Comparing life cycle assessment modelling of linear vs. circular building components

Malabi Larsen, Leonora Charlotte; Birgisdottir, Harpa; Birkved, Morten

Published in:
SBE19 Brussels - BAMB-CIRCPATH "Buildings as Material Banks - A Pathway For A Circular Future" 5–7 February 2019, Brussels, Belgium

DOI (link to publication from Publisher):
10.1088/1755-1315/225/1/012039

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Comparing life cycle assessment modelling of linear vs. circular building components

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.

Comparing life cycle assessment modelling of linear vs. circular building components

L Eberhardt [1], H Birgisdottir [1] and M Birkved[2]

[1] Danish Building Research Institute, Department of Energy Efficiency, Indoor Climate and Sustainability, Aalborg University, A. C. Meyers Vænge 15, 2450 Copenhagen SW, Denmark
[2] SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology and Environmental Technology University of Southern Denmark, Campusvej 55, 5230 Odense-M, Denmark

lcl@sbi.aau.dk

Abstract. As the construction industry consumes vast amounts of natural resources and in return produces large waste quantities, interest in circular economy has emerged as the means to reduce sector specific environmental impacts meanwhile ensuring continued economic growth. Life cycle assessment is a scientifically based and ISO standardized method for assessing resource consumptions and environmental impacts of products, systems or services over its entire life cycle and has been increasingly used in the construction industry and in some recently published circular economy studies. However, circular economy brings about 'rethinking' present well established building systems as well as the future life cycle scenario of these. Hence, this also means rethinking how life cycle assessments are performed on these building systems as it is suggested by some that life cycle assessment is a linear environmental impact assessment approach that misfits the circular economy idea of multiple product life cycles. The paper at hand aims at visually demonstrating variations in life cycle environmental impacts and material flows when supplying buildings with linear components compared to prospective circular designed building components for reuse and recycling and how they are modelled in life cycle assessments.

Keywords: Life cycle assessment (LCA), Design for Disassembly (DfD), Circular Economy (CE), buildings, environmental performance, reuse

1. Introduction

The construction industry is responsible for significant environmental impacts, resource consumption and waste production contributing to the rapid depletion and inefficient use of natural resources [1]. As the demands for resources from an increasing world population and urbanisation continues to grow so will these issues if present industry practices are continued. Circular economy (CE) has been suggested as it seeks to extend resource life through e.g. reducing, reusing and recycling thereby potentially increasing resource efficiency, decreasing environmental impacts and maintains material and product value [2]. Using CE strategies such as design for disassembly (DfD) to 'rethink' present well established building systems' life cycle design and management, extraction and availability of buildings' massive stock of potential future resources could be improved. As political and industrial CE initiatives are beginning to form at a greater extent [3–5] understanding buildings complex life cycle material metabolism and resulting environmental impacts becomes increasingly important to identify CE potentials (i.e. alternative reuse and recycling scenarios) within the building stock and ensure meaningful waste and resource management initiatives. One way to achieve this understanding is by performing life cycle assessment (LCA) [6]. Although LCA tools, methods and standards exists and the method is increasingly used within the construction industry as well as in some recently published studies seeking to demonstrate benefits of CE [7–9], the practical application of LCA for decision support is limited as the decision makers lack knowledge to both perform and interpret environmental information. LCA is also not fully suitable for meaningful interpretation of results within a CE setting as it only analyses environmental impacts of the primary function of individual product systems [6]. Hence, CE also means 'rethinking' how LCAs are performed and interpreted as there are no readily applicable tools that can assist in assessing the environmental impacts and benefits of CE, support decision making and create motivation for industry stakeholders.

To close this knowledge gap between research and industry the paper at hand suggests a method for visually communicating scientific life cycle environmental impacts and material flows and how they are modelled in LCA. A LCA is performed comparing linear design versus a prospective circular DfD for reuse and recycling of three common building components based on existing market products: a concrete column, a window and roof felt with a long-, medium- and short service life respectively. The LCA results are then reported and interpreted using a visual dissemination approach that highlight the potential for circular material loops of the three building components and at which point in time these will occur followed by a discussion of the identified challenges.

2. Methodology

2.1. Case study

As concrete elements are often casted together it is impossible to separate them for reuse without damage. Instead, the elements are crushed into concrete gravel for use as road filling and the reinforcement steel recycled into new steel products. However, the Finnish company, Peikko, produces large bolted mechanical steel connections for concrete elements enabling disassembly for reuse in subsequent buildings thereby prolonging the elements' service life and avoiding environmentally burdensome production of new concrete elements [10]. Windows are likewise disposed of by crushing and collecting the glass for recycling and either landfilling or incinerating the window frame. However, the Danish window manufacturer, Velfac, has designed their window series, Velfac Energy 200, in such a way that the individual materials can easily be disassembled and replaced/maintained or extracted for energy recovery or potential recycling. However, the frame can also be reused in its original form and only the glass replaced [11]. Roof felt is most commonly disposed of through landfill, energy recovery or recycling for asphalt roads. However, a recycling program at the Danish roof felt manufacturer, Viva Tagdækning A/S, extracts the bitumen and slate through shredding and heating for production of new roof felt [12].

Although, high recycling rates are well established for construction and demolition waste in Denmark, each of the above stated products are modelled applying a traditional (linear) end-of-life scenario, A, reflecting worst case practice i.e. landfill and a DfD scenario, B, reflecting best case practice based on the already existing marketed solution previously mentioned enabling a higher degree of recycling or reuse, see table 1. However, for the reusable DfD column the end-of-life scenario at its' final disposal is the same for scenario A and B. Material losses when extracting materials for recycling are assumed for both the column, roof felt and window glass. However, as the individual window frame parts are easily retrieved 100% recycling and energy recovery is hence assumed.. Althoug, Velfac states a window service life of 50 years the service life of the glass was set to 25 years and 50 years for the frame according to [13].

Table 1. bill of materials.

Component	Material	Mass [kg]	End-of-life A 1st and 2nd use	End-of-life B	
				1st use	2nd use
420x420x3500mm peikko column Service life: 80 years	Reinforcement steel	76	99% recycling with no substitution, 1% landfill		
	Steel connection	26[a]			
	Concrete	1489	90% recycling substituting virgin gravel, 10% landfill		
1230x1480mm Velfac energy 200 window Service life of frame: 50 years Service life of glass: 25 years	Glass	32.3	90% recycling substituting white packaging glass from virgin materials, 10% landfill		
	Wood	10.3	100% landfill of frame	100% reuse of frame	100% recycling substituting virgin wood chips
	Aluminium	4.8			100% recycling, substituting virgin aluminium
	Steel	0.9			100% recycling with no substitution
	Zink	0.3			100% recycling substituting virgin zink
	PVC	1.1			100% energy recovery by incineration substituting Danish energy grid mix
	Rubber	0.7			100% energy recovery by incineration substituting Danish energy grid mix
1 m² Icopal Top 500 P roof felt Service life: 15 years	Bitumen	4.0	100% landfill	90% recycling replacing virgin bitumen, 10% landfill	
	Slate	1.1			
	Polyester	0.2		100% energy recovery by incineration substituting Danish energy grid mix	

[a] Extra steel modelled for the joints in the DfD scenario of the column.

2.2. Life cycle assessment

The embodied carbon of each component was assessed following the LCA methodology stated in the standard EN 15978 using the openLCA v1.4 software and baseline characterization factors from the Centre for Environmental Studies (CML) baseline 2001. The functional unit was set to provide the function of each of the components across two component life cycles based on the component service life stated in table 1. The life cycle inventory (LCI) of the background system was based on the Ecoinvent 3.2 database using system processes to get aggregated results and the foreground system was compiled using the manufacturers' product specifications stated in table 1. The system boundaries include production of the building materials, waste recovery for reuse, recycling or incineration and disposal by landfilling at end-of-life, and credits for potential reuse, energy recovery and recycling of materials and components in a next product system. Embodied carbon for transportation of the DfD column has been included and set to the longest possible transportation distance in Denmark of approximately 480 km. Allocation of environmental impacts and credits are modelled following the 100:0 (cut-off) approach of EN 17978. The EN 15978 standard states that crediting of reuse and recycling should be reported separately [14]. As these credits result in a negative embodied carbon,

IOP Conf. Series: Earth and Environmental Science 225 (2019) 012039 doi:10.1088/1755-1315/225/1/012039

when included in the LCA results, they dilute the environmental embodied carbon. However, when excluded from the LCA results the potential of CE becomes invisible. In other words, the LCA does not promote CE initiatives such as reuse or recycling. Thus, the crediting of reuse and recycling has been included, however, reported in a detailed manner so the exact origin of the impacts and credits becomes evident. To avoid double counting, credits originating from materials that are either recycled or directly reused (i.e. shared between the use cycles) in both the next product system stage of the first use cycle as well as the production stage of the second use cycle, crediting only happens in the production of the second use cycle as production using virgin materials has been avoided. However, materials that leave the product system entirely for recycling or energy recovery elsewhere are credited in the next product system of the two use cycles of the products studied here. Environmental credits of different end-of-life scenarios are modelled as substitution of either virgin materials or Danish energy grid mix as stated in table 1. As steel is assumed produced using scrap steel, no environmental crediting is achieved when recycled again [14]. Hence, environmental impacts and credits are distributed as shown in figure 1, figure 2 and figure 3.

3. Results

The temporal material life cycle environmental embodied carbon and material flows resulting from the LCA study of the linear versus the circular design of the column, window and roof felt are shown in figure 1, figure 2 and figure 3 respectively. End-of-life and next product system material flows are represented in the figures with curved arrows (recycling outside the product system), vertical arrows (energy recovery), horizontal arrows (recycling in subsequent use cycle) and horizontal arrows with an ‘x’ (landfill). The size of the arrows approximately represents the amount of the input flow that is directed for recycling, energy recovery or landfill.

From figure 1 it is seen that the highest material related embodied carbon comes from production of concrete for both column A and B. Since column A is not suitable for reuse at the first use cycles’ end-of-life, supplying a second use cycle with the same kind of column requires the production of a new one. Hence, the embodied carbon of column A originates from production at year 0, treatment of 90% concrete and 99% reinforcement steel for recycling and 10% concrete and 1% concrete for landfilling at end-of-life in year 80. Furthermore, embodied carbon comes from the production of a new column in year 80 and repeating the aforementioned end-of-life scenario in year 160. In comparison, the embodied carbon of column B comes from production at year 0, transporting it 480km to a subsequent building in year 80, treatment of 90% concrete and 99% reinforcement steel for recycling and 10% concrete and 1% reinforcement steel for landfilling at end-of-life in year 160. The embodied carbon of producing column B at year 0 is slightly higher compared to column A due to the use of extra steel for the connections allowing assembly and disassembly. The negative embodied carbon occurring at year 80 and 160 is a result of avoided embodied carbon due to recycling of the concrete and reinforcements steel substituting use of virgin materials. From the accumulated embodied carbon it becomes apparent that reusing column B to supply two life cycles is less burdensome compared to producing two columns of type A to supply the same two life cycles.

Figure 2 shows that the highest material related embodied carbon comes from production of glass and aluminium for both window A and B. Presently, the 25 year service life of the glass is the determining factor for replacing an entire window, hence, supplying a second use cycle with the same kind of window requires the production of a new one. Thus, embodied carbon from window A originates from production at year 0, treatment of 90% glass for recycling and the remaining materials for landfilling at end-of-life in year 25. Furthermore, additional embodied carbon comes from the production of a new window in year 25 and repeating the aforementioned end-of-life scenario in year 50. The negative embodied carbon occurring for window A at year 25 and 50 is a result of avoided embodied carbon due to recycling of the glass substituting use of virgin materials for packaging glass. In comparison, as window B can be disassembled the frame consisting of steel, rubber, wood, zink, aluminium and PVC can be reused in year 25 whereas the glass must be replaced with new glass.

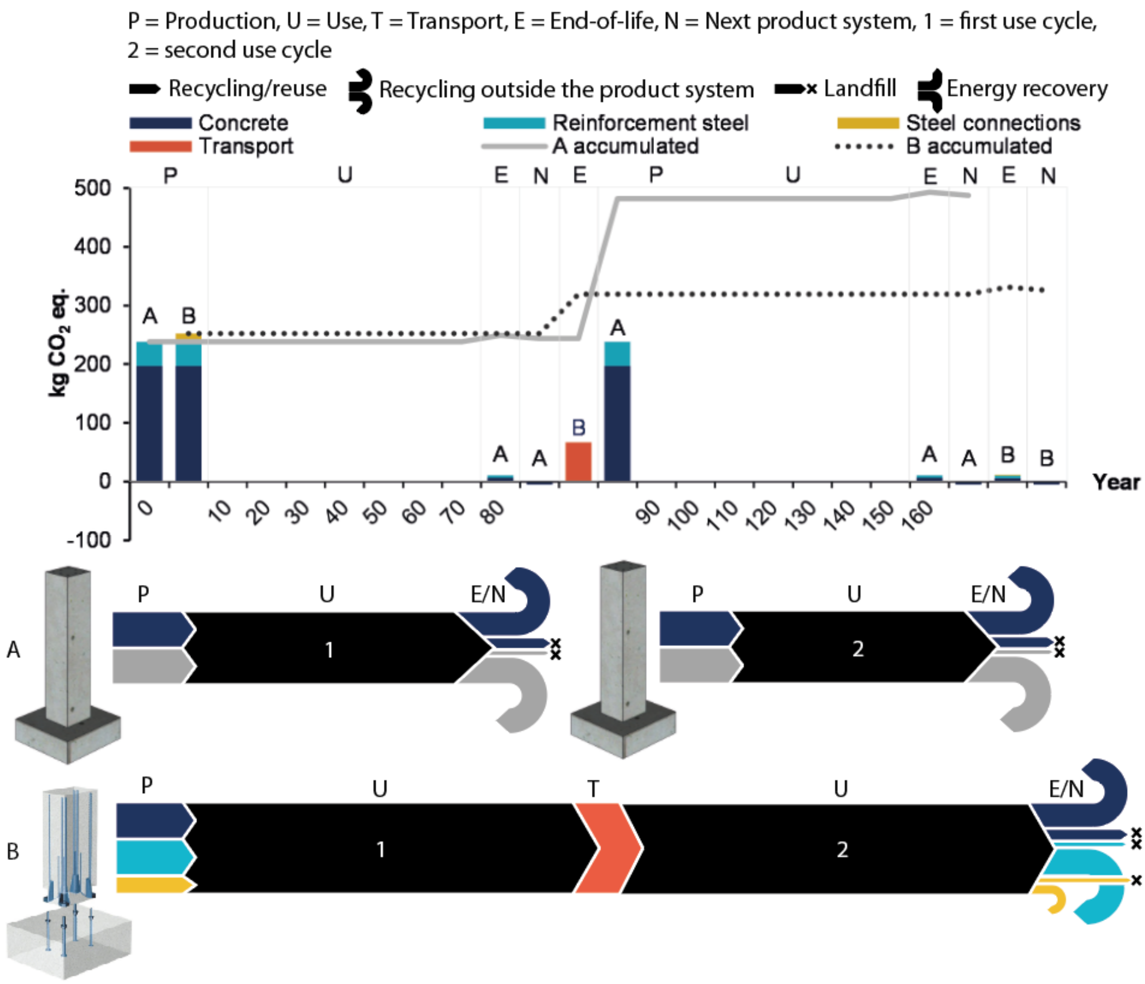

Figure 1. Comparison of life cycle environmental embodied carbon and material flows of a traditional column and a DfD column.

As a result, the embodied carbon from window B comes from production in year 0, treatment of 90% of the glass for recycling and 10% glass for landfill as well as the production of new glass for the window in year 25. As the quality of the frame of window B will have degraded after 50 years it must be disposed of. Due to the ease of separating all components of the window the materials can be diverted from landfill to recycling or energy recovery compared to window A. Hence, the embodied carbon emission from window B's end-of-life at year 50 comes from treatment of 90% glass and 100% wood, aluminium, steel and zink respectively for recycling and 10% glass for landfill, furthermore, incineration of 100% of the PVC and rubber. The negative embodied carbon occurring for window B at year 25 and 50 is a result of avoided embodied carbon due to recycling 90% of the glass in year 25 as well as recycling 100% of the wood, aluminium, steel and zink respectively substituting use of virgin materials, furthermore, energy recovery from incineration of 100% of the rubber and PVC. Whereas, the negative embodied carbon appearing in the production of the window comes from biogenic CO_2 that has been bound to/stored in the wood yielding a negative impact value when modelled in LCA. From the accumulated graph of window A compared to B at year 50 it becomes apparent that reusing the window frame is preferable over production of a completely new window.

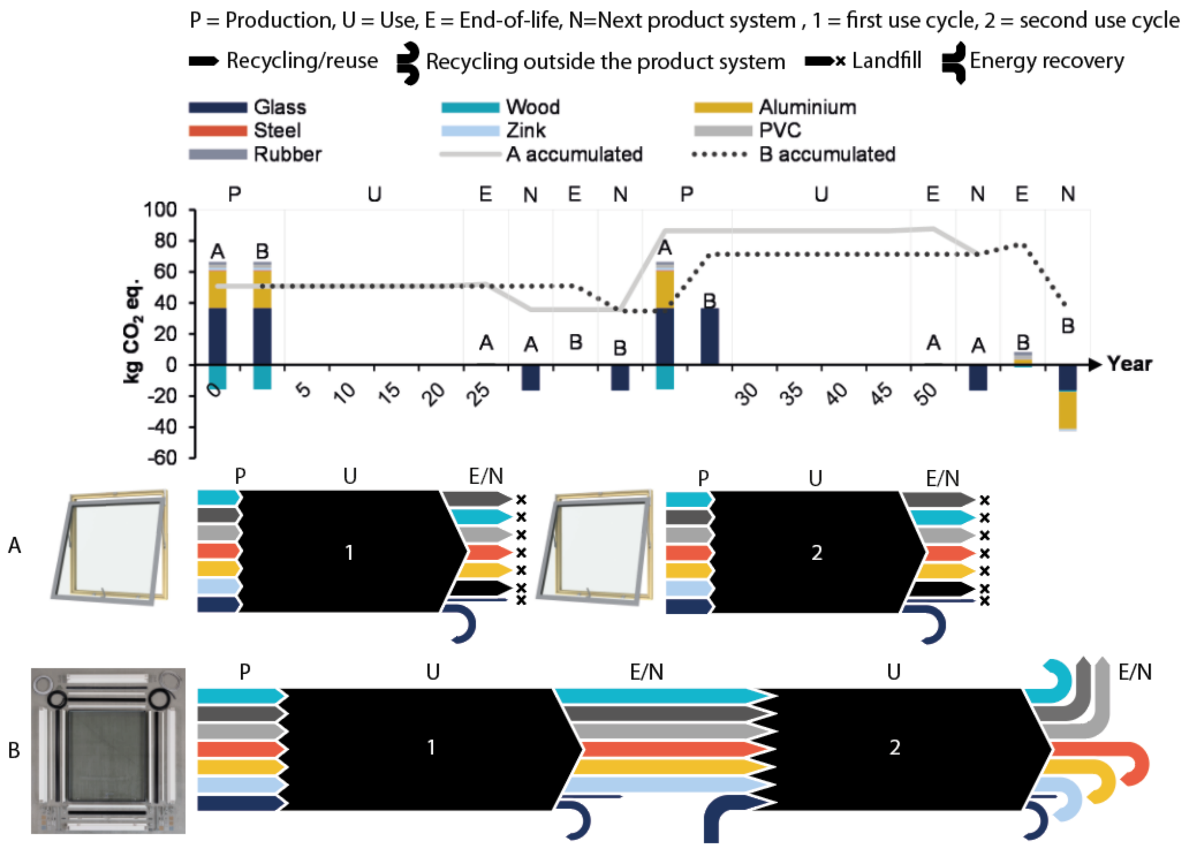

Figure 2. Comparison of life cycle environmental embodied carbon and material flow of a traditional window and a DfD window.

For the roof felt, figure 3 shows that the highest material related embodied carbon comes from production of bitumen for both window A and B. If the roof felt is disposed by landfill at the first use cycles' end-of-life, supplying a second use cycle requires the production of new roof felt. In this case, the embodied carbon emissions from roof felt A originates from production at year 0, landfilling of the roof felt at its'end-of-life in year 15, production of a new roof felt in year 15 and landfilling of the roof felt at the second use cycles' end-of-life in year 30. In comparison, using the recycling process of Viva Tagdækning A/S a large percentage of the slate and bitumen can be redirected from landfill into the production of a new roof felt. However, the quality of the polyester will have degraded after 15 years and must be replaced with new polyester felt resulting in input flows for production of new polyester felt at the second use cycle. Hence, the material embodied carbon of roof felt B originates from production at year 0, treatment of 90% bitumen and slate for recycling and 10% for landfilling at the end-of-life in year 15, the production of new roof felt using 90% recycled bitumen and slate and 10% new bitumen and slate, furthermore, treatment of 90% bitumen and slate and 10% for landfilling at the end-of-life in year 30. The negative embodied carbon of roof felt B occurring at year 30 is a result of avoided embodied carbon due the assumption that the 90% bitumen and slate can be recycled once again in new roof felt in a subsequent system substituting virgin material for production. However, the bitumen could potentially also be recycled in the production of new roof felt in a third use cycle keeping these material flows within a product loop. A very small negative value also occurs at year 15 due to energy recovery from incineration of 100% polyester. The benefit of diverting materials from disposal into the production of a new roof felt becomes clear from the much lower accumulated embodied carbon emissions of roof felt B compared to A.

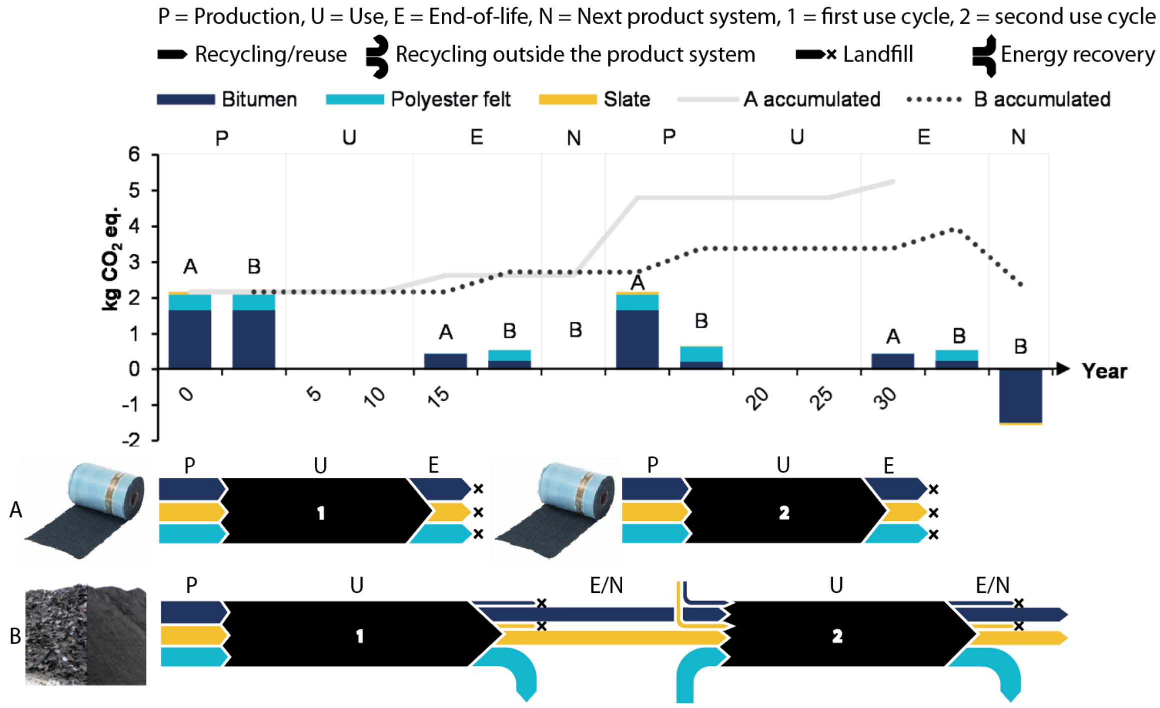

Figure 3. Comparison of life cycle environmental embodied carbon and material flow of traditional roof felt and recyclable roof felt.

4. Discussion and conclusion

From figure 1-3 material flow and the potential for and of CE becomes immediately visible to a non LCA practitioner compared to traditional LCA results which requires further interpretation and reporting to translate its meaning to industry stakeholders for them to base decisions on. Additionally, it becomes clear that the potential benefit of reusing and recycling the materials and components is not gained immediately but at the point of future retrieval i.e. in the case of the column this happens 80 years into the future. What is not obvious, however, is the future circumstances in which the environmental impacts and future reuse or recycling will occur along with how long these material loops can be maintained as the changes in the inherent properties of the materials resulting from reuse and recycling are not taken into account as it is still not determined how to account for it within LCA [7]. Furthermore, it becomes apparent that the material loops are not 100% circular as additional input materials are needed to uphold the material loop due to system losses between the use cycles. The analysis also shows that increased complexity of a given product results in a higher complexity of material flows and the derived impacts, hence, it becomes increasingly difficult for non-experts to gain a quick understanding and interpretation of the results. With the already well established recycling rates of construction and demolition waste in Denmark it can be discussed if the worst case scenario used in this case study actually represents current worst case practice and the use of a scenario that is closer to current practices would most likely give a different picture of the products' embodied carbon and the potential for material loops identified here. The use of allocation can help account for environmental benefits of multiple material life-cycles resulting from e.g. DfD. However, besides the 100:0 approach applied in this study, allocation can be performed using an array of different parameters such as economic value, mass, number of recycling/reuse cycles, recycled content, recycling potential etc. Hence, using another allocation methodology will most likely influence the results significantly and promote various CE strategies differently. E.g. using the 100:0 approach where all environmental impacts and benefits of the column B is allocated to the second use cycle leaving no environmental benefits to the first use cycle i.e. a stakeholder in the first use cycle will have no environmental motivation for designing the column for disassembly in the first place. In contrast, allocating all environmental benefits to the first use cycle leaves no environmental benefits to the second use cycle i.e. stakeholder in the second use cycle will have no environmental motivation for reusing column B. For that reason it is not obvious to which use cycle the environmental impacts and credits should be attributed or how substituted materials an product should be accounted for [7]. Hence, there is a need for a consistent LCA allocation approach for promoting CE in the building industry to provide key stakeholders with a reliable basis for decision-making. However, this way of displaying the LCA results can support a closer link between production and end-of-life of products to help establishing and improving these material loops to develop suitable CE design strategies targeted the building industry as well as providing a better understanding of what our design decisions will leave future generations with.

5. References

[1] Aye L, Ngo T, Crawford RH, Gammampila R, Mendis P 2012 Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules *Energy Build.* **47** pp 159–68

[2] Ellen MacArthur Foundation 2015 Growth within: a circular economy vision for a competitive Europe

[3] The Danish Government 2018 Strategi for cirkulær økonomi - Mere vædi og bedre miljø gennem design, forbrug og genanvendelse [Circular economy strategy - More value and a better environment through design, consumption and recycling]

[4] Advisory Board for Cirkulær Økonomi 2017 Advisory Board for cirkulær økonomi. Anbefalinger til regeringen [Circular Economy Advisory Board. Recommendations for the gorvernment]

[5] European Commission 2017 Circular Economy Strategy - Environment - European Commission [Internet]. 2017 [cited 2018 Oct 1] from: http://ec.europa.eu/environment/circular economy/index_en.htm

[6] Hauschild M, Rosenbaum R K, Olsen S I 2018 *Life Cycle Assessment theory and practice* (Switzerland: Springer International Publishing AG) pp 9-197.

[7] Haupt M, Zschokke M 2016 How can LCA support the circular economy?—63rd discussion forum on life cycle assessment *Int. J. Life Cycle Assess.* (November 30rd: Zurich, Switzerland)

[8] Nasir MHA, Genovese A, Acquaye AA, Koh SCL, Yamoah F 2017 Comparing linear and circular supply chains: A case study from the construction industry *Int. J. Prod. Econ.* **183** pp 443–457

[9] Malmqvist T, Nehasilova M, Moncaster A, Birgisdottir H, Nygaard F. 2018 Energy and buildings design and construction strategies for reducing embodied impacts from buildings – case study analysis. *Energy Build.* **166** pp 35–47

[10] Paananen T, Suur-Askola P 2018 In search of a bright, circular future! *Peikko Group Coperation*

[11] Velfac 2018 Bortskaffelse og genanvendelse [Disposal and recycling] [Internet] [cited 2018 Oct 1]. Available from: https://velfac.dk/vinduer-erhverv/teknisk-raadgivning/dgnb/velfac-og -dgnb/bortskaffelse-og-genanvendelse/

[12] Viva Tagdækning. Genbrug af tagpap [Recycling of roof felt] [Internet]. [cited 2018 Oct 1]. Available from: http://www.vivatag.dk/loesninger-plus-referencer/groenne-loesninger/genbrug-af-tagpap/

[13] Aagaard N-J, Brandt E, Aggerholm S, Haugbølle K 2013 Levetider af bygningsdele ved vurdering af bæredygtighed og totaløkonomi [Service life of building components when assessing sustainability and life cycle costing] *The Danish Building Research Institute* pp 49-50

[14] EN 15978:2012 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method