A BIM-based framework to visually evaluate Circularity and Life Cycle Cost of buildings.

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Abstract. The Circular Economy paradigm seeks to shift products and systems from linear to "closed loop" life cycles applying specific business models and strategies to their designs and lifelines. The implementation of the circular economy in buildings depends on the efforts made by all the stakeholder involved in the life cycle of a building, where it can draw most of the benefits if the application of a circular business model is planned during the design phases. Building Information Modelling is an approach that helps designers in creating and managing semantically rich 3D-models describing the status of the building over its life cycle. In this paper, a BIM-based framework for evaluating the application of circular business models of buildings from the circularity and the life cycle cost points of views is proposed.

1. Introduction

The Circular Economy (CE) paradigm is among the strategies fostered by the EU to improve the sustainability of state members' economy. This effort led to the adoption of the Circular Economy package [1]. The Ellen MacArthur Foundation defines the CE as "*an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.*" [2].

The major characteristic of CE is applying a closed-loop life cycle to products instead of a linear one [3]. In order to obtain a closed loop life cycle, a number of business models can be adopted [2] [4] [5] : reduce, reuse, recycle, recover, redesign, remanufacturing (usually referred as 6R) [6], industrial symbiosis, Product Service Systems, etc.…

Despite its recognized potential, the application of CE to the construction industry is still in its infancy and limited mainly to waste prevention and material management (mainly recycling) [7]. Usually, designers do not consider the CE as it requires detailed information about the components used and their materials. Many studies suggest the need for indicators of the implementation of the CE thinking in the construction industry [8] [9] especially to express the circularity of single buildings [10]. Decision makers in the construction industry (architects, engineers, tenders, etc.) need tools to support

them to exploit the value of CE approach with a systemic view of the effects of "circular" business models [8].

Life Cycle Costing is one of the methodologies to evaluate the different design and process alternatives to close the loop of a building's life cycle, from the point of view of the costs associated.

Building Information Modelling (BIM) is a promising approach that supports managing and exchanging semantically rich 3D-models between the project disciplines [11]. BIM is also defined as a "*set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life cycle*" [12]. Using Building Information Modelling (BIM), a building model is depicted as a database which creates an opportunity for incorporating various kinds of sustainability analysis [13]. Therefore BIM can be an instrument suitable to perform assessments (environmental and/or economic) that take into consideration the life cycle of a building and that may be required multiple times over the life cycle.

This paper proposes a framework to enable the assessment of the "circularity" and the LCC of a building in the different life-cycle phases using BIM to collect inputs and visualize the results. The framework was tested using the BIM model of one existing building as a case study.

The paper is organized as follows: Section 2 reviews the state of the art and highlights a gap. Section 3 describes the methodology applied to this research and the output framework and Section 4 presents a case study for applying the framework on a sample building model, highlighting its support for improving the decision-making process through the visualization of different parameters on 3D geometry. Finally, Section 5 summarizes our progress hitherto and presents an outlook for future works.

2. State of the art

2.1. Business models for Circular Economy

"*The term business model refers to the conceptual logic of how the firm creates and appropriates economic value*" [14]. When a business model allows for utilizing the value retained in products after the use to produce new offerings can be called Circular Business Model (CBM). Different CBMs may be required at different phases of a product's life cycle and their successful implementation depends on the actions taken by all the stakeholders [15]. The CBM concept is well addressed in the literature [16] [17] and, at the same time, many attempts have been made to normalize or grouping the variety of CMBs under standard categories [18] [19] [20].

When it comes to CBMs for the construction industry, The Ellen MacArthur foundation states the need for highlighting the value proposition of the CBMs to all the stakeholders, especially to manufacturers and suppliers [21]. The project Building as Material Banks (BAMB), suggests the use of business models that create a win-win situation among the various stakeholders in the life cycle of a building in order to encourage the adoption of circular strategies [22].

In this research, we consider the five business models for circular growth suggested by [16], ranked in order of circularity from "low" to "high" as a measure of environmental gain, as proposed by the Netherlands Environmental Assessment Agency [24]. The CDM proposed by [21] [22] [23] have been mapped to this rank as shown in table1.

Table 1. Business Models and Rank of Circularity

Circular Business Models (CBM)					
[16]	Recovery Recycling	Circular Supply Chain	Product as a Service (PSS)	Product Life cycle extension	Sharing Platforms
[21]		Systemic Circular Product and Process Design	PSS/tracking Facilities	Lifetime extension/support Life Cycle	Sharing Platforms/Sella and Buy Back
[22]	Product/component/material driven	Value Network/ collaboration Driven	Building Performance Driven Product Performance Driven		Collaboration Driven
[23]	Recycle/Compost	Remanufacture	Refit/Refurbish	Retain	

[24]	Recycle/Recover	Repurpose/Remanufacture	Refurbish	Repair/Reuse	Reduce/Rethink/Refuse
Rank	Low	Medium-low	Medium	Medium-High	High

2.2. Life Cycle Costing for Buildings

The Life cycle cost of a system/product includes all costs incurred during its life cycle discounted over its lifetime [25]. Relevant costs or cash flows, if agreed, even income and externalities (usually as Net Present Values [25] [26] [27]) are to be taken into account from acquisition through operation to disposal. LCC is used to make comparisons between different alternatives or to estimate future costs at different levels of project, building or individual component. It may relate to the complete life cycle or have a focus on a specific phase and it can be carried out at every point in time in the building's life cycle [27].

LCC is a dynamic, holistic and systemic procedure [25], as the system, i.e. the building, should undergo this analysis multiple times during its existence for monitoring purposes. In order to cope with uncertainty, multiple scenarios should be forecasted and evaluated.

Depending on the information available on the building, more or less detailed methodologies for LCC can be applied. For example, order of magnitude methods (e.g. cost of construction) when very few information is available and detailed estimates during the executive design phase and during construction. Detailed methodologies for costs calculation require the Work Breakdown Structure (WBS) and the Cost Breakdown Structure (CBS) [25] [28] .

The Net Present Value (NPV) is also one of the most adopted approach in literature and in construction [29] [26] [30] to describe the components of the CBS. In this research, we used NPV as the discounted cash flow technique calculated according to American Society for Testing and Materials (ASTM) as in equation (1).

$$NPV = C + R - S + A + M + E \; (+W + O) \; [31] \tag{1}$$

where C = investment costs R = replacement costs S = the resale value at end of study period (residual costs) A = Annually recurring operating, maintenance and repair costs M = Non-annually recurring operating maintenance and repair cost E = energy costs W = often isolated – water costs O = other costs (e.g. costs of contract). Usually WBS, CBS and the LCC are developed in dedicated software applications separated from the authoring tools.

2.3. BIM and Circular Economy

Many works have focused on the possibility of integrating BIM, LCC and various methodologies for sustainability assessment. A number of tools are available for the integration of LCC and Life Cycle Assessment (LCA) in BIM but these tools are mostly dedicated to new constructions and don't allow for the evaluation of circular strategies like material salvaging and recycle [9]. Liu et al. [32] propose a BIM-based optimization approach to facilitate designers select and improve the buildings' sustainability by applying a particle swarm optimization (PSO) algorithm to find a tradeoff between life cycle costs (LCC) and life cycle emissions (LCCE). Jalalei et al. [33] focused on using BIM for facilitating the selection of sustainable building components at the conceptual design stage, proposing a multi-criteria decision making (MCDM) framework considering three main criteria: environmental, economic, and social factors for identifying the impact of design variations on the building's sustainability.

BIM technology can also support CE by retaining data on materials locked in built assets [21] and as general building data management [22]. In [9], a BIM-based Whole-life Performance Estimator (BWPE) is proposed. Nevertheless, the BWPE is limited to the description of the salvage performance of structural steel components and focuses only on two possible strategies for circularity of the material: reuse and recycle. The BWPE is visualized using a 2D line chart embedded in the BIM authoring tool. The project BAMB [22] will also produce a BIM-compliant prototype to assess buildings capability as "material bank" and will be displayed in a 3D form. From the literature review, it emerged that currently no tool allows for the visualization of a "circularity" indicator directly in BIM authoring tools as an attribute of 3D geometry. This paper wants to address this gap proposing the methodological framework

descrbed in the following section. The framework has been translated into a BIM authoring add-in as proof of concept.

3. Methodology and proposed framework

This research has been developed following the Design Research methodology resulting in an "*artifact created to address a problem*" related to the solution of a relevant business problem [34]. Providing the designer with a framework and a tool to speed up the assessment of design alternatives based on their circularity level and their total life cycle cost is the problem addressed in this paper and the artifact produced is a framework expressed through a software prototype as proof of concept.

Our approach leverages the capability of the BIM-authoring tools to: (i) produce precise bills of quantity using the automation of volume estimation, (ii) enable an easier definition of the WBS using the automation of Product Breakdown Structures (PBS) creation, (iii) link software tools for CBS. This framework is meant for technical users, able to define the activities to be included in the full life cycle WBS for a specific CBM. BIM authoring tools also allows for including information in the building model about the procedures that have to be followed to assure the correct application of the CBM.

A schema of the framework is given in Figure 1. Throughout the process, an LCA database (e.g. GEMIS, openLCA Nexus, etc.), a kernel for LCA calculation and price list databases for construction activities are incorporated to provide a degree of automation of the estimation of LCC and environmental impact as the result of LCA for a specific design variant.
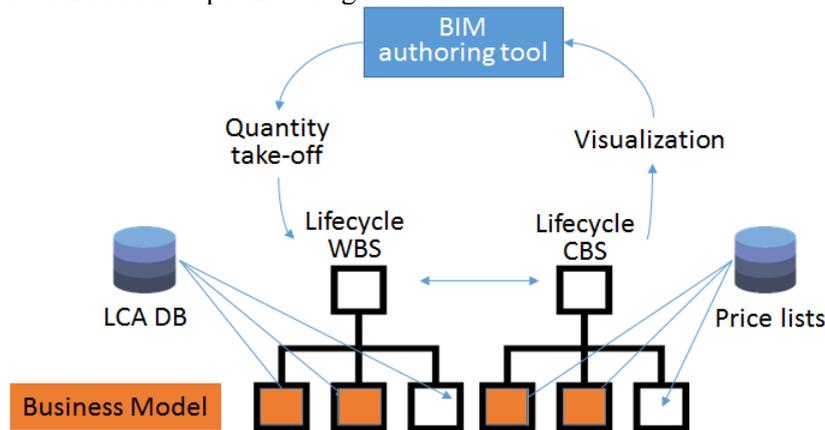

Figure 1. The Proposed Framework.

The framework is implemented as a Revit add-in that allows visualizing a degree of circularity for each group of BIM components involved in a CBM and the life cycle cost associated.

The degree of circularity can take five increasing values from low to high. A color has been associated with each value. For the scope of testing the framework, in this paper a sample Circular Indicator (CI) has been proposed to measure the degree of circularity (2).

$$CI = (CBM+V+E)/3 \qquad (2)$$

Where:
- CBM is a value from 1 to 5 representing the score from "low" to "high" for the CBM assigned to the group of BIM components by identifying the group to which it belongs from the table 1 following the rule in table 2.
- V is a value from 1 to 5 assigned on the basis of the volume involved in the CBM (v). For example, if a group of BIM components is going to be recycled through a process that allows for recycling 80% of its volume, 80% is the volume involved in the CBM "recycling" and the value of V is 4, as in table 2.
- E is a value from 1 to 5 assigned on the basis of the environmental impact obtained in terms of CO_2 calculated with a comparative LCA performed for the design variant with a CBM of a group

of BIM components against the baseline LCA of the same group without a CBM. The default values are assigned as in table 2 (the user has the opportunity to customize the percentages).

Table 2. How to assign values to the terms of the formula (2)

CBM score from table1	Scores and Values assigned				
	Low	Medium-low	Medium	Medium-high	high
V	v ≤ 20%	20% < v ≤ 40%	40% < v ≤ 60%	60% < v ≤ 80%	80% < v ≤ 100%
E	-50% baseline > LCA	-50% baseline < LCA < -10% baseline	-10% baseline < LCA < +10% baseline	+10% baseline < LCA < +50% baseline	LCA > +50%baseline
Value assigned	1	2	3	4	5

Summing up, the "circularity" indicator is based on the rank of the CBM adopted, the volume of the component affected by the CBM and the results of the LCA analysis expressed in terms of CO2. This choice has been based on the will of proposing a sample of simplified index leveraging BIM performance in automating volume calculation.

The LCC is calculated via CBS applying NPV to each component of the structure. The baseline LCC is established as the LCC value of the design variant (DV) not involving a CBM. The design variants involving a CBM, once modelled, are then compared to the baseline. A value among low, low-medium, medium, medium-high, high is associated by default to the LCC of the design variant as follows (the user has the opportunity to customize the percentages):

- -50% baseline > DV → low
- -50% baseline < DV < -10% baseline →low medium
- -10% baseline < DV < +10% baseline → medium
- +10% baseline < DV < +50% baseline → medium – high
- DV > +50%baseline → high

Once the circularity and cost evaluation is completed, it is important to convey the results and communicate their impact to the designer in a proper way. Hence, as illustrated in figure 2, we propose the use of a set of warm colors, including yellow and orange, to warn the designer about the poor circularity or high costs as well as a set of cool colors, like Green and Blue, to imply that the results are good. This proposed approached has been evaluated by our research group as convenient for supporting the decision of choosing which design variant is more suitable and fulfilling the client's intention.
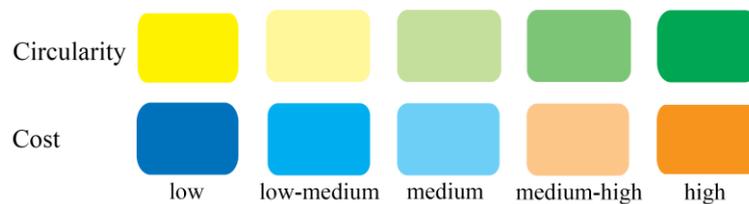

Figure 2. Visualization legend for sustainability and cost ranking**.**

4. Case study

To evaluate the proposed framework's effectiveness, we created a Revit add-in as a prototype, integrating the framework in the BIM authoring environment. The prototype has been tested on two design variants of a BIM model of a building storey. The first variant includes walls with natural hemp insulation and aluminum/wood windows frames. The second variant features thermal insulation in EPS and wooden window frames. Business models and Volume involved in the business model are shown in table 3.

Table 3. Design variants' features.

Variant	Component Group	Material	Volume involved in the CBM	CBM	Circularity	LCC
1	Thermal Insulation	Natural Hemp	80%	Recycling	Medium	Medium
1	Window Frame	Aluminum - Wood	70%	Recycling	Low	High
2	Thermal Insulation	EPS	20%	Recycling	low	Medium-high
2	Window Frame	Wood	100%	Re-use	Medium-high	Low

Based on the inputs of the variants, the add-in calculated the circularity scores reported in table 3 and visualized the related results as shown in figure 3. By clicking on the single component the user can also visualize the LCC of the component in €. All the other groups of BIM components apart from the ones mentioned in table 3 have been hidden for the sake of clarity.
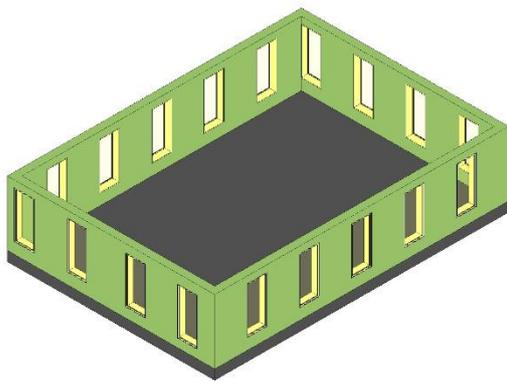
(a) **Variant1: Circularity results**   (b) **Variant1: LCC results**
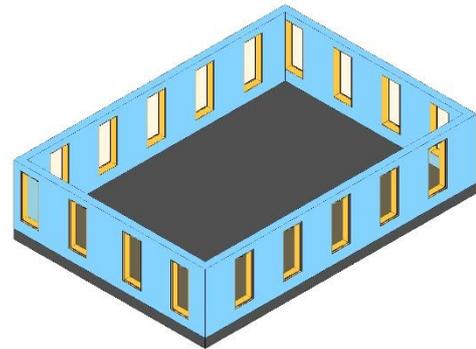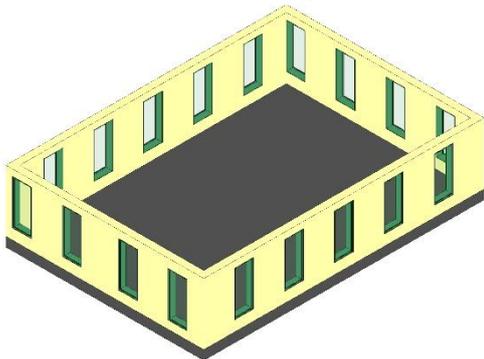
(c) **Variant2: Circularity results**   (d) **Variant2: LCC results**
Figure 3. Visualization of analysis results in Autodesk Revit.
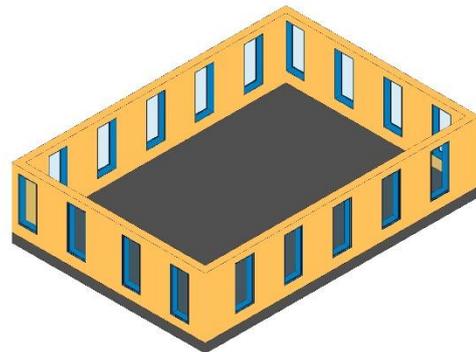
From visualizing the results using the color codes introduced in figure 2, the designer gets an overview of variants performance. As green implies more circularity and blue is less in terms of cost, the designer can compare both variants easily; the insulation of the first variant has higher degree of circularity and lower cost in comparison to the second variant. On the other hand, the window frame of the second variant has higher circularity and lower cost than the first variant. This way, the designer is capable of evaluating the variants' performance visually at a glance using the color codes displayed.

5. Lessons learned and conclusions

In this paper, a framework and a software prototype to improve the assessment of design alternatives based on their circularity level and their total life cycle cost have been proposed. The design process of the framework and the prototype revealed some limitations of the out of the box BIM tool for the visualization of layered elements, like walls, for example limiting the assessment of single layers. It was necessary to manually add categories tag to BIM objects in the authoring tool in order to group them accordingly to the WBS. Sharing quantity data with WBS tools is still a task with a low level of automation with room for improvement. Whole costs for activities related to circular business models where sometimes missed in publicly available price lists (e.g. cost of recycling activities) and manual cost analysis was needed. As a next step, it is necessary to perform iterative rounds of surveys for obtaining feedback from different experts and practitioners in the AEC industry in terms of simplicity, clearness, and support for the decision-making process.

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