4 waste treatment and disposal of materials at end-of-life. Furthermore, module D is included, however for the DfD building only. Module D expresses the net benefits and loads from the reuse, recycling and recovery of materials in the next product system. In effect, this corresponds to quantifying impacts and avoided impacts from the next loop(s) for the building materials. The benefits and loads are determined when materials leave the system under study at the replacement stage as well as at the building’s end-of-life stage. All benefits and loads throughout the life cycle of the building are usually summed and reported in one single number as module D impacts.

Inventory system boundaries include foundations, structural frame, external walls, doors, staircases, internal walls, windows, roof, floor and ceiling. Technical systems and external works are not included. Neither are connectors, brackets etc. from the building elements. Inventory data originates from initial designs by the buildings’ architects. Hence, only sketches of the buildings form the bases of the assessment, which means that amounts and types of insulation materials and windows are estimated for the DfD building.

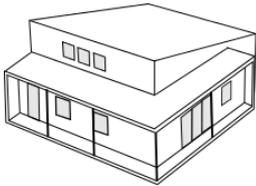
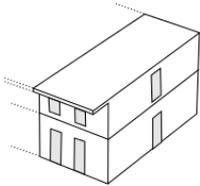
Both buildings are modelled in the Danish LCAByg tool [11] that builds on a translated version of (mainly) generic LCIA data from the Ökobau database version 2016 [12]. The reference study period of the buildings is set to 120 years following the Danish guidelines on service lives of buildings [13]. Same report specifies the applied service lives for materials replaced during the use stage (module B4).

For reasons of simplicity only results of the indicator global warming potential (GWP) are reported in this paper.

2.2. Case study buildings

Details of the two buildings assessed for current study are summarized in Table 1. Note that for this study only embodied impacts are investigated, not operational impacts from heating and electricity. However, both buildings are constructed following the building class 2015 of the Danish building regulation, which means that the expected operational energy use is at identical levels.

Table 1. Details of case buildings.

	Upcycle building	DfD building
Type	Residential, single-family	Residential, multi-family
Heated floor area, m²	129	77
Description of building	1-storey house with structural system of steel (shipping containers), light shell and built-up roof	2-storey apartment block concept of pre-cast concrete structure with a tile cladding shell and built-up roof
Upcycling/DfD strategies employed	Direct reuse of shipping containers as constructive elements. Direct reuse of concrete strip foundations, EPS, construction wood, windows and facing tiles. Material recycling of gypsum boards and aluminium	Elements designed for 2 service lives: constructive elements (concrete) designed for disassembly; façade system, gypsum and wood wool boards installed with rails and brackets; carpet tiles with take-back cleaning service and resale
Specification of 10 most prominent amounts of building materials (weight/volume)	102 m ³ Cellulose fibre ins. (45 kg/m ³) 159 m ² Aluminium sheet for roof (0.7 mm) 5.9 m ³ Construction wood 200 m ² Wood-plastic composite cladding 8000 kg Steel profile (shipping containers) 710 m ² Gypsum boards (12 mm) 295 m ² OSB boards (22 mm) 31 m ² Windows (triple-glass) and frames 5 m ³ Facing tiles 6 m ³ Glass foam insulation	7.6 m ³ Concrete C50/60 (hollow core slabs) 6 m ³ Concrete C35/45 (ext. wall elements) 155 m ² Tile for façade cladding (35 kg/m ²) 69 m ² Wood wool boards (25 mm) 70 m ² Carpet tiles, nylon 8.3 m ³ Expanded Polystyrene 30 m ³ mineral wool insulation (26 kg/m ³) 13 m ³ mineral wool, roof ins. (145 kg/m ³) 21 m ² Windows (triple-glass) and frames 800 kg aluminium profile for façade system
Illustration of case building		

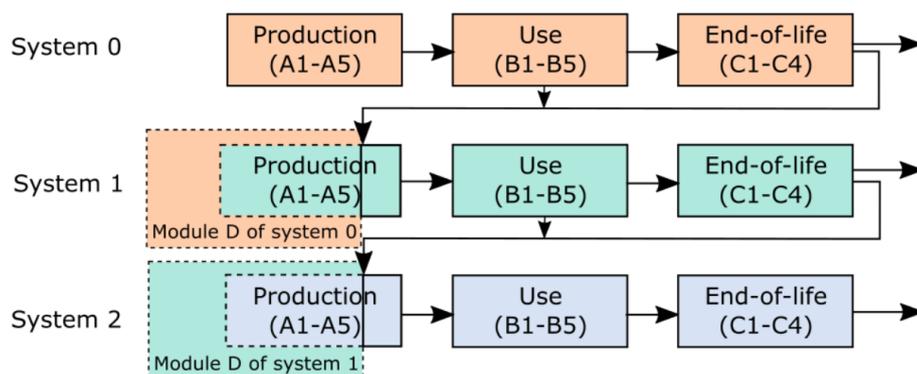


Figure 1. Principle of distribution in the 100:0 allocation approach of the EN 15804/15978 standards.

2.3. Allocation details in study

Allocation of impacts from production and end-of-life are calculated according to the 100:0 (or ‘cut-off’) approach of the EN 15804/15978. From this follows that environmental impacts are distributed as illustrated in Figure 1. In the case where system 1 is the assessed building, recyclable items (upcycled materials) from system 0 are burden free as input circularity to system 1, except for the processes of remanufacturing the materials. Recyclable items from system 1, i.e. output circularity (DfD) avoids production impacts in system 2, and these benefits for system 2 are reported as module D of system 1.

LCIA data gaps are present for the upcycled materials, i.e. the aggregated impacts from processes taking place between the end-of-waste state of the previous system and up to the production/re-manufacturing of the product in the system under study. Market prices of new and upcycled materials are used as proxy for estimating impacts associated with these processes. Hence, impacts of upcycled materials are calculated from data on virgin material multiplied with an upcycle-factor that expresses the relationship between prices of upcycled products and the total price of the material in a 2-loop system, where the material is sold initially in the first loop, then sold as upcycled and later as waste material in a second loop, i.e:

$$Fu = \frac{Pu}{Pu+Pi+Pw} \quad (1)$$

Where Fu is the upcycle factor, Pu is the price of the upcycled product, Pi is the initial price of the virgin product and Pw is the price of the waste after use [14].

Table 2 specifies the upcycle-factors used for the calculation of specific materials and products. Material recycling are, in some cases, e.g. aluminium or OSB boards, common industrial practice. Generic data of Ökobau can be expected to already incorporate the recycling benefits of those cases although documentation about this is limited. Hence, to avoid double counting of recycling benefits in current study, the upcycling factor is only applied to materials where direct reuse or recycling is judged not to represent common industrial practice. The end-of-life of upcycled materials in the Upcycle building are assumed parallel to regular Danish end-of-life practice [11].

Table 2. Upcycle factors of products and materials.

Product/material	Upcycle factor of material production
Concrete strip foundation	0.12
Shipping container	0.12
Expanded polystyrene	0.35
Construction wood	0.14
Wood-plastic composite	0.80
Gypsum boards	0.35
Window glass	0.12
Window frames	0.67
Facing tiles	0.10

Scenarios for the DfD elements of the DfD building are shown in Table 3 for the modelling of uses available in the next product system. The DfD products chosen for assessment are the products where producers, as part of the DfD building project, stated their products’ potential for servicing two service lives. The materials for reuse are assumed to displace virgin-based products in module D at the percentage given in Table 3. Remanufacturing/adaptation processes of products at the start of their second service life are not taken into account in the calculations for this study.

Table 3. Scenarios for modelling of reuses of DfD elements. Scenarios for concrete elements are based on Eberhardt et al [9]. Other values are based on estimates.

Building element	Materials for reuse in 2 nd system (%)	Service life per life cycle (years)
Concrete beams	80	120
Concrete roof hollow core slabs	60	120
Concrete floor hollow core slabs	90	120
Concrete walls	80	120
Façade system, battens, alu profiles	80	120
Façade system, clay tile	80	60
Wood wool ceiling boards	60	60
Gypsum wall boards	40	50
Carpet tiles	30	10

3. Results

Results of the global warming potential of the Upcycle building and the DfD building are presented in Table 4. Note that the Upcycle building construction is calculated in two versions, one (regular construction) covering the generic material data of the construction and the other where upcycle factors on materials from Table 2 are applied. The DfD building's results are calculated from generic materials data and present the benefits of next product system (module D) separately in accordance with the EN 15978 approach.

Table 4. GWP results of functional equivalence of the Upcycle building and the DfD building. Module D result of the DfD building is reported separately in parentheses.

Construction	GWP in kg CO ₂ -eq/m ² /year
Upcycle building – regular construction	4.7
Upcycle building – upcycled construction	3.6
DfD building	6.7 (-2.4)

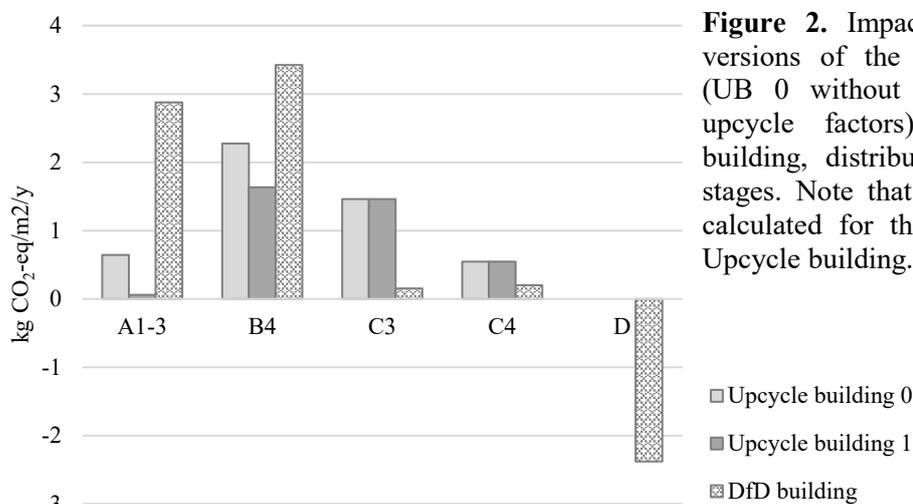


Figure 2. Impacts from the two versions of the Upcycle building (UB 0 without and UB 1 with upcycle factors) and the DfD building, distributed on life cycle stages. Note that module D is not calculated for the versions of the Upcycle building.

Figure 2 presents details of the life cycle stages in the calculated versions of the Upcycle building and the DfD building. The low impacts of the upcycled construction in the production stage A1-A3 is a combination of the low impacts from upcycled materials and the notable use of wood products with negative GWP. Replacement and incineration of wooden products, hence release of the stored carbon, result in relatively large impacts from the replacement stage (B4) and end-of-life stages (C3-C4) in both versions of the upcycle building. The DfD building causes notable emissions in production (A1-A3) and replacements (B4) compared with the Upcycle buildings. The DfD building entail potential savings in module D when (only) directly re-usable elements are assumed to have a 2nd life in a next product system as specified in Table 3. The module D potential benefits of next product system corresponds to 36 % of the impacts from the building’s other life cycle stages in total.

Figure 3 presents details of the life cycle stages of the DfD building. The figure shows the time line of the construction’s expected service life and the GWP ‘pulses’ from replacements. Furthermore, the figure shows, via the module D potentials, at which points in time DfD products are sent for reuse in other product systems, and the expected benefits these products can bring in a next system by replacing virgin-based products.

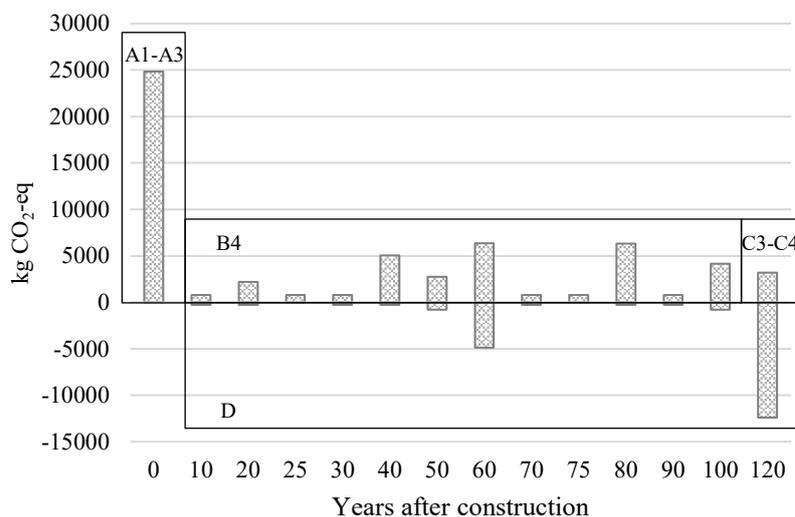


Figure 3. Details of the DfD building’s life cycle stages and the GWP ‘pulses’ at certain points in time after the construction.

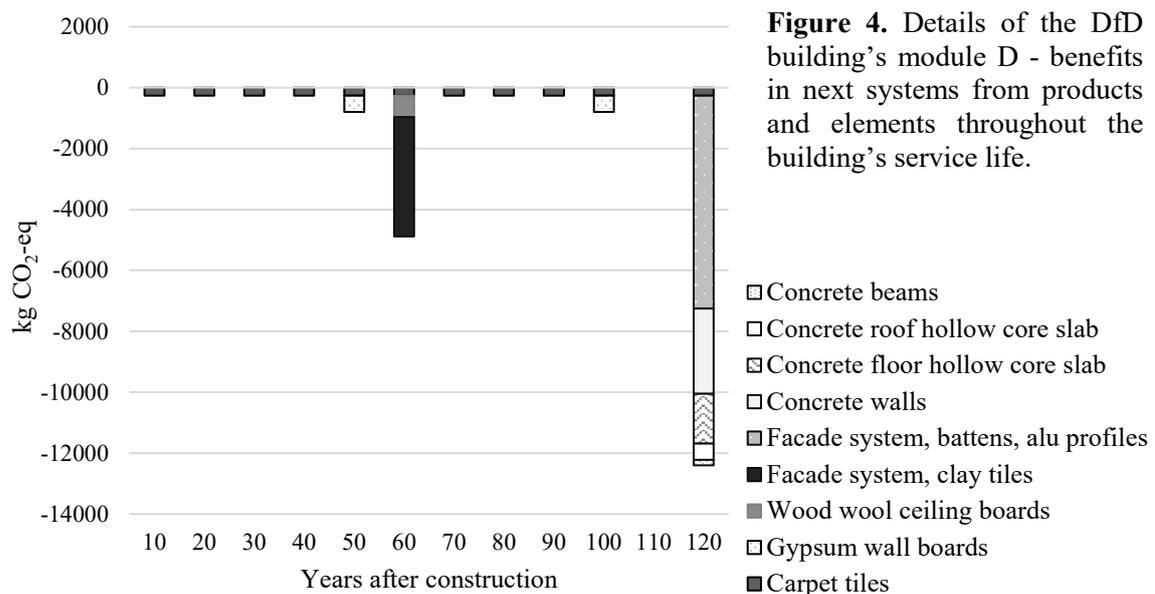


Figure 4. Details of the DfD building’s module D - benefits in next systems from products and elements throughout the building’s service life.

Figure 4 displays the significance of the building elements sent for direct re-use in other product systems. Apart from the decade-frequent replacement of re-usable carpet tiles, the notable pulses of benefits happen after 60 years when the ceramic tiles are reused and after 120 years when the concrete elements and aluminium profiles are reused. The concrete-based elements of the construction are contributing with 25 % and the aluminium profiles with 34 % of the DfD building's total benefits in next product systems.

4. Discussion

Amounts of insulation and windows for the DfD building are estimated, and thus subject to uncertainties regarding the inventory. Furthermore, the economic-based upcycle factors of the Upcycle building calculations is an important methodological choice in obtaining the results presented in this paper. There could be other ways of dealing with the data gap on recycled materials, which can be further explored in future research. However, even though inventory and method may affect the accuracy of results, the analysis showcase the standardized environmental assessment approach and the significance of allocation practice all the same.

Evidently, the GWP of the Upcycle building is lower than that of the DfD building. Some causes of the Upcycle building's better GWP results can be ascribed the general construction and the material choices, i.e. light frame construction with extensive use of wood-based materials (with carbon storage). However, the allocation approach of the EN 15804/15978 standards specifically promotes a system's use of recycling/reuse rather than a system providing recyclable/reusable materials by including the merits of the first strategy, but not the second strategy, to the system under study. Although module D captures the environmental benefits of the DfD strategy, it does so separated from the system's actual results, in a fashion that clearly marks the benefits as potential rather than factual, and furthermore belonging to the next system and not the system under study. The 100:0 allocation of the EN standards thus focuses on the immediate impacts rather than the impacts (potentially) happening in 120 years and encourages current low-emission design by a risk-averse approach [15] in line with the polluter-pays principle.

The scenario-based life cycle stages, i.e. the replacements (B4), end-of-life (C3-C4) and module D are notable contributors to the GWP of both building cases. These life cycle stages are subject to uncertainties about the future processes. Hence, the prolonged time perspective of 120 years bears the likely risk that modelled scenarios will be far from reality. However, even at shorter assessment spans, the separated reporting of module D ensures a conservative approach where these speculative benefits do not 'greenwash' the overall results, but merely puts perspective on the potential after-life of the materials.

Figure 4 reveals how most contributions to module D is situated at the end-of-life of the building system in 120 years. However, recurring replacements of materials and elements throughout the service life also delivers materials for reuse, hence adding to the benefits in module D. Thus, module D's potential benefits are, in effect, relevant not only at the demolition stage of the building but also at every point in time a building product is being replaced. Only products/elements for direct reuse are considered in these calculations. However, future research on DfD in buildings could focus on shorter-lived elements of high benefit potentials. In this way it would be possible to address potentials that are not so far distanced in the future but timely relevant to promote the sustainability of the built environment.

5. Conclusions

This study quantifies the 'looping' potentials of two circular strategies applied to building design, upcycling and DfD, in the assessment practice of the European standards EN 15804/15978.

The 100:0 allocation approach of the standard means that the upcycling strategy results in lower level GWP, especially from the production stage, whereas the DfD strategy does not realize an environmental advantage within the framework of the EN standards. The standards thus represent a focus on lowering current emissions rather than crediting (potential) future emission savings to current systems.

Current analysis of module D contribution in a DfD building furthermore highlights the environmental importance of ensuring ‘looping’ of specific materials. Hence, the direct reuse of 800 kg installed aluminium frames in the building is the single most contributing product to the module D benefits. Thus, even though the concrete elements are notable components of the building, in weight as well as volume, developing DfD-solutions for these exact elements might not be the preferred focus for optimizing the environmental benefits provided by the building. Instead focus could be on shorter-lived elements of high benefit potentials.

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