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Development of a circularity assessment method for facade systems

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Lisa Van Gulck[1,3], Eline Leenknecht[1], Emiel Debusseré[1], Jona Van Steenkiste[2], Marijke Steeman[1] and Nathan Van Den Bossche[1]

[1] Ghent University, Faculty of Engineering and Architecture, Research group of Building Physics, Sint Pietersnieuwstraat 41 B4, 9000 Ghent, Belgium
[2] Bureau Bouwtechniek, Kammenstraat 18, 2000 Antwerp, Belgium
[3] Corresponding author: lisa.vangulck@ugent.be

Various authorities identify the circular building strategy as the best way to reduce the environmental impact of the building sector. The EURECA project aims to develop a circular facade system for the renovation of high-rise buildings. The circularity of the facade systems proposed within the project should be evaluated in an objective manner. Current circularity assessment methods exist, however, they appear unfit to evaluate facade systems at an early design stage. Based on the analysis of existing assessment methods a new circularity assessment method is developed. The developed method allows to measure the circularity on element level with a limited amount of required information, allowing early stage decision-making. The method considers the parameters recycling, environmental cost, expected service life, component dependency, layer dependency and flexibility for reuse. The method is tested on four facade renovation systems: standard ETICS, circular ETICS, ventilated facade with rigid insulation and ventilated facade with flexible insulation. The circularity of each system can be represented by a radar chart, giving the score per parameter, or by a single score. In addition to the circular aspect, the financial aspect is added in the evaluation of the facade systems by using the Pareto front method.

1. Introduction

1.1. Context

Population growth and the rapidly changing demands of society require a continuous stream of new buildings. In Europe the building sector is responsible for half of all energy use, 40% of all greenhouse gas emissions, half of all raw material extraction and a third of all water use [1]. These astounding numbers show the need for a shift in our way of building. Various authorities identify the circular building strategy as the best way to move forward and reduce the environmental impact of the building sector. The circular building strategy is the translation of the circular economy to the building sector.

The recognized urgency to move towards a circular economy is positive, but also results in a certain level of confusion [2]. A study by Kircherr et al. shows there are over 114 definitions of the circular economy [3]. Most of these definitions refer to a combination of reduce, reuse and recycle activities. This broad comprehension of the circular economy illustrates the numerous aspects it entails, making it difficult to define what exactly a circular product is and how to know which aspects to focus on. Applied to the building sector this results in the question ‘what criteria must a building meet in order to be considered a circular building’?

Different methods to measure the performance of a building on circularity exist. These assessment methods allow to objectively compare the circularity of different building solutions and facilitate the practical implementation of the circular building strategy. Within each assessment method different aspects of circularity are quantified; each method has a set of circular parameters on which the building solutions are scored.

1.2. EURECA project

EURECA, or Effectively Upscaling the Renovation of Envelopes with a Circular Approach, is a two-year research project funded by the Flemish government under the Circular Flanders initiative [4]. The aim of the project is to develop a circular facade system that is scalable and allows existing high-rise buildings to be renovated quickly in a circular manner. Building types with a repetitive facade have the greatest potential for this project. In Flanders, many apartment buildings from the 1960s and 1970s are in need of a renovation. These apartment buildings and university buildings with a similar typology are interesting for the EURECA project. The facade renovation system will be tested on three case studies: two high-rise apartment buildings and a university building. The modular facade renovation system must be demountable and should have potential for future reuse in another building. Apart from the Building Physics research group of Ghent University, the project consortium consists of Algemene Bouw Maes nv, a general contractor, the multidisciplinary research and consultancy agency specialized in building techniques Bureau Bouwtechniek and the aluminum constructor De Witte.

A decisive factor to evaluate the possible facade renovation systems (different construction methods and accompanying materials) on their application potential is their degree of circularity. One system may use materials with a low environmental impact but which are connected irreversibly, while a second system might have reversible connections and independent layers but requires more materials. To make objective decisions regarding the circularity of the different facade systems, their circularity will be measured by a circularity assessment method.

1.3. Objectives

Different circularity assessment methods exist, such as ‘Material Circularity Indicator’ [5], ‘C-calc’ [6], ‘Label Circular Building’ [7] and ‘Building Circularity Index’ [8]. However, when analysing these four assessment methods no method is completely appropriate to evaluate the circularity of the facade renovation systems for the EURECA project. The existing methods often evaluate circularity on building level, while for the facade renovation systems an evaluation on element level is necessary. Most methods require a lot of detailed information, e.g. specific material properties such as geographical origin. The assessment method for EURECA should facilitate early stage decision-making when only aspects such as construction method and general choices of materials for the facade system are known. Lastly, many assessment methods also evaluate project specific parameters such as the use of BIM-models and material passports. Again, these parameters are less relevant for the early stage decision-making regarding the facade systems.

The goal of this research is to develop a circularity assessment method that can be applied for the comparison of the different facade renovation systems of the EURECA project. This method will allow to make objective decisions regarding circularity on element level, without having the requirement of a lot of detailed information or the choice of a specific project. The assessment method is thought out for renovation systems, but will also contain interesting information for new build scenarios. Existing circularity assessment methods provide very useful information on which parameters and scoring systems can be applied when evaluating circularity. This information will serve as a basis for the developed method.

2. Methodology

2.1. Research steps

In a first research step, four existing circularity assessment methods are briefly discussed, it is stated why the methods are not fully suited for the assessment of facade renovation systems at an early design stage, and which aspects (circular parameters and scoring systems) are useful for the development of the new circularity assessment method.

Using the insight and information gained from analysing existing methods, the new circularity assessment method is developed in a second research step. The circular parameters included in the developed method are described and their accompanying scoring system is worked out. The developed method is tested on four facade renovation systems: standard ETICS, circular ETICS, ventilated facade with rigid insulation boards and ventilated facade with flexible insulation. Subsequently, the method is analysed to identify the most objective way to present the results of the assessment. Should circularity be represented by a single score, should weighting factors be applied?

In reality the financial aspect plays a crucial role when making renovation decisions. Because circular building solutions are often considered (too) expensive their practical implementation can be limited and linear building solutions can be favoured. In a third and last research step the financial aspect is included in the evaluation of the facade renovation systems. This aspect is not part of the circular score, but in addition to the circular score, it is a criterion on which the evaluation of the facade systems is based. The aim is to identify facade renovation systems that have both a solid circular score and a financially interesting profile. A common method to find the optima between two criteria is the Pareto front [9,10].

2.2. Financial aspect

To include the financial aspect in the evaluation of the facade renovation systems, the Net Present Value (NPV) of each system is calculated. The NPV is the sum of the initial investment cost and the discounted future costs occurring over the life span of the building. For the calculations, a real discount rate of 1,8% is used [11] and a life span of thirty years is considered. The investment, replacement and maintenance phase are taken into account. Construction costs are based on the ASPEN price dataset, valid for the Belgian context [12]. This research looks at the micro-economic level, taking into account costs as paid by the end consumer (including taxes). For renovation and replacement works a VAT rate of 6% is used.

3. Research

3.1. Existing circularity assessment methods

Four existing circularity assessment methods are briefly discussed. It is analysed why the methods are not completely adequate for assessment of facade renovation systems at an early design stage and which aspects (circular parameters and scoring systems) are useful for the development of the new circularity assessment method.

3.1.1. Material Circularity Indicator (MCI). The Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation measures the circularity of material flows of a product [5]. The parameters used to calculate the MCI relate to material properties such as the recycled and reused content, the recycling efficiency, fraction sent to reuse and fraction sent to recycling. A detailed bill of materials is required to compute the MCI.

As detailed insight into the material flows is necessary, the MCI is not appropriate for early stage decision-making. The method is suited for optimizing products, allowing companies to identify additional circular value of their products and materials. Furthermore, the MCI is not developed specifically for the building sector. For the assessment of facade systems a larger focus on construction techniques (connectors, layers,…) is desired.

3.1.2. C-Calc. C-Calc developed by Cenergie, a firm specialized in innovative sustainable energy in the building sector, is a tool that measures the circularity of buildings based on the materials used on or removed from site (50%), the flexibility of the building for future use or deconstruction (30%) and project management (20%) [13].

C-Calc is not completely adequate to assess facade renovation systems at an early stage because the tool evaluates on building level, contains parameters that require detailed knowledge about the applied materials (e.g. geographical origin) and parameters that relate to project management (e.g. material passports). For the eventual facade system used in the EURECA project it is assumed that no reused materials are used for the initial construction of the system. However, future reuse of the materials or modules of the system should be inherent to the developed facade system. Although the C-Calc parameter 'fraction of reused materials (in initial construction)' is decidedly a relevant parameter for the evaluation of the circularity of building elements, the parameter seems less relevant to distinguish the different facade systems of the EURECA project. Future evolutions of the developed method could entail the inclusion of this parameter.

Parameters used in C-Calc that are interesting for the assessment of the facade systems are: the environmental impact, the recycled content and recycling potential of materials, the type of connection and the use of independent layers.

3.1.3. Label Circular Building. Label Circular Building developed by Flemish Construction Confederation, VLISOG and BBRI aims to be a guideline for circular construction. Because it allows to calculate a score it can also be used to measure the circularity of buildings and building processes [7]. Currently only a Beta version of the tool exists. Label Circular Building consists of a quantitative (60%) and qualitative (40%) assessment. The four themes of the quantitative assessment are environmental impact (10%), build and design for change (20%), urban mining (20%) and transition (10%).

As illustrated by the name, Label Circular Building evaluates circularity on building level. The quantitative themes 'urban mining' and 'transition' are not suitable for evaluating facade renovation systems at an early stage because they relate to topics such as building and material information and synergy with the environment.

The dimensions of construction elements should be modular to enable reuse in other projects and should be manageable to ensure easy handling. Within the EURECA project there is a separate research on the 'optimal' dimensions of the facade system taking into account the easy (de)construction of the system and the possibility of reuse on different facades. As with the C-Calc parameter 'fraction of reused materials', parameters that relate to the dimensions of a system are surely relevant for the evaluation of the circularity of building elements but are less useful for the developed assessment method for the EURECA project .

Other parameters than those assessed in C-Calc that are fit for the assessment of the facade renovation systems are: layering according to life span, simple and fast connections and the use of a limited amount of materials.

3.1.4. Building Circularity Index (BCI). According to Alba Concepts circularity consists of two components: origin and application of materials. These two components are measured by the Material Index with the parameters 'origin of materials', 'disposal scenario', 'technical life span' and 'volume' and by the Detachability Index with the parameters 'type of connection' and 'accessibility of connection' [14,15].

Alba Concepts considers a building a hierarchical cluster of elements and elements a hierarchical cluster of products. They have developed the Building Circularity Index (BCI), for which it is necessary to determine the Product Circularity Index (PCI) and Element Circularity Index (ECI).

The method developed by Alba Concepts forms a strong starting point for the developed assessment method, but certain parameters that are evaluated by the other assessment methods, such as environmental impact and layering according to life span, are also valuable to take into account when assessing facade renovation systems.

3.2. Circularity assessment method for facade renovation systems

Using the information from the first research step the circularity assessment method for facade renovation systems at an early design stage is developed. The goal is to use parameters for which the input can be found easily from transparent and publicly accessible sources. In what follows, the different parameters for the developed method are described and their corresponding scoring systems worked out. For the assessment method the following rule applies: the higher the score, the less circular a solution.

3.2.1. Parameters.

1. Recycling (%). The recycled content and recyclability of a material are taken into account by the parameter 'recycling'. NIBE, an independent consultancy firm specialized in sustainable building, has developed the concept 'material reutilization'[16]. For different construction materials they have defined the material reutilization score (%), which takes the recycled content of the material into account for 1/3 of the score and the recyclability of the material for 2/3 of the score.

In the developed method the value for the parameter 'recycling' is defined for each individual material layer of the facade system according to: *100% – material reutilization value in NIBE.* For example, the reutilization value for stone wool is 7% according to NIBE. Therefore the value of the layer stone wool for the parameter 'recycling' is 93% (100-7).

2. Environmental cost (€/m²). The environmental impact of a facade system is represented by the parameter 'environmental cost'. The environmental cost is the amount of damage to the environment and/or people expressed in terms of the financial amount needed to avoid the potential harm or to resolve the harm incurred [17]. The Belgian life cycle assessment tool TOTEM is used calculate the environmental cost [18]. The analysed assessment methods C-Calc and Label Circular Building also use this tool to determine the parameter 'environmental impact'.

When calculating the environmental cost of a building element, TOTEM makes a distinction between the environmental cost due to the materials and the environmental cost due to the operational energy use (i.e. transmission losses through the building element). For the developed method only the environmental cost due to the materials is considered.

3. Expected service life (years). The parameter 'expected service life' accounts for the circular principles 'durable materials' (long life span) and 'layering according to life span'. The service life of construction materials can be found in 'Rapport Technische Levensduur van Gebouwcomponenten' by OVAM [19].

In the assessment method the 'expected service life' of each individual material layer of the facade system is defined: *100 - expected service life of a material*. The principle 'layering according to life span' is taken into account by introducing the following rule: the service life of a layer cannot be longer than that of the previous (more internal) layer. The determination of the service life of each layer should be done from the inside to the outside of the construction.

4. Component dependency (%). The more independent the components within a layer are, the easier future replacements, repairs or adaptions of one component can happen without influencing the other components. The parameter 'component dependency' takes this principle into account. Table 1 gives an overview of the scoring system for the parameter.

Table 1. *Scoring system for parameter 'component dependency'.*

Component dependency	Score (%)	Additional clarification
Completely independent	0	
Remove connectors to separate (material and connectors remain intact)	10-20	*How complex is the removal of the connector*
Sequential disassembly: disconnect all to disconnect one	40-50	*How many elements need to be disconnected (few large – many small)*
Destroy connectors to separate	60-80	*How labor-intensive is the destruction of the connector*
Completely dependent	100	

As an example, bricks connected with a traditional cement mortar are inseparable and are scored 100, while bricks connected with lime mortar can be separated with a lot of labor and are scored 80. Rigid insulation boards with a tongue and groove joint are scored 40, while flexible insulation that is connected with plugs to the bearing layer is scored 0.

5. Layer dependency (%). While the parameter 'component dependency' takes into account the dependency of the components within a layer, the parameter 'layer dependency' represents the dependency between the layers. It takes into account the type of connection between the layer and the previous (more internal) layer. The scoring system for this parameter is based on the scoring system developed by Alba Concepts for the parameter 'type of connection' which is part of the Detachability Index [20]. Table 2 presents the scoring system for the parameter 'layer dependency'.

Table 2. *Scoring system for parameter 'layer dependency' (based on Alba Concepts).*

Layer dependency		Score (%)
Dry connection	Dry connection	0
	Click connection	0
	Velcro connection	0
	Magnetic connection	0
Connection with added elements	Bolt and nut connection	20
	Spring connection	20
	Corner connection	20
	Screw connection	20
Direct integrated connection	Peg connection	40
	Nail connection	40
Soft chemical connection	Sealant connection	80
	Foam connection (PUR)	80
Hard chemical connection	Glue connection	100
	Cement-bound connection	100
	Chemical anchor	100

6. Flexibility for reuse (%). The parameter 'flexibility for reuse' represents the possibility of a material layer to be adapted (altering of dimensions) for it to be reused in another building. Table 3 shows the scoring system for the parameter.

Table 3. *Scoring system for parameter 'flexibility for reuse'.*

Flexibility for reuse	Score (%)	Additional clarification
Easily adaptable	0-20	*How labor-intensive are actions*
Flexible because of small dimensions, but hard or impossible to adapt	40	*E.g. bricks, small tiles,…*
Adaptable by more complex/specialized actions	50-60	*How specialized are the used machines,…*
Reuse not possible	100	

For instance, the dimensions of bricks or tiles cannot be easily changed, but these building blocks allow a certain degree of flexibility because of their small dimensions. Therefore they are attributed a relatively low score.

3.2.2. Calculating the circular scores. Per facade system, a score is defined for each parameter. The parameter 'environmental cost' is determined for the whole system at once; for the other parameters, first a score is established per material layer and subsequently these scores are added up to a total parameter score. To comply with the circular principles 'independent layers' and 'reversible connections' building solutions often require additional materials, which results in an additional material layer that must be taken into account for the total parameter score. Therefore, a distinction is made between parameters for which the material aspect is the most important (parameters: recycling, estimated service life, flexibility for reuse) and parameters which focus on the layers of the construction (parameters: component dependency, layer dependency). For the three parameters with focus on the material aspect, the total score for each parameter is obtained by multiplying the score of the material layer with the relative contribution of that material to the environmental cost of the facade system (this info is provided by the TOTEM tool). It is desirable that materials with a high environmental impact can be recycled, have a long service life and have potential for reuse. Therefore, it is fair that they have a higher contribution to the total score of these three parameters. For the two parameters that focus on the layers of a construction, a total score per parameter is obtained by simply adding up the scores of the materials layers.

When comparing the different facade systems, for each parameter an average score is defined by taking the average of the scores of all systems for that parameter. Next the score for each system on that parameter is expressed relatively to the average. This gives a relative score per parameter and converts all scores to the same unit. Finally, all the relative parameter scores of that system are added to a single score. The developed method does not set benchmarks, but is about comparing the circular scores of the facade renovation systems and choosing the most interesting system. The method allows to compare each parameter individually and to compare the single scores.

When assigning the scores to each parameter it is important to apply a holistic approach. For example, if a layer cannot be disassembled (parameter layer dependency), that layer and the previous layer are also not flexible for reuse or the components of the previous layers can also not be adjusted independently (parameter component dependency). The different parameters are interconnected and applying logical reasoning when assigning the scores is important.

3.2.3. Application circularity assessment method to facade renovation systems. The developed method is applied to four facade renovation systems: a standard and a circular variant of ETICS and a ventilated facade with rigid and with flexible insulation boards.

ETICS is a common renovation strategy that has proven to be an interesting choice from the environmental viewpoint because of its relatively simple construction [21]. However, due to its plaster finishing and the glued fixation of the insulation, ETICS is not a circular construction method. A more circular variant can be obtained by replacing the mortar connection with a mechanical connection of PVC-profiles [22]. The circular variant of ETICS does still have a plaster finishing. For the ventilated facade the variant with flexible insulation requires a more extensive supporting structure than the variant with rigid insulation boards. Figure 1 and 2 show drawings of the facade systems.

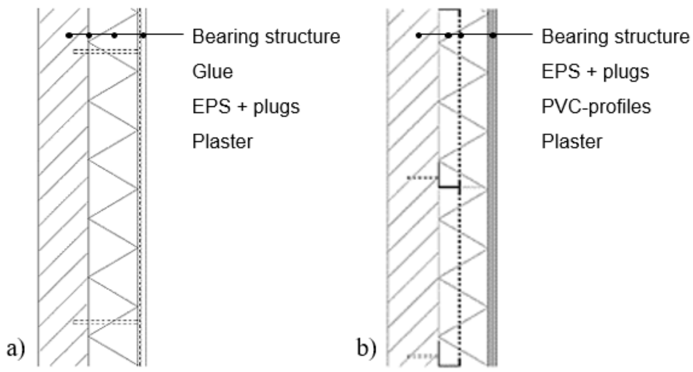

Figure 1. *Drawings facade systems: a) ETICS standard; b) ETICS circular.*

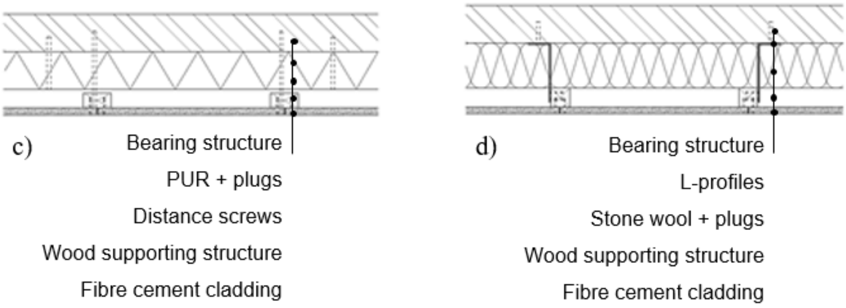

Figure 2. *Drawings facade systems: c) ventilated facade rigid insulation; d)ventilated facade flexible insulation.*

Table 4 shows the development of the circular score per parameter for each facade renovation system. The different systems have the same U-value. For each system the different material layers are shown and their relative contribution to the environmental cost is stated. The connectors for each layer are mentioned; if one layer is connected with different types of connectors to the previous one, the most 'negative' connector counts. The material impact of the connectors is included in the environmental cost. If a relative score is highlighted green the system scores better than average on that parameter. If the relative score is highlighted red, the system scores worse than average on that parameter.

For the parameter 'component dependency' plaster is assigned the maximum score because although to a certain extent it is possible to repair plaster locally, this repair will always remain visible. EPS also gets the maximum score for this parameter since the plaster layer cannot be removed without damaging the EPS or other parts of the plaster and it is not realistic that EPS boards will be replaced or adapted independently.

The circular variant of ETICS has a higher environmental cost than the standard variant (PVC profiles have a higher material impact than glue) but has a better score on the parameter 'layer dependency'. The mechanical connection of the PVC profiles is a reversible connection while the glue connection is not. The biggest difference between the variants of the ventilated facade is in the parameter 'environmental cost'. The ventilated facade with flexible insulation requires a more extensive supporting structure (and connections), resulting in a higher material impact.

The ventilated facade systems have an additional material layer compared to the ETICS systems. This enables the ventilated facade systems to comply with the circular principles 'independent layers' and 'reversible connections', and, as a result, to have a better score than ETICS for the parameters 'component dependency', 'layer dependency' and 'flexibility for reuse'.

If the relative scores per parameter are added to a single score per facade renovation system (without weighting factors), the ventilated facade variants have a better circular single score than the ETICS variants and the ventilated facade system with hard insulation boards has the best circular single score.

The scores of the facade renovation systems on the parameter 'recycling' are relatively high. The values defined in NIBE are most likely on the conservative side. If more specific material choices have been made, more correct information on the recycled content and recycling potential of the material can be found in the product-specific EPDs.

3.3 Representation of circularity

For each facade system Table 4 gives the score per parameter and a single score by adding the relative scores of each parameter. This single score makes it easy to compare the different systems and choose the most circular one. It is also possible to use weighting factors following the logic that some parameters are more important regarding circularity than others. The four analysed assessment methods also allow to express circularity by a single score (or by a label in the case of C-Calc). For C-Calc and Label Circular Building the relative share of the themes to the total score is mentioned. However, it seems rather subjective to decide which parameters contribute more to the circularity of a building than others. For example, for the developed circularity assessment method the parameters that evaluate a more general sense of sustainability (e.g. parameters recycling, environmental cost and expected service life)

Table 4. *Circularity assessment method applied to four facade renovation systems.*

ETICS stand	*Contribution environmental cost*	**Recycling**	*Relative*	**Environmental cost**	*Relative*	**Expected service life**	*Relative*	**Component dependency**	*Relative*	**Layer dependency**	*Relative*	**Flexibility for reuse**	*Relative*	**Total**
EPS 15cm	0,63	97				37		100		100		100		
Plaster	0,37	100		4,37		67		100		100		100		
		98,11	1,00	4,37	0,67	48,10	0,95	200	1,82	200	1,82	100	1,46	**7,71**

Connectors
Insulation: Glue + plugs

ETICS circ	*Contribution environmental cost*	**Recycling**	*Relative*	**Environmental cost**	*Relative*	**Expected service life**	*Relative*	**Component dependency**	*Relative*	**Layer dependency**	*Relative*	**Flexibility for reuse**	*Relative*	**Total**
EPS 16cm	0,66	97				37		100		20		100		
Plaster	0,34	100		5,47		67		100		100		100		
		98	1,00	5,47	0,84	47,2	0,93	200	1,82	120	1,09	100	1,46	**7,14**

Connectors
Insulation: PVC profiles + plugs

Ventilated hard	*Contribution environmental cost*	**Recycling**	*Relative*	**Environmental cost**	*Relative*	**Expected service life**	*Relative*	**Component dependency**	*Relative*	**Layer dependency**	*Relative*	**Flexibility for reuse**	*Relative*	**Total**
PUR 9cm	0,36	95				37		40		20		10		
Wood support structure	0,07	100				50		0		20		20		
Fibre cement cladding	0,57	100		5,9		63		0		20		50		
		98,18	1,00	5,9	0,90	52,63	1,03	40	0,36	60	0,55	33,33	0,49	**4,33**

Connectors
Insulation: Plugs
Wood support structure: Distance screws
Cladding: Screws

Ventilated soft	*Contribution environmental cost*	**Recycling**	*Relative*	**Environmental cost**	*Relative*	**Expected service life**	*Relative*	**Component dependency**	*Relative*	**Layer dependency**	*Relative*	**Flexibility for reuse**	*Relative*	**Total**
Stone wool 13cm	0,16	93				25		0		20		0		
Wood support structure	0,09	100				50		0		20		20		
Fibre cement cladding	0,75	100		10,41		63		0		20		50		
		98,89	1,01	10,41	1,59	55,77	1,10	0	0	60	0,55	39,32	0,58	**4,82**

Connectors
Insulation: Plugs
Wood support structure: L-profile + screws
Cladding: Screws

	AVERAGE	98,30		6,54		50,92		110		110		68,16		**6**

could be given a lower weighting factor than the parameters focusing more specifically on circularity (e.g. parameters component dependency, layer dependency and flexibility for reuse). However, making the distinction between sustainability and circularity is very challenging since circularity is a part of sustainability and this results in an overlap between both topics [23].

Even without using weighting factors, the representation of the circularity of a construction element by a single score can push more nuanced information to the background. Therefore it could be argued that the relative scores per parameter should be displayed separately, for example with a radar chart. This allows to identify the parameters for which the facade system could be further optimized, without worsening the scores of the other parameters. Figure 3 shows a radar chart for the four facade systems. Each axis of the radar chart represents a different parameter. The closer the lines are to the centre of the chart, the more circular a solution.

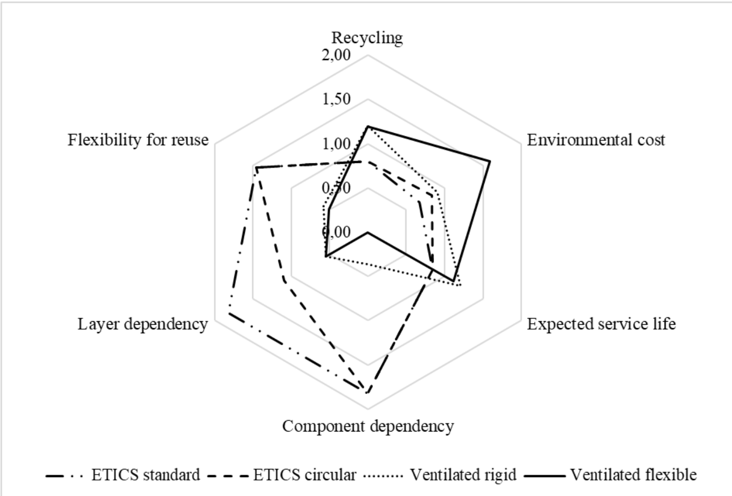

Figure 3. *Radar chart for circularity of four facade renovation systems.*

3.4. Inclusion of the financial aspect

In addition to the degree of circularity of the facade systems, the financial aspect will also play a decisive role when evaluating the different systems. To include the financial aspect in the evaluation the NPV of each facade system is calculated. To find the optima between the two criteria circular score and NPV the Pareto front method is used. The rule 'the lower, the better' applies for both criteria. Figure 4 shows a diagram with on each axis a different criterion. The circular score (single score as determined in Table 4) and NPV of the different facade renovation systems are plotted.

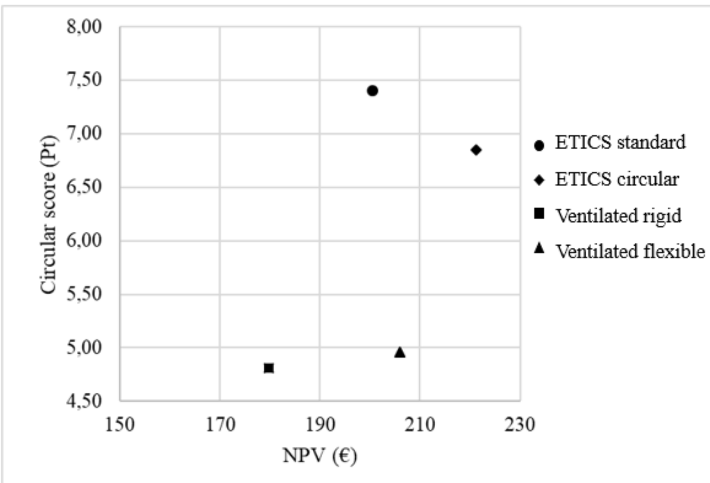

Figure 4. *Multi-objective optimization circular score and NPV for four facade renovation systems.*

The most interesting facade system is clearly the ventilated facade with rigid insulation boards. It has the best circular score and the lowest NPV. The extensive maintenance of ETICS significantly increases its NPV. ETICS is neither financially nor circularly an interesting option. Only four facade systems are evaluated in this study. If the circular score and NPV of more systems is determined and plotted there will most likely not be one optimal solution, but rather an actual Pareto front.

4. Discussion and conclusion

The EURECA project aims to develop a circular facade system for the renovation of high-rise buildings. To objectively evaluate the circularity of the facade systems proposed within the project, a circularity assessment method must be used. Different circularity assessment methods exist but none are completely suited to evaluate facade renovation systems at an early design stage. Based on the evaluation of four existing assessment methods, this research develops a new circularity assessment method, suited to measure the circularity on element level with a limited amount of information necessary, allowing early-stage decisions.

The assessment method considers six parameters: recycling, environmental cost, expected service life, component dependency, layer dependency and flexibility for reuse. The method is tested on four existing facade renovation systems: standard ETICS, circular ETICS, ventilated facade with rigid insulation boards and ventilated facade with flexible insulation.

The ventilated facade systems have an additional material layer compared to the ETICS systems, which enables them to comply with the circular principles ‘independent layers’ and ‘reversible connections’. As a result the ventilated facade systems have a better score than ETICS for the parameters ‘component dependency’, ‘layer dependency’ and ‘flexibility for reuse’.

If per facade renovation system the relative scores of each parameter are added to a single score, without weighting, the ventilated facade with rigid insulation boards is the most circular system, standard ETICS the least. The use of weighting factors can be considered subjective and the representation of the circularity of a facade by a single score can erase nuances. A possible representation of the circularity of a facade system is through a radar chart, with each axis representing a circular parameter. This gives more background information but renders decision-making less straightforward because there is not one single score to take into account.

In reality, the financial aspect is a determining parameter when making renovation decisions. Therefore, the financial aspect is included in the evaluation of the different facade renovation systems by calculating their NPV. Using the Pareto front method, the ventilated facade with rigid insulation boards is circularly and financially the most interesting facade system. In this study the NPV was calculated as if the facade renovation system will stay on the same building for thirty years. It would have been more accurate to consider a scenario where the system is reused multiple times after a shorter time frame on the building, e.g. a scenario where the system is reused three times, each time for a time frame of about fifteen to twenty years on a building. However, the reuse of construction elements is currently no common practice and the prices related to deconstruction and remounting are often unknown.

The assessment method is developed for a renovation scenario. However, in hindsight many parameters and their corresponding scoring systems used in the developed assessment method are independent from the scenario ‘renovation’ or ‘new build’. The developed circularity assessment method can also be used for the new build scenario, but as opposed to the renovation scenario, the bearing structure is taken into account for the scoring of the parameters because this layer is new and therefore its properties can be influenced. The developed assessment method is also suitable for the evaluation of other building elements besides the facade.

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References

[1] European Commission 2019 *Levels Report: Taking Action on the TOTAL Impact of the Construction Sector* (Luxembourg: Publications Office of the European Union)
[2] Bronsvoort E and van Oppen C 2020. *Madaster circularity indicator:* https://www.madaster.com/en/latest-news/blog/madaster-circularity-indicator (accessed October 2020)
[3] Kirchherr J, Reike D and Hekkert M 2017 Conceptualizing the circular economy : an analysis of 114 definitions *Resour Conserv Recycl* **127** 221–32
[4] Circular Flanders 2019 *EURECA*: https://vlaanderen-circulair.be/en/cases/detail/eureca (accessed October 2020)
[5] Ellen MacArthur Foundation 2015 *Circularity Indicators - An Approach to Measuring Circularity* (Ellen MacArthur Foundation)
[6] Cenergie 2020 *C-Calc*: https://www.cenergie.be/nl/diensten/advies/c-calc (accessed October 2020)
[7] Vergauwen A 2020 *Circulair Gebouw – Leidraad Meetsysteem* (WTCB)
[8] Alba Concepts 2020 *Building Circularity Index*: https://albaconcepts.nl/building-circularity-index/#slide-4-informatie (accessed October 2020)
[9] Sierra-Pérez J, Boschmonart-Rives J and Gabarrell X 2016 Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions *J. Clean. Prod* **113** 102–13
[10] Ostermeyer Y, Wallbaum H and Reuter F 2013 Multidimensional Pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment *Int J Life Cycle Assess* **18** 1762–79
[11] Federal planbureau 2019 *Economische Vooruitzichten 2019-2024 – Versie van Februari 2019* (Brussels: Federaal Planbureau)
[12] ASPEN 2019 *ASPEN INDEX - Onderhoud, Ombouw, editie* 53. (East-Flanders: ASPEN)
[13] C-Calc 2020 *Webinar C-calc (10/06/20)*: https://www.youtube.com/watch?v=TkdeRExZ0qw&feature=youtu.be (accessed June 2020)
[14] Alba Concepts 2015 *Building Circularity Index:* https://albaconcepts.nl/building-circularity-index-nieuwsbericht/ (accessed November 2020)
[15] Alba Concepts 2015 *100% circulair in 2050, is jouw organisatie er klaar voor?* (Rosmalen: Alba Concepts)
[16] NIBE 2011 *Bron 2 Bron*: https://www.nibe.info/nl/b2b (accessed October 2020)
[17] OVAM 2020 *Environmental Profile of Building Elements - update 2020* (Mechelen: OVAM)
[18] TOTEM 2018 TOTEM: https://www.totem-building.be/ (accessed October 2020)
[19] Vandenbroucke M 2018 *Rapport Technische Levensduur van Gebouwcomponenten* (OVAM)
[20] Alba Concepts 2019 *Een meetmethode voor losmaakbaarheid* (Eindhoven: Alba Concepts)
[21] Wang W, Zmeureanu R and Rivard H 2004 Applying multi-objective genetic algorithms in green building design optimization *Build Environ.* **40** 1512-25
[22] Zolpan 2019 *Gamme Armaterm – Guide de Composants* (Zolpan)
[23] Rahla K M, Bragança L and Mateus R 2019 Obstacles and barriers for measuring buildings' circularity *IOP Conf. Ser.: Earth Environ. Sci.* **225** 012058