Advancing Circular Economy in the Built Environment: A Framework for User-Centered Software Tool Development

Sai Karthik Vakkanthula[1,2] and Mazdak Nik-Bakht[1,3]

[1]Dept. of Building, Civil, & Environmental Engineering, Concordia University, Canada
[2]s_vakkan@live.concordia.ca, [3]mazdak.nikbakht@concordia.ca

Abstract –

The construction industry (CI) is widely recognized for its inherent reluctance to adopt new digital tools, largely due to less than optimum user interface and user-centered functionalities compared to other sectors. Poorly designed software tools that fail to consider users' needs, such as ease of use, adaptability, and intuitive learning experiences face limited acceptance. Despite this understanding, few studies have reviewed user-oriented capabilities in software tools for the construction industry, particularly those designed for circular economy applications, resulting in tools with fragmented functionalities. This qualitative study addresses this gap by identifying key user-centered requirements for circular economy (CE) software tools (STs), focusing on tools for material inventorying. A literature-based review is performed to develop an evaluation framework adapting the framework of life-cycle assessment (LCA) tools for early-design stages four themes: Input, Analysis, Output, and User Interface (UI) or User Experience (UX). Using this framework, four commercially available STs for material inventorying of built facilities were evaluated to understand their relevance to support CE practices. Results indicate that essential user requirements such as integration, decision-making support, adaptability, and interoperability with other CE technologies are largely unmet. Additionally, no comprehensive tool currently addresses performing financial analyses of various deconstruction techniques, and disposal choices. The proposed framework with user-centered criteria provides a valuable roadmap for developing user-friendly software tools, to advance circular economy practices. While the user-centered needs are defined based on literature, there is a necessity to assign an order of importance to these criteria from the perspective of industry stakeholders.

Keywords –

Deconstruction, Circular Economy, User-Centered Design, Evaluation Framework, Tool Review

1 Introduction

The construction industry significantly contributes to global solid waste. In Canada, the construction, renovation, and demolition (CRD) waste accounts for 12% (4 million tonnes) of Canada’s total solid waste, with only about 16% diverted from landfills in 2010 [1]. Circular economy (CE) offers an effective solution to manage CRD waste by eliminating the end-of-life (EOL) phase of materials. CE aims to extend the materials and components lifespan in the built environment, maximizing their economic, environmental, and social value [2]. This is achieved through the direct reuse of materials and components from old structures as secondary resources in new construction [3].

Maximizing recovery of secondary resources requires understanding of material and component stock (MCS) composition of built facilities nearing EOL. This knowledge guides the selection of deconstruction techniques and their sequence, and in turn, influences the type of resources generated and second-life use decisions [4]. However, in legacy buildings, this data in the format of as-built documentation is often unavailable or incomplete [5], necessitating labour-intensive and non-scalable manual pre-demolition audits.

Demonstrating the potential secondary resources is necessary to shift stakeholders' perception from conventional demolition to selective demolition, if not deconstruction. However, most of the current research to simplify estimation of MCS composition and reduce manual efforts focuses on urban-scale and above, helping governments assess potential and formulate regulations for urban mining. They fall short in supporting other industry stakeholders, especially contractors and developers, who require MCS information at smaller spatial scales, preferably building level or lower [6].

With increasing recognition of the value of inventorying existing facilities [7], there is a need for reliable, quick, accurate, and affordable software tools (STs) that estimates MCS of built facilities, effectively transferring frameworks devised in research to industry. Despite this pressing need, few STs exist and most lack practical functionalities, limiting their use to inform decision making.

Yet, a tool that only estimates the material and component stock may not be able to provide enough value to advance the idea of circular economy practices or get widely adopted by the industry users. If a tool does not follow needs-driven development or imposes labor-intensive workflows, adoption is unlikely [7]. For instance, a Dutch social housing organization generating material passports (MPs) for its building stock as a pilot project preferred a service provider that automated MP creation via artificial intelligence (AI) vision techniques over a provider's tool that made use of building information modelling (BIM) data and required manual input. The users in the latter case perceived MPs as just another task, rather than recognizing its underlying value [8]. This user perception reflects that even with identical outputs, tools that address user needs and minimize workload are favored.

Evaluating how well existing STs are designed to meet the needs of stakeholders is crucial, considering the wide recognition of the construction industry's (CI) inherent reluctance to adopt new digital tools [8]. This reluctance is often paired by less than optimum user interface (UI) and user-centered functionalities in CI compared to other sectors [9]. This understanding is essential for developing STs for fast quantity take-off (QTO) of built facilities, which are still in their infancy, that go beyond material stock estimation and account for other user-centered needs.

What are these user-centered design requirements that must be incorporated into software tools for fast QTO of built facilities to advance CE? This paper seeks to evaluate the technical features, and user-centered design requirements for such a tool by addressing the following specific objectives:

1. Understand user-centered requirements to increase a software tool's acceptance; and
2. Identify the capabilities and limitations of commercially available software that support automated QTO by assessing their alignment with the defined user-centered requirements.

2 Methods

This paper achieves its objectives in two steps. In first step, the criteria from existing studies on Life Cycle Assessment (LCA) tools for early design stages are utilised to establish user-centered design requirements of STs for automated QTO in the CE space. In second step, commercial software tools are identified and evaluated based on their features, shortcomings, and alignment with the defined criteria, providing insights for future ST development. The two steps are discussed in detail below.

To define user-centered requirements, criteria formulated by [10] -[12] to assess LCA tools for early design stages were taken as a starting point, see Figure 1. This is because these tools share the similar context: limited data availability on building geometry and materials during early design stages, and they aid users in decision-making of design choices. This parallels the requirements for STs for fast QTO of built facilities.

These criteria were refined and adapted to fit the specific nature of fast QTO for built facilities, through a review of articles on digital technologies for the circular economy, resulting in a revised framework with four themes: Input, Analysis, Output, and User Interface (UI) or User Experience (UX).

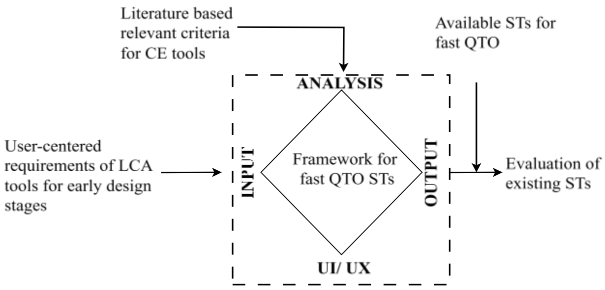

Figure 1. Methodology for framework development

The list of STs for automated QTO was compiled through a review of published and grey literature as well as an informal Google search. A keyword search using ("Software Tools" OR "Digital Tools") AND ("existing buildings" OR "building stock" OR "legacy buildings" OR "built environment") was conducted in "Scopus" and "Google Scholar" yielding many results. The search identified tools that are either proposed in research, existed as proprietary software, or function primarily as material inventory management software for recovered materials at a building's EoL. While these STs come under the broader CE context, they are either underdeveloped as research projects or unavailable for purchase or subscription, or lack core CE functionalities, making them unsuitable for this study's scope. To ensure relevance, the STs presented in this study are selected based on the following criteria:

- focus on built facilities (as opposed to new construction);
- generate material composition as a primary function or as part of other functionality, such as LCA;
- provide granularity at the building level or lower (i.e., building assemblies and subsystems);
- do not require detailed as-built drawings or 3D

digital models; and

- are not BIM software plugins or addons.

The selected STs were evaluated based on their software characteristics, purpose, data requirements, analysis mechanisms, output generation, and limitations, gathered from software websites, documentation, and literature. Subsequently, their alignment with the user-centered requirements was analysed.

3 Framework Development

Few studies analysed the essential functionalities required for software tools to promote a circular economy but have done so in a fragmented way. Rexfelt and Selvefors [7] provided a comprehensive review of circular design tools and their characteristics. Çetin et al. [8] and Yu et al. [9] identified barriers to adopting digital technologies for circularity in the built environment. Akinade et al. [13] outlined the essential technical functionalities for a BIM-based deconstruction tool to ensure wider acceptance. Relevant recommendations from these studies were used to revise and adapt original framework, LCA tools for early design stages, to suit the context of STs for fast quantity take-off of built facilities. These user-centered requirements are categorized into four key themes: Input, Analysis, Output, and UI/UX, and are summarized in Figure 2, with each theme represented by a distinct colour. These criteria are discussed in detail in the following subsections.

3.1 Input theme

In terms of inputs, the primary requirement is the integration of software tools into existing systems of users' organizations, with minimal need for new infrastructure or adjustments, and the ability to read information from existing databases. Additional requirements include limited data input, indicating the use of easy-to-access building characteristics or properties, and support for scalability.

3.2 Analysis theme

In the analysis theme, users favour transparency concerning the assumptions, equations, and thumb rules used to derive the material quantities [12], for a better understanding of a software tool's performance. Another key requirement is fast calculation, which in the current context implies minimal run time to generate results through reduced computational complexity and resource intensity. The tool's acceptance is also affected by its ability to support decision-making through the evaluation of alternative disposal choices, respective financial costs and returns [8], making the potential profits tangible.

Apart from the above, Kobylinska et al. [14] suggested that STs using machine learning to predict material quantities should include a pipeline in the system architecture for continuous training of machine learning (ML) models on the expanded dataset when certain preset criteria are met.

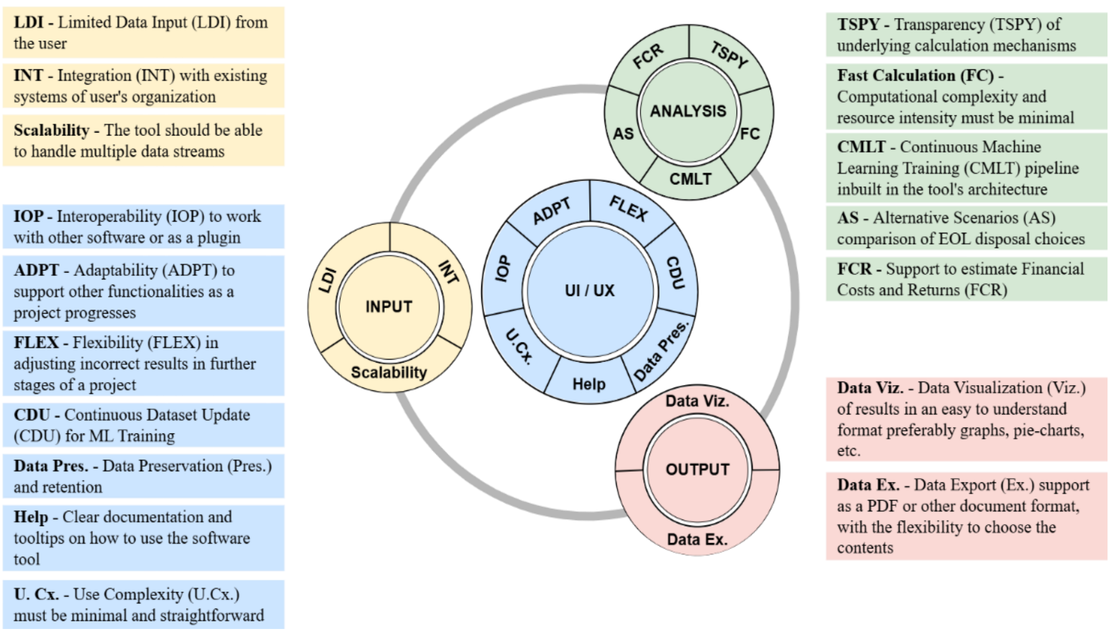

Figure 2. User-centered requirements for software tools

3.3 Output theme

The qualities favoured in the output theme include results presentation in visually appealing formats such as bar charts, pie-charts, etc., and the ability to generate reports in commonly used file formats for data sharing among stakeholders [12]. The tool should also allow users to query material quantities aggregated at the whole building level as well as by building systems and assemblies. Additionally, it should enable exporting the results in an open file format for use in other circular digital tools.

3.4 UI/ UX theme

Under this theme user-centered requirements, which are general, include ease of use and intuitive learning, floating tooltips, data preservation to prevent loss, and documentation for tool use and troubleshooting. Other characteristics preferred include interoperability, representing communicability with other software such as geographical information systems (GIS) to query geometrical information of a building, circularity indices, LCA, MPs, and digital marketplaces for secondary resources. These tools are being increasingly used in the construction industry to drive CE initiatives. The adaptability of a tool as the project advances into the next stages is another important requirement, which for the circular economy means support for deconstruction scheduling, in-built material passport generation, end-of-life LCA, etc. Since the material quantities generated by the STs are not always accurate, the tools should be flexible enough to allow users to modify quantities and specifications when inaccuracies are identified in later project stages.

4 Evaluation of Commercially Available Software Tools

To assess the extent to which the user-centered criteria were incorporated into commercial software, STs were identified and evaluated for alignment, with results provided below.

4.1 Existing Software Tools

Four software tools, with an overview provided in Table 1, were identified and selected after performing the search outlined in section 2: Demolition Waste Generation (DWG) Calculator for Metro Vancouver, EVALMETAB, Carbon Designer 3D add-on for One Click LCA, and the LCAbyg tool. Of the four tools, two tools focus on demolition waste, and the other two are designed for the whole building LCA.

DWG Calculator, Metro Vancouver is a web-based developed for the Vancouver Metropolitan Area, British Columbia to allow denizens to estimate the waste generated from residential demolitions [15]. The tool estimates the quantities of five materials, in kg (or) lb, using MICs based on gross floor area (GFA) and the municipality where the house is located.

EVALMETAB is a web-based tool, specific to France, that quantifies fourteen materials, in tons, based on GFA and covers 14 typologies of existing buildings and 12 typologies of new buildings. The tool allows users to visualize the materials generated from the demolition of old buildings and those required for new construction. It also supports the evaluation of various recycling scenarios, transportation cost estimation for waste disposal, and the associated greenhouse gas emissions [16], [17].

Carbon Designer 3D is a web-based add-on for the One Click LCA tool, originally designed for early design stages, generates predefined assemblies and corresponding material quantities of existing buildings to perform whole building LCA. The areas of predefined assemblies and material quantities are calculated based on parametric equations and thumb rules. Users start by selecting country-specific representative buildings from predefined types and input information regarding building characteristics to estimate the areas of assemblies aggregated by building systems [18], [19]. The tool allows users to modify the estimated quantities, assembly types, and material composition of the assemblies, and inventory is presented to the user in tabular format and carbon footprint as a heatmap on a 3D model of the building.

LCAbyg is a desktop-based building LCA tool for Danish buildings and features an automated material inventory functionality [20], [21]. The tool requires users to input information for eight variables, which are then used to calculate the quantities of predefined component layers of assemblies using predefined geometrical constants and parametric equations. At present, the tool provides automated inventorying of only one typology, masonry apartment – 1850 to 1920, and has the flexibility of allowing users to modify the generated results.

4.2 Discussion

The few software tools available in the market are not comprehensive and focus on demolition waste prediction at the whole building level for limited typologies or support whole building LCA rather than building material inventorying, falling short in supporting the circular economy for built facilities. Apart from technical functionalities, the available STs fall short in their lack of alignment with user-centered requirements.

Key user requirements, as outlined in Figure 3, missing from available tools include integration, decision-making support, adaptability, interoperability with other CE technologies, and enhanced data output

Table 1. Overview of software tools for automated inventorying of built facilities

	Tool name	DWGR Calculator	EVALMETAB	Carbon Designer 3D	LCAbyg
CHARACTERISTICS	Type	WebApp	WebApp	WebApp – add-on for OneClick LCA	Desktop Application
	Country	Canada	France	Europe, USA, Canada, and International	Denmark
	Release Date	July 2018[1]	June 2021	May 2022	October 2020
	Access	Open-Access	Open-Access	Paid	Open-Access
	Purpose	Demolition Waste	Material Flows and Demolition Waste	WBLCA	WBLCA
	Calculation Algorithm	MIC*	N.S. *	Geometrical and parametric equations, average ratios, and thumb rules	Geometrical and parametric equations
CAPABILITIES	Number of Typologies	1	14 - Existing and 12 - New	15	1
	Number of Building Systems	0	0	6	7
	Lifecycle Phase	End-of-Life	End-of-Life and Early-Design	Early-Design and Renovation	Renovation and End-of-Life
	Unit of Measurement	kg (or) lb	Tons	m^2 or m	m^2 or m
	Level of Granularity	Whole Building	Whole Building	Assemblies	Assemblies
	Level of Recovery	Materials	Materials	N.A. [2]	N.A. [2]
	Calculable Materials	5	12	N.A. [2]	N.A. [2]
INPUT	Input Features (Total/ Categorical/ Numerical)	2 / 1 / 1	1 / 0 / 1	17 / 3 / 14	8 / 5 / 3
OUTPUTS	Special Features	None	Recycling Costs	3D building model with carbon heatmap	None
	Data Export	None	Excel	PDF, Excel, CSV, XML	PDF, Excel, JSON
	Data Visualization	None	Bar charts	Predefined charts, Sankey, Spidergrams	Predefined charts

* MIC – Material Intensity Coefficient (material weight in kg/ m2 of floor area), WBLCA – Whole Building LCA,
N.S. – Not Specified, N.A. – Not Applicable
1. Reflects the first known reference to the tool. However, exact release date remains unavailable
2. The software tools provide a detailed material composition of each assembly; however, material quantities must be added manually if required.

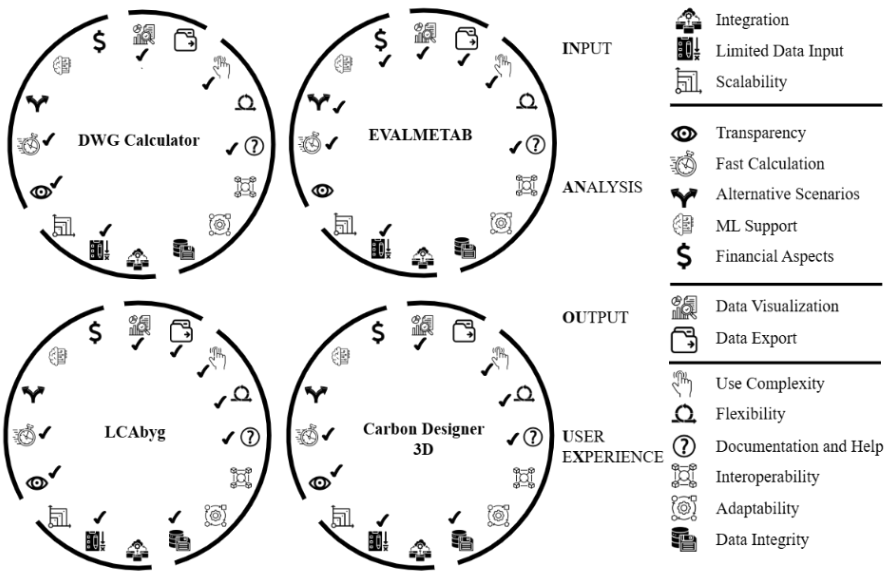

Figure 3. Alignment of identified software tools with user-centered requirements

capabilities. Although the reviewed tools provided some knowledge of the underlying calculation mechanisms, the information is neither comprehensive nor complete. This lack of transparency hinders user acceptance, as potential users may not fully understand the results [22]. The reviewed tools also have limited capabilities for performing financial analyses of alternative demolition techniques and disposal choices, and the absence of these affects their usefulness in decision-making. The lack of these functionalities in Carbon Designer 3D and LCAbyg tools is understandable as they are not primarily designed for material inventorying.

Currently, the STs for circular economy possess stand-alone functionalities requiring the use of several tools to accomplish diverse tasks as a project advances. As the data requirements for circularity applications are not yet standardized [8], the variety of digital technologies used by stakeholders can result in interoperability challenges. Accommodating different functionalities under the umbrella of a single tool or establishing data standards for data sharing among different tools can solve adaptability and interoperability challenges.

Most digital tools in the CE environment such as OneClick LCA and GaBi Circularity Toolkit, focus on LCA component during the early design stages, as the decision-making strategy [18],[23]. The research on software tools for CE has focused on developing digital marketplaces (DMP), data management, and material passport generation tools such as Madaster [24], Cirdax [25], and Loopfront **Error! Reference source not found.** require material information to be entered manually and are useful only once the material inventorying is completed.

As an industry known for the slow adoption and the workforce's inherent resistance to modern technologies, the shift to circularity is further complicated by high implementation costs, lack of trained personnel, and difficulty in identifying available tools [27]. To address these issues STs should be robust, effective, comprehensive, and meet the actual needs of CE stakeholders. Future tools developed for the circular economy should consider these requirements and aim to bridge the gaps in the existing STs to improve their quality.

5 Conclusion

The results indicate a consensus among the industry stakeholders on the potential of mining buildings for secondary resources and the vital role of digital technologies in driving circularity. However, a gap remains in the availability of STs for rapid, accurate, and affordable material inventorying of existing buildings.

This paper derived a literature-based framework on user-centered design requirements to guide the development of software tool that performs fast quantity take-off of built facilities to support a circular economy. Based on this review, an evaluation framework with criteria for user-friendly software tools in circular economy applications was developed and used to determine the adequacy of four identified commercial tools for automated inventorying. The development of this key-criteria is a valuable step toward designing new STs for CE in built environment.

This study is limited to the user-centered requirements derived from published literature, and the software tools were evaluated based on these criteria, highlighting only theoretical requirements. Consequently, further research will focus on identifying user-centered design requirements and technical functionalities considered critical and feasible by industry stakeholders, through surveys and interviews. Based on these insights, the feasibility of implementing the prioritized criteria in a software tool for fast QTO of built facilities will be investigated.

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