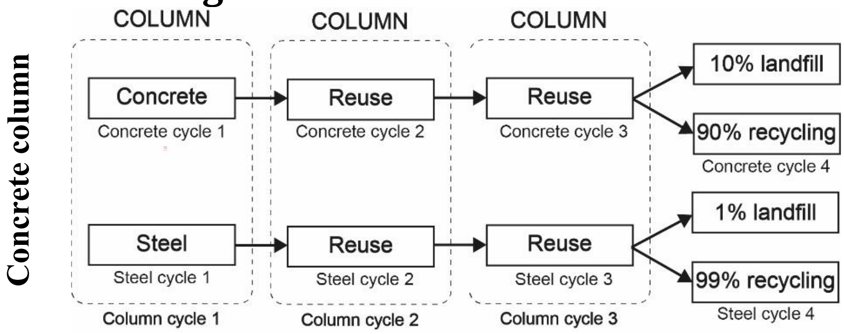
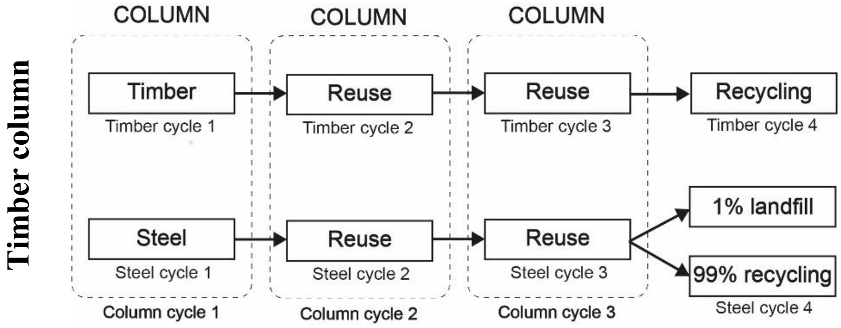
Development of a life cycle assessment allocation approach for circular economy in the built environment

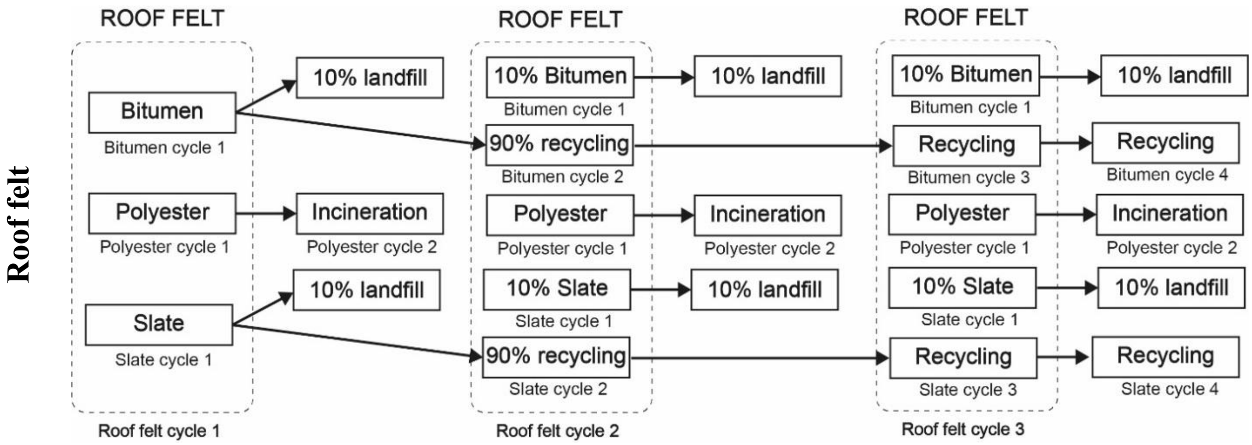
Supplementary material

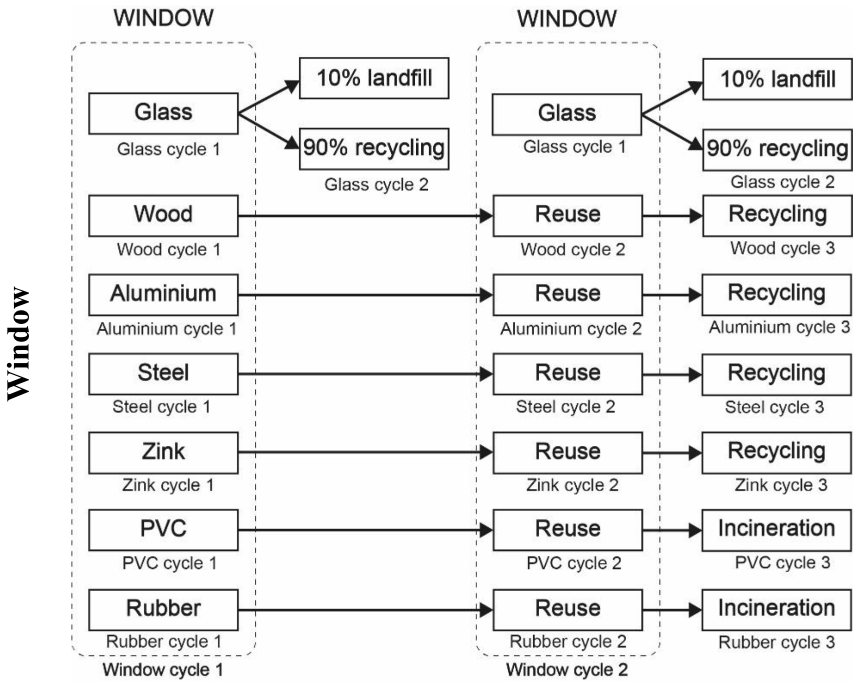
Content

S1. Flow diagrams









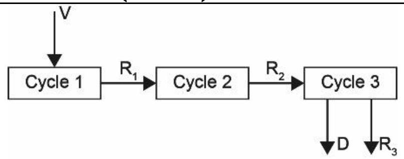
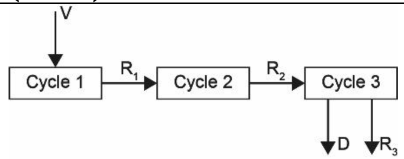
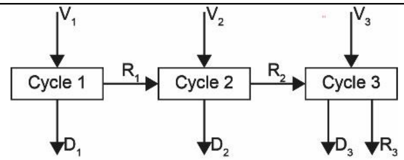
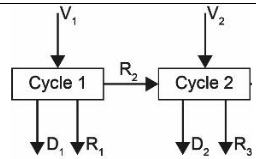
Note: punctered boxes indicate cycles of the primary function i.e. column, roof felt or window

S2. Mathematical expressions for the allocation of the reusable and recyclable material fractions of the exemplary circular building components.

Note: Mathematical expressions have been harmonised for comparison reasons. The CFF has been shortened according to each of the circular building components. The LD approach and the impact distribution between the cycles is based on an example from Allacker et al. (2017)

Common abbreviations used in equations	**Unit pr. Unit value**	**Definition**
V	kg CO_2 eq. /kg	Emissions from virgin material production
R	kg CO_2 eq. /kg	Emissions from reuse/recycling of material
D	kg CO_2 eq. /kg	Emissions from disposal of waste material
A		Allocation factor
R*	kg CO_2 eq. /kg	Emissions assumed to be substituted by reused or recycled material
r_1	unitless	Share of recycled content
r_2	unitless	Share of material that will be recycled at EoL
r_3	unitless	Share of material that will be used for energy recovery at EoL
Q_p	unitless	The quality of the primary material respectively
Q_i	unitless	The quality of the ingoing secondary material
Q_o	unitless	The quality of the outgoing secondary material
L	MJ/kg	Lower heating value of the material in the component that is used for energy recovery at EoL
$X_{ER,elec}$	unitless	The efficiency of the electricity energy recovery process
$X_{ER,heat}$	unitless	The efficiency of the heat energy recovery process

$E_{SE,elec}$	kg CO_2 eq.	The impact assumed to be substituted by the electricity energy recovery
$E_{SE,heat}$	kg CO_2 eq.	The impact assumed to be substituted by the heat energy recovery

Allocation approach	420x420x3500mm Peikko prefabricated concrete column (reuse)	350x350x3500mm cross laminated timber column (reuse)	1 m^2 Icopal Top 500 P roof felt (recycling)	1230x1480mm Velfac energy 200 window (reuse)
				
EN 15804/15978 cut-off	**Cycle 1** = $V+R_1$ **Cycle 2** = R_2 **Cycle 3** = R_3+D	**Cycle 1** = $V+R_1$ **Cycle 2** = R_2 **Cycle 3** = R_3+D	**Cycle 1** = $V_1+R_1+D_1$ **Cycle 2** = $V_2+R_2+D_2$ **Cycle 3** = $V_3+R_3+D_3$	**Cycle 1** = $V_1+ R_1+R_2+D_1$ **Cycle 2** = $V_2+R_3+D_2$
50:50	**Cycle 1** = $V+0.5\cdot R_1$ **Cycle 2** = $0.5\cdot R_1+0.5\cdot R_2$ **Cycle 3** = $0.5\cdot R_2+0.5\cdot R_3+D$ Where $0.5\cdot R_3$ is allocated to the subsequent cycle	**Cycle 1** = $V+0.5\cdot R_1$ **Cycle 2** = $0.5\cdot R_1+0.5\cdot R_2$ **Cycle 3** = $0.5\cdot R_2+0.5\cdot R_3+D$ Where $0.5\cdot R_3$ is allocated to the subsequent cycle	**Cycle 1** = $V_1+0.5\cdot R_1+D_1$ **Cycle 2** = $V_2+0.5\cdot R_1+0.5\cdot R_2+D_1$ **Cycle 3** = $V_3+0.5\cdot R_2+0.5\cdot R_3+ D_3$ Where $0.5\cdot R_3$ is allocated to the subsequent cycle	**Cycle 1** = $V_1+0.5\cdot R_1+D_1$ **Cycle 2** = $V_2+0.5\cdot R_1+0.5\cdot R_2+D_1$ Where $0.5\cdot R_2$ is allocated to the subsequent cycle
CFF	**Cycle 1,2,3** = $V+(1-A)\cdot r_2\cdot((R_1+R_2+R_3)-R_3^{*}\cdot(Q_o/Q_p))+(1-r_2)\cdot D)/3$ Where r_2 is 90% concrete and 99% steel recycling at EoL, R_3^{*} is 90% concrete and 99% steel recycling.	**Cycle 1,2,3 =** $V+(1-A)\cdot r_2\cdot((R_1+R_2+R_3)-R_3^{*}\cdot(Q_o/Q_p))+(1-r_2)\cdot D)/3$ Where r_2 is 100% wood and 99% steel recycling at EoL, R_3^{*} is 90% concrete and 99% steel recycling.	**Cycle 1** $_{\textbf{bitumen/slate}}$ = $V_1+(1-A)\cdot V_1\cdot(Q_iQ_p)+(1-A)\cdot r_2+(R_1-V_1^{*}\cdot(Q_o/Q_p))+(1-r_2)\cdot D_1$ **Cycle 2** $_{\textbf{bitumen/slate}}$ = $(1-r_1)\cdot V_2+r_1\cdot (A\cdot R_1+(1-A)\cdot V_2\cdot(Q_i/Q_p))+(1-A)\cdot r_2\cdot(R_2-R_2{*}\cdot(Q_o/Q_p))+(1-r_2)\cdot D_2$	**Cycle 1,2**$_{\textbf{glass}}$ =$V_{1,2}+(1-A)\cdot r_2\cdot(R_{1,3}+R_{1,3}^{*}\cdot(Q_o/Q_p))+(1-r_2)\cdot D$ Where r_2 is 90% glass recycling at EoL, $R_{1,3}^{*}$ is 90% glass recycling **Cycle 1,2**$_{\textbf{wood, aluminium, steel, zinc}}$ = $V_1+(1-A)\cdot r_2\cdot((R_3+R_4)-R_4^{*}\cdot(Q_o/Q_p))/2$

CFF continued			**Cycle 3** $_{\textbf{bitumen/slate}}$ = $(1-r_1)\cdot V_3+r_1\cdot(A\cdot R_2+(1-A)\cdot V_3\cdot(Q_i/Q_p))+(1-A)\cdot r_2\cdot(R_3-R_3^*\cdot(Q_o/Q_p))+(1-r_2)\cdot D_3$ r_1 is 90% bitumen and slate, r_2 is 90% bitumen and slate that will be recycled at EoL, $R_{2,3}^*$ is 90% bitumen and slate recycling, **Cycle 1,2,3** $_{\textbf{polyester}}$ **=** $V_{1,2,3}+r_3\cdot(D_{1,2,3}-L\cdot X_{ER,heat}\cdot E_{SE,heat}-L\cdot X_{ER,elect}\cdot E_{SE,elec})$ Where r_3 is 100% polyester energy recovery at EoL	**Cycle 1,2**$_{\textbf{rubber, PVC}}$ **=** $V_1+r_3\cdot(D_2-L\cdot X_{ER,heat}\cdot E_{SE,heat}-L\cdot X_{ER,elect}\cdot E_{SE,elec})/2$ Where r_3 is 100% rubber and PVC energy recovery at EoL
LD	**Cycle 1** = $0.56\cdot V+0.11\cdot R_3+0.11\cdot D+0.5\cdot R_1$ **Cycle 2** = $0.33\cdot V+0.33\cdot R_3+0.33\cdot D+0{,}5\cdot R_1+0{,}5\cdot R_2$ **Cycle 3** = $0.11\cdot V+0.56\cdot R_3+0.56\cdot D+0.5\cdot R_2$ Where R_3 is counted as disposal	**Cycle 1** = $0.56\cdot V+0.11\cdot R_3+0.11\cdot D+0.5\cdot R_1$ **Cycle 2** = $0.33\cdot V+0.33\cdot R_3+0.33\cdot D+0{,}5\cdot R_1+0{,}5\cdot R_2$ **Cycle 3** = $0.11\cdot V+0.56\cdot R_3+0.56\cdot D+0.5\cdot R_2$ Where R_3 is counted as disposal	**Cycle 1** = $0.56\cdot V_1+0.11\cdot R_3+0.11\cdot D_3+0.5\cdot R_1$ **Cycle 2** = $0.33\cdot V_2+0.33\cdot R_3+0.33\cdot D_3+0{,}5\cdot R_1+0{,}5R_2$ **Cycle 3** = $0.11\cdot V_3 + 0.56\cdot R_3 +0.56\cdot D_3 + 0.5\cdot R_2$ Where R_3 is counted as disposal	**<u>Glass:</u>** **Cycle 1 =** $V_1+0.5\cdot R_1+D_1$ **Cycle 2 =** $V_2+0.5\cdot R_3+D_2$ **<u>Frame:</u>** **Cycle 1** = $0.85\cdot V_1+0.5\cdot R_2+0.15\cdot(D_2+R4)$ **Cycle 2** = $0.15\cdot V_1+0.5\cdot R_2+0.85\cdot(D_2+R4)$

S3. Deriving the CE LD approach

A graphical representation of how the CE LD equation for dividing the production impacts was derived is shown in the figure below. The red line represents (in this case) the virgin material production impacts' distribution between the use cycles, where the distribution decreases linear degressively from use cycle 1 to 'n'. The distribution is calculated in percentage emission.

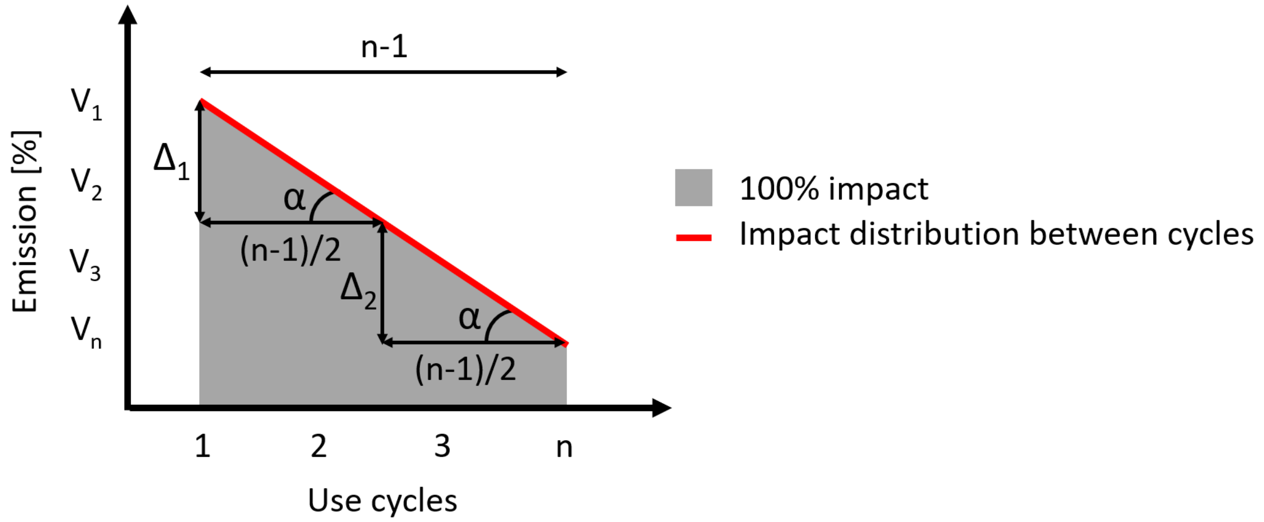


Figure 2. Explanatory illustration of the developed LD equation

The total impact over the use cycles will always be 100% (i.e. the grey area of the graph), thus the average impact in percentage is:

$$Av = \frac{100\%}{n} \quad (1)$$

Where n is the total number of use cycles. The coefficient, α, i.e. the slope of the graph in Figure 2 is:

$$\alpha = \frac{V_1 - V_n}{n-1} \quad (2)$$

Where V_1 is the emission from virgin material production allocated to the first use cycle, V_n is the emission from virgin material production allocated to the last use cycle and (n-1) is the number of spaces between the use cycles. The environmental impact allocated to the first use cycle is then:

$$V_1 = Av + \Delta_1 \text{ where } \Delta_1 = \alpha * \frac{(n-1)}{2} \quad (3)$$

$$V_1 = \frac{100\%}{n} + \frac{V_1 - V_n}{n-1} \cdot \frac{(n-1)}{2}$$

The average impact is added to the slope of the line to find out how much impact should be added to the average impact towards the first use cycle. The slope is multiplied by (n-1)/2 which represents the distance from the first use cycle to the middle of the line. (n-1)/2 is used as a calculation technicality to account for situations when there is an odd number of cycles. Similarly, the n'th cycle is:

$$V_n = Av - \Delta \text{ , where } \Delta_2 = \alpha * \frac{(n-1)}{2} \tag{4}$$

$$V_n = \frac{100\%}{n} - \frac{V_1 - V_n}{n-1} \cdot \frac{(n-1)}{2}$$

However, here the average impact is subtracted from the slope of the line to find out how much impact should be deducted from the average impact towards the last use cycle.
It is decided that the first use cycle should be impacted 'F'-times as much as the last use cycle:

$$V_1 = F \cdot V_n \tag{5}$$

V_1 from (5) is inserted into (3) which gives:

$$F \cdot V_n = \frac{100\%}{n} + \frac{V_1 - V_n}{n-1} \cdot \frac{(n-1)}{2} \tag{6}$$

By adding (4) with (6) the equations can be reduced to:

$$V_n = \frac{100\%}{n} - \frac{V_1 - V_n}{n-1} \cdot \frac{(n-1)}{2} \tag{7}$$

$$+$$

$$F \cdot V_n = \frac{100\%}{n} + \frac{V_1 - V_n}{n-1} \cdot \frac{(n-1)}{2}$$

$$\overline{(F+1) \cdot V_n = 2 \cdot \frac{100\%}{n}}$$

The percentage of the total environmental impact from all use cycles allocated to the n'th user is:

$$V_n = 2 \cdot \frac{\frac{100\%}{n}}{(F+1)} = \frac{2 \cdot 100\%}{n \cdot (F+1)} \tag{8}$$

Inserting V_n from (8) into (5) then gives V_1:

$$V_1 = F \cdot 2 \cdot \frac{\frac{100\%}{n}}{(F+1)} = \frac{F \cdot 2 \cdot 100\%}{n \cdot (F+1)} \tag{9}$$

Concrete column calculation example: distribution of virgin concrete production impact between the cycles
Number of cycles:

n = 4

Allocation factor:

F = 50

The average impact is:

$$Av = \frac{100\%}{n} = \frac{100\%}{4} = 25\% \tag{1}$$

V_1 is:

$$V_1 = \frac{F \cdot 2 \cdot 100\%}{n \cdot (F+1)} = \frac{50 \cdot 2 \cdot 100\%}{4 \cdot (50+1)} = \mathbf{49}\% \tag{9}$$

V_4 is:

$$V_4 = \frac{2 \cdot 100\%}{n \cdot (F+1)} = \frac{2 \cdot 100\%}{4 \cdot (50+1)} = \mathbf{1}\% \tag{8}$$

The coefficient, α, (i.e. the difference between one use cycle and the next) is:

$$\alpha = \frac{V_1 - V_n}{n-1} = \frac{49\% - 1\%}{4-1} = 16\% \tag{2}$$

The impact percentage of intermediate cycle V_2 is then:

$$V_2 = V_1 - \alpha = 49\% - 16\% = \mathbf{33}\%$$

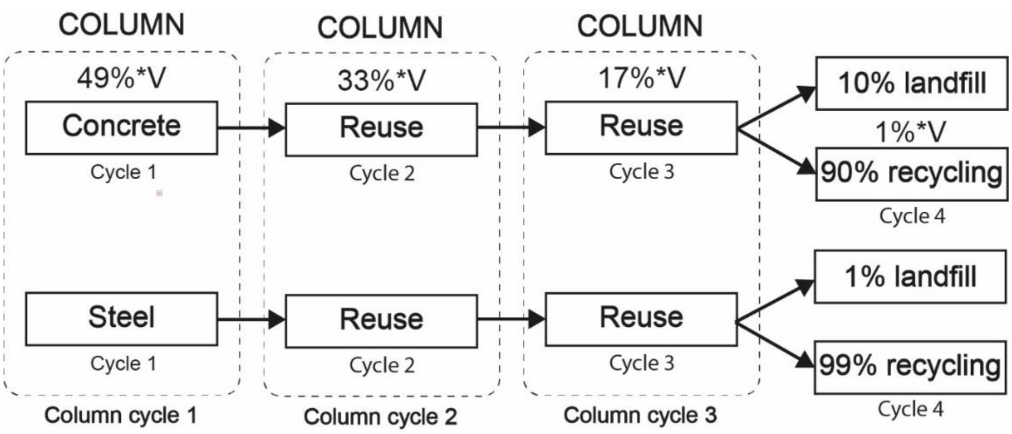
And The impact percentage of intermediate cycle V_3 is:

$$V_3 = V_2 - \alpha = 33\% - 16\% = \mathbf{17}\%$$

The impacts of each cycle are summed to check if the total impact adds up to 100%:

$$V_1 + V_2 + V_3 + V_4 = 49\% + 33\% + 17\% + 1\% = 100\%$$

On the concrete column flow chart from Appendix C, the distribution is thus:



S4. Expert session evaluation of the developed CE LD approach

Note: The percentage of expert sessions in which each issue under each category was raised is shown using a grey-scale were dark grey indicates the most counts and white the least counts.

	Category	Remarks	Percentage of expert sessions in which the issue was raised
Advantages	**Applicability**	Suitable for ex-ante assessment (e.g., in policymaking, early stage design)	30%
		Suitable to assess multiple (future) cycles	60%
		Most suitable for (reproducible) building component or product level	60%
		Supports determining more ideal CE (e.g., ideal vision for back-casting)	30%
		Also suitable when materials cannot be re-used or recycled at same value	10%
	Incentives CE	Method incentivises not only narrowing, but also slowing and (high-value) closing cycles	30%
	Levels	CE-LCA introduces 'missing' building component level in LCA	10%
	Fair accounting impacts	The linear degressive method divides burden fairly between cycles; no double crediting possible	20%
		All cycles are included; impacts from other cycles (e.g., production, disposal) remain visible in all cycles	20%
	Ease of use	The allocation formula understandable and transparent (better than the PEF)	30%
	Instrument for discussion	Method stimulates (re)discussing problems and incentives in current LCA standards	20%
		Method show how we could include CE in LCA	30%
		Method shows how complex CE in design and the Built environment is	10%
Disadvantages	**Non-applicability**	Less suitable for ex-post assessments.	20%
		Less suitable for building scale (too complex, uncertain, no control by producing supply chain)	40%
	Uncertainty in assumptions	Difficult to determine and guarantee future cycles; leads to not-accurate results	60%
		Uncertainty in assumptions far in the future (cycles, processes, energy mix are unknown)	50%
		Sensitive to assumptions on functional, technical and economic lifespan	30%
	Greenwashing impacts	Burdens can be shifted towards [non-existent cycles] the future, diluting impacts	60%

		Easy to mis-use by industry by adding future cycles.	60%
	Challenging to implement	Requires transition in building industry to determine all cycles (i.e., from one-off projects to a (closed loop) component-wise industry)	50%
		Difficult to implement a new LCA methods in practice, it is easier to adapt the current LCA standard	30%
		All cycles need to be documented and kept tracible over long-term (e.g., government regulation is needed)	30%
		Current LCA tools in practice cannot do a CE-LCA calculation	10%
	Difficulties in use	Method is complex	50%
		Method is time consuming	30%
	Urgency	Virgin production burdens should be in first cycles to reduce our impacts now	40%
Improvements	**Improvements ease of use**	Make the method understandable and simple to use, (e.g., include a manual, concrete examples, clarify terms, single indicator system)	50%
		Make method affordable and fast to use	20%
		Provide (more) background data; make data accessible to industry	40%
		Shift burden of proof for CE-LCA proof from building level to component level (i.e., component-EPD's)	10%
		Translate to a design synthesis tool (e.g., guidelines, flowchart) and practice assessment tool	50%
	Improvement accuracy and certainty in allocation approach	Differentiate between different objects of assessment in CE-LCA	10%
		Differentiate different cycles (i.e., known or unknown, high-value or low-value, open or closed)	40%
		Prefer system expansion with up-front crediting over allocation for known cycles, mass production, direct re-use and recycling	20%
		Include market situation and material quality factors in allocation approach	20%
		Add probability factor for cycles to CE-LCA	10%
		Include (use) time in allocation approach	20%
	Improvement ease of implementation in practice	Differentiate LCA levels (do not interlink them)	30%
		Develop rules, template or regulation for cycles (i.e., amount, division of impact, types of cycles, system boundary)	60%
		Prefer an LCA 'tax' system: producer takes initial production and EOL impacts; cycles can be added over time	10%
		Test the method in a real-life case with stakeholders	40%
	Improvement of certainty and prevention of misuse	Use CE-LCA as an additional informational module "circular potential" next to standard LCA	20%
		Obligatory peer review of CE-LCA	10%
		Include a sensitivity analysis on influence of varying future cycles	10%

Widen scope CE assessment	Assessment on other criteria should be part of CE assessment (i.e., value, costs, material flow, social factors)	30%