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Validation of a Gamified Circular Design Methodology through a Design Workshop

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ABSTRACT

This research integrates theory with practice (thought and action) connecting real-life problems to theorical foundations, with the dual aim of solving a design problem in the circular economy (CE) and delivering new knowledge through experimentation. This paper stems from the observation that architects commonly rely on their personal experience while designing without adopting structured frameworks. The present study aims at validating a previously proposed circular design methodological framework in practice. To achieve this aim, the research employed a design workshop to test this design methodology. This is followed by an analysis of how non-expert architects in CE perceived and applied it. The study recorded participants' interaction with the gamification sense implied in the methodology and assessed their ability to develop designs compatible with CE principles. Data collection included sketches, video recordings, observations, and written notes. The findings highlight the potential of the circular design methodology to support the design process in CE. Participants reported positive experiences, describing the methodology as flexible, easy to comprehend, enjoyable, time-efficient, and educational. The results validate the applicability of this circular design methodology, leading to setting a step-by-step guideline for its future implementation. Ultimately, the validation of this design methodology may promote wider dissemination and acceleration of the culture of circular design in architectural practices, even for non-expert architects in CE.

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1. Introduction

Circular Economy (CE) emerged as a distinct concept in the late 90s [1]. CE differs from sustainability by having its unique principles and strategies, prompting research on its impact on architectural design. In this context, CE differs from traditional sustainability practices by emphasizing efficient material use, waste reduction [2, 3] and lifecycle extension [4] through different design strategies such as adaptive design and reusing. Implementing CE in architecture requires new design approaches, knowledge, and interdisciplinary collaboration [5]. Whereas sustainability broadly addresses environmental impacts, CE specifically targets resource efficiency and waste reduction in building design [6]. Overall, CE represents a shift towards more lifecycle-oriented architectural design compared to traditional sustainability approaches. Since CE focuses on extending lifecycles, reducing waste, and reusing resources [7, 8], circular design plays a crucial role in implementing these principles by integrating circularity considerations from the ideation stage [9]. Circular design strategies focus on regenerating, slowing down, narrowing, and closing resource flows [10, 11].

The CE addresses and responds to global challenges such as resource depletion, waste generation [12], and climate change. In building design, several CE strategies offer significant potential for mitigating climate change impacts [13-15]. For instance, reusing, recycling discarded waste, design for disassembly [16, 17], using bio-based materials [18, 19], enhancing indoor and outdoor environment, stimulating biodiversity through vegetation, and adaptive reuse. Such strategies aim to reduce greenhouse gas emissions, minimize waste, and conserve resources throughout a building's lifecycle [20]. Moreover, the design process is critical, as 33% of construction waste results from inadequate waste minimization strategies at this phase [21]. Implementing practices like design for disassembly, renewable energy use, design for durability, prefabrication, repair, refurbishment, recycling, and recovery [22-25] can significantly reduce waste, environmental impacts, and lifecycle costs [26, 27].

Furthermore, the CE offers solutions for shrinking economies by transforming waste into resources, potentially reducing costs and conserving resources. This is particularly relevant for emerging economies facing economic challenges. According to the World Bank, many emerging economies have experienced economic shrinkage, which consequently has negatively affected multiple sectors [28]. In this context, circular design is a route for new opportunities, in which waste in one cycle becomes resource in another cycle [29]. A major challenge associated with shrinking economies is increasing costs, while circular design offers promising opportunities to save costs and resource. Expanding the application of CE in architectural design is therefore essential, as its outcomes may be relatively effective in the face of economic decline.

The adoption and application of the CE concept and its strategies in Egypt and other developing countries remains at an early stage. Egypt's Sustainable Development Strategy 2030 [30] emphasizes waste management, resource efficiency [31], and the use of modular construction [32], aligning with CE principles of modularity, flexibility, and adaptability. Additionally, studies suggest that vernacular architecture techniques and local building materials can inspire contemporary circular practices in Egypt's built environment [33]. Current applications of waste reduction primarily focus on the construction phase [12, 34, 35], while the early design phase remains overlooked. Although Egypt’s Vision 2030 promotes recycling initiatives, integration of a broader range of CE strategies into architectural practices is still limited [36]. Key barriers to implementation in developing countries include lack of frameworks, regulations, and awareness [37]. This made it a necessity to develop frameworks that link CE with architectural design, emphasizing circular resource use to bridge the gap between economic theories and architectural practices. The reason for choosing this research area is the absence of a circular design culture in architecture. Circular design is underrecognized due to the lack of clear methodologies and architects’ limited knowledge of the full spectrum of CE strategies.

The significance of this study lies in enabling architectural circular design to be communicative and repeatable through a gamified design methodology. Methodology development is central to design research, as it provides a structured approach for conveying knowledge about how design aspects can or should be carried out in a structured way [38, 39]. At the same time, gamification is widely recognized as an impactful pedagogical tool that stimulates design thinking [40-44]. In previous research, the authors developed a circular design methodological framework in a gamified format to aid in quickly and effectively understanding the content of the methodology and circularity concepts [45]. Building on this, the present study aims to operationalize circular design in architecture by experimenting this design methodology to pave the way for non-expert architects in CE to practice it. This study questions how non-expert architects in CE can be methodically stimulated and systematically guided while practicing circular design.

The paper is organized into four sections. The first outlines the research methodology, describing the preparation of the design workshop. The second builds on this to implement the circular design methodology in solving a design problem by a group of architects and reports the results, showing participants' feedback and observations of their interaction with the investigated design methodology. The third discusses the findings from testing the design methodology and proposes guidelines for its future application. Finally, the paper is concluded with brief remarks.

2. Materials and Methods

This section introduces a previously developed design methodology intended to guide architects in designing buildings in compliance with CE principles. Afterwards, this part suggests experimenting the design methodology in practice, to validate its future application, through a design workshop. The second part of this section describes the design task selection, the setup planning of the workshop, its implementation, and participants' profile.

2.1. A Gamified Architectural Circular Design Methodology

The previously developed circular design methodology by the authors acts as an accelerator method as it is represented in a gamified way. It is aimed to support architects, non-experts to CE, during the design process. The proposed design methodology in its sense of gamification features user-friendly, haptic, and playful tools: (1) a tabletop gameboard for a step-by-step design process, (2) a circular design strategies wheel, (3) design action cards, (4) a holistic circularity calculator (Hol. C-Calculator), and (5) a dynamic sunburst chart that illustrates the contribution of various circular strategies [45]. Fig. (**1**) demonstrates these five tools in order.

The previously developed methodology can be utilized by architects at various stages of the design process. The step-by-step design process incorporates enablers such as supporting digital tools, roles of architects, and key competencies required. The strategies wheel acts as an exploratory guide, allowing users to navigate through different categories and learn about various circular design strategies. The strategies wheel comprises 20 circular design strategies applicable to building design. They are arranged clockwise in a hierarchical order, from the most impactful (green) to the least impactful (red). Each strategy is supported by available digital tools, shown in shades of blue, and key competencies and roles of architects, indicated in red with the initials R and C. Then, each strategy is supported by a set of design action cards to facilitate its implementation. This results into 92 actionable cards, each color-coded to match its corresponding strategy in the wheel. Each card contains a textual description of the design action, an illustrative drawing, suggested tools to be used during the design process, and the required competencies and roles of architects.

Additionally, the methodology can serve as a tool for making design decisions and can assess design proposals to enhance circularity. Assessment of design proposals can be conducted through a circularity calculator, which provides both quantitative and qualitative indicators. The developed calculator strikes a compromise between details of different circularity aspects and computation simplicity to be applicable during early design phases. After entering some data into an Excel sheet, automatic calculations generate a circularity score, percentage representing the degree of circularity, and circularity classes based on the obtained score (class 5: most circular and class 1: least circular). The score and classification are complementary, aligning with each other to provide a coherent evaluation. The sunburst chart further allows for identifying the shares of all integrated circular design strategies in a design solution. The next step is to validate this proposed design methodology to encourage architects to adopt and test it in their practice.

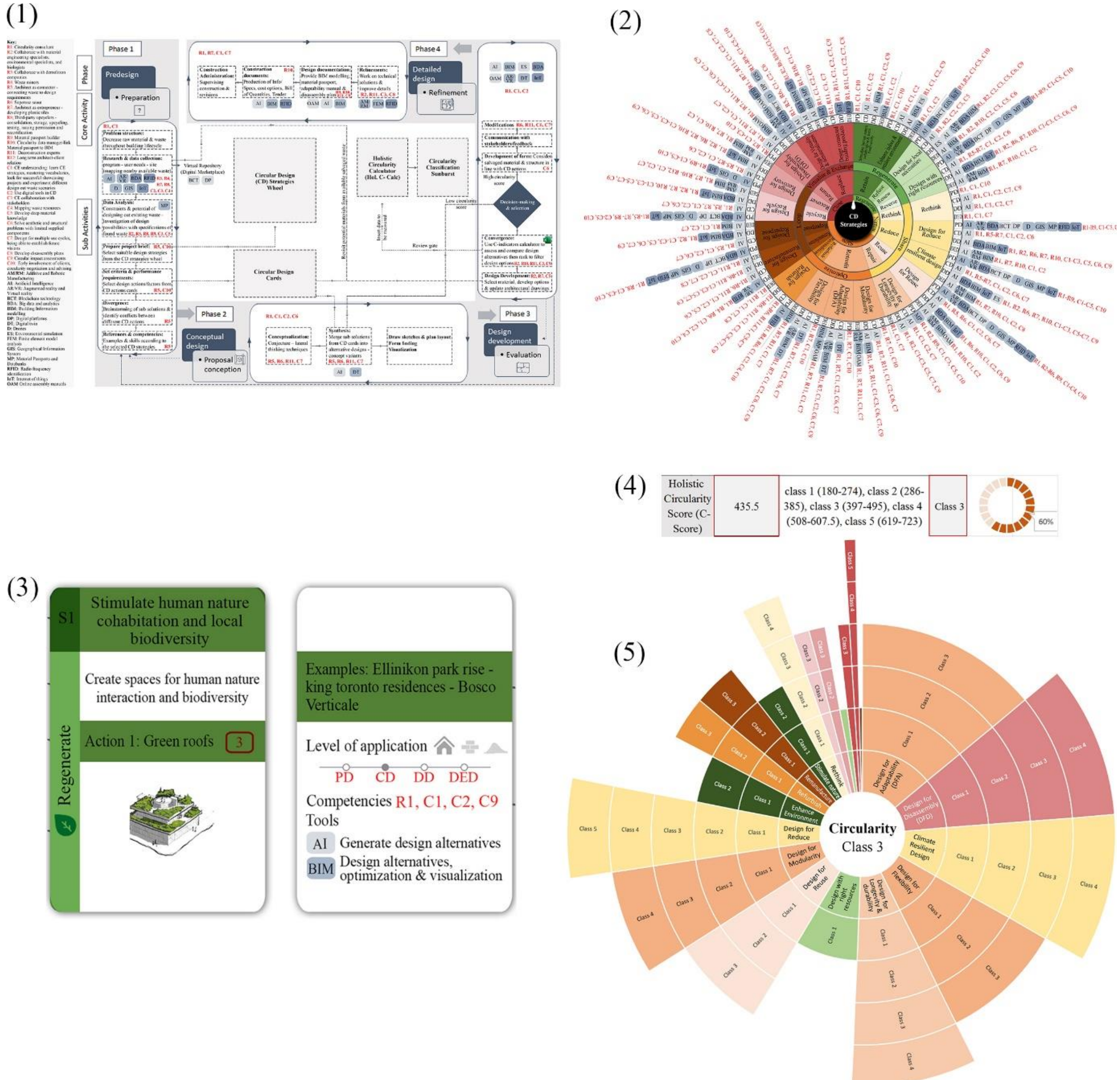


Figure 1: An overview on the gamified developed tools that form a circular design methodology. (Source: Adapted from [45]).

2.2. Design Workshop Preparation

Cambier, Galle and De Temmerman emphasize the significance of a participatory, practice-oriented approach when developing and studying design support methods for circular building [46]. Therefore, this research employs experimentation through a design workshop. A workshop is a practical approach to working, thinking, and learning, serving as a structured tool for generating ideas and making decisions. In academic contexts, it facilitates knowledge transfer by equipping participants with relevant skills [47, 48]. What sets workshops apart from other methods is their ability to stimulate imagination and creativity [49]. Therefore, to demonstrate the applicability of the developed methodology, shaped by the considerations outlined in previous research, it is tested in a design workshop.

The conducted workshop was attended by four architects with professional experience ranging from 3 to 15 years, none of them had previously practiced circular design. They engaged in a collaborative design process for developing solutions that respond to CE principles. The workshop is planned to be concluded with a follow-up discussion on key insights, generated ideas, and participants' impressions of utilizing the circular design methodological framework. The workshop is intended to observe the design pattern followed when using the proposed circular design methodology and to collect participants' feedback. This section outlines steps undertaken to prepare for this workshop.

2.3.1. Design Task Selection

To manage time and effort and to enable prompt feedback, restrictions have been set to the scale and scope of the design problem. The chosen design intervention is a small-scale building situated in an informal district within the Al-Fustat area of Cairo, Egypt. The task was to add an extension of two storeys to an existing cultural building at the lowest possible costs, as it belongs to a non-governmental organization. This cultural center, named 'Dawar El Ezba', is located in Ezbet Khairallah, one of the largest informal areas in Cairo. In this project, the client, 'Dawar for Arts and development', requested adding upper floors and renovating the existing building to expand its spaces. This design problem is already approached by the Egyptian architect Ahmed Saafan in 2019 and his design - an award winning - has adopted some CE principles. The architect presented this project in 2020 at one of the UN online seminars, illustrating the participatory approach he experienced using some of the CE principles. Table **1** provides collective data for this case study. The challenge of applying reusing and recycling concepts in an informal area is the reason behind choosing this case study. Thus, it is specifically chosen to test the proposed circular design methodology. If the methodology managed to guide architects for a more circular design, this would validate its applicability in promoting circular design thinking.

Table 1: Collective data for the chosen case study, as presented by the original architect.

	Case Study	Dawar El Ezba
General Information	Location	Ezbet Khairallah, Fustat District, Cairo, Egypt
	Year	2019
	Architect	Ahmed Hossam Saafan
	Consultant	ARABCO Consultants
	Manufacturers	ARABCO Consultants, Albrecht Von Bremen, and Divinus Designs
	Plot size (Footprint)	81 m²
	Existing number of floors	2
	Footprint area	11m*7.25m

This case shows contextualizing of reusing and recycling at different scales by superusing any discarded elements and materials that can be integrated. These resources may include what is considered waste or even non-standard building materials. In this case, designs are adapted to the found resources, regardless of their homogeneity or compatibility with each other. Instead, the design needs to reuse or recycle a collage of a wide range of available resources. The architect decided to integrate locally available resources to meet the requirements. Since the site was surrounded by many metal and wood workshops, as demonstrated in Fig. (**2**), the architect chose wood as both the principle structural and finishing material. Recycled materials were deliberately left exposed, whether as roof structure or as finishing materials. Corrugated sheets were reused for the roof and facades, reassembled into sandwich panels (Fig. **3-4**). These materials were sourced from nearby sites to cut down expenses by eliminating transportation and basing the design on an already existing and discarded resources. In addition, the architect added a vertical green wall inside the building to serve the kitchen, while also helping cool and purify the air in this densely district. All these features, as illustrated in Fig. (**5-6**), make the building a living agent in such a highly polluted urban context. Moreover, the use of locally sourced materials reformulates the architectural language of this area [50].

Figure 2: An Ariel view for the case study (the yellow building) showing its location in an informal district and the surrounding wood workshops (Source:[50]).

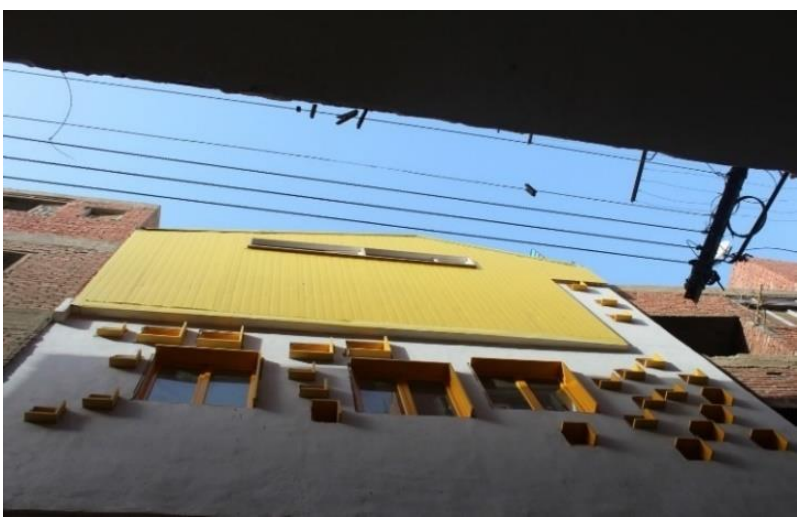


Figure 3: An exterior shot from the street showing the southern elevation (Source:[50]).

Using the proposed Hol. C-Calculator, this project was assessed before carrying out the design workshop to evaluate its circularity level. The Holistic Circularity Score (C-Score) obtained was 322.7, representing 45% and this is considered class 2. Detailed classes of different design strategies, as presented in Fig. (**7**), show that the design focuses on strategies such as 'rethink', 'design for reduce', and 'design for recovery', while ignores CE strategies like 'design for local necessities', 'design for reuse', 'adaptability', 'flexibility', 'design for repurpose', and 'design connected building products'. This evaluation is conducted to enable comparison with the new designs created using the developed design methodology. Consequently, this can assist in validating the assessment method proposed.

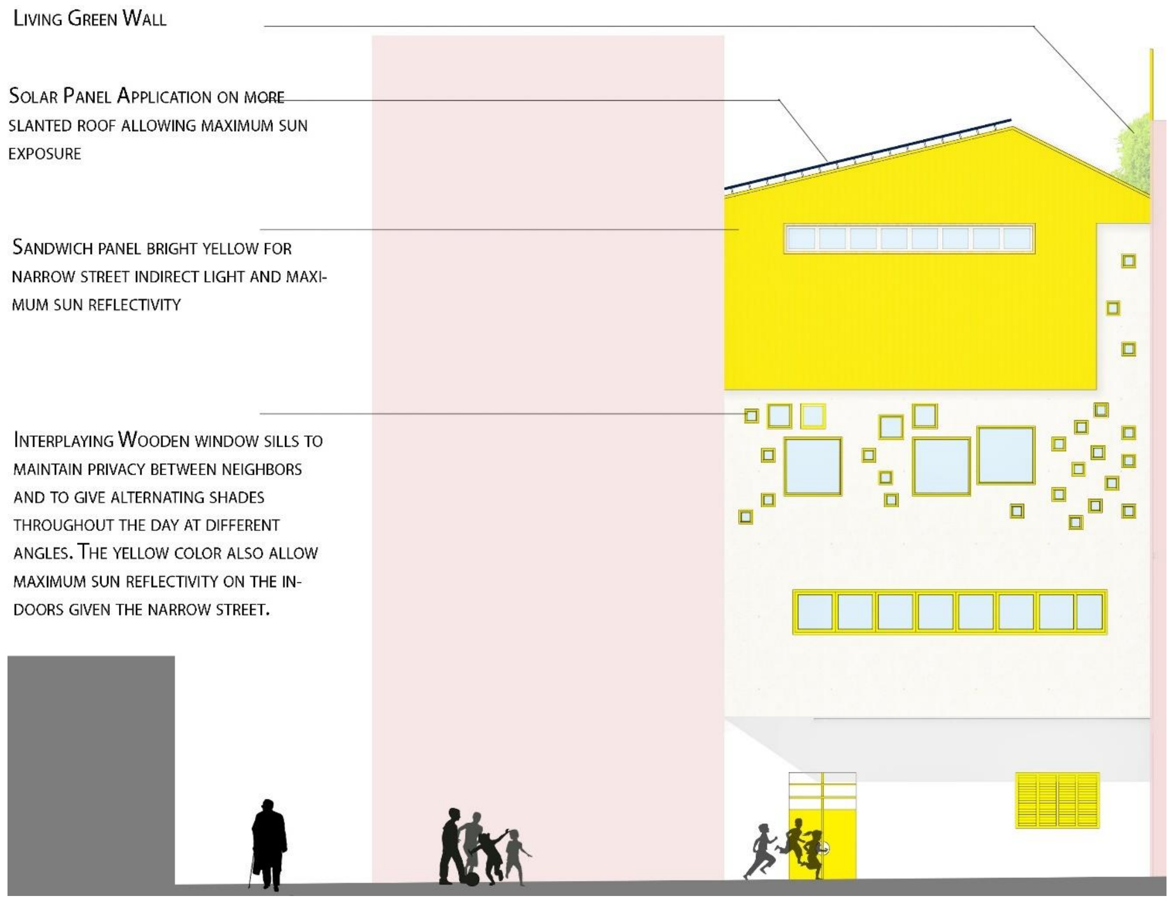


Figure 4: Design elements forming the southern facade (the street). (Source:[50]).

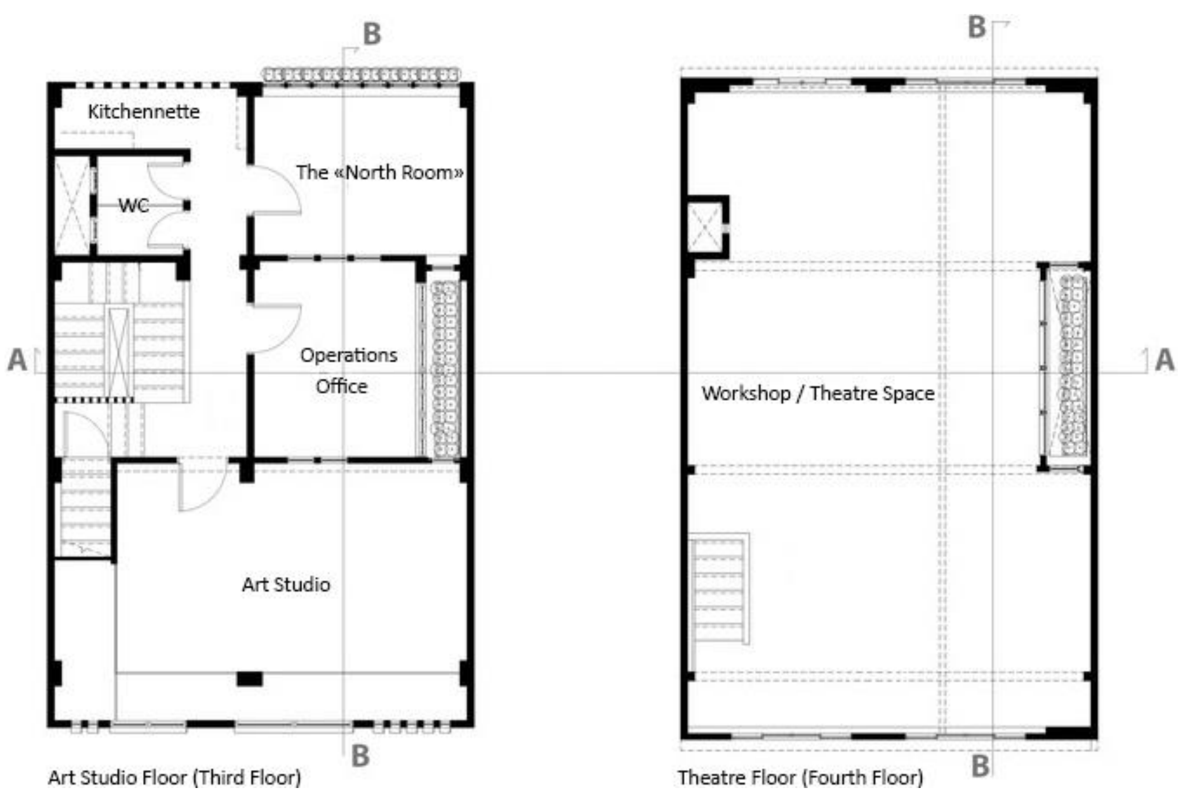


Figure 5: Added floors plans (Source:[50]).

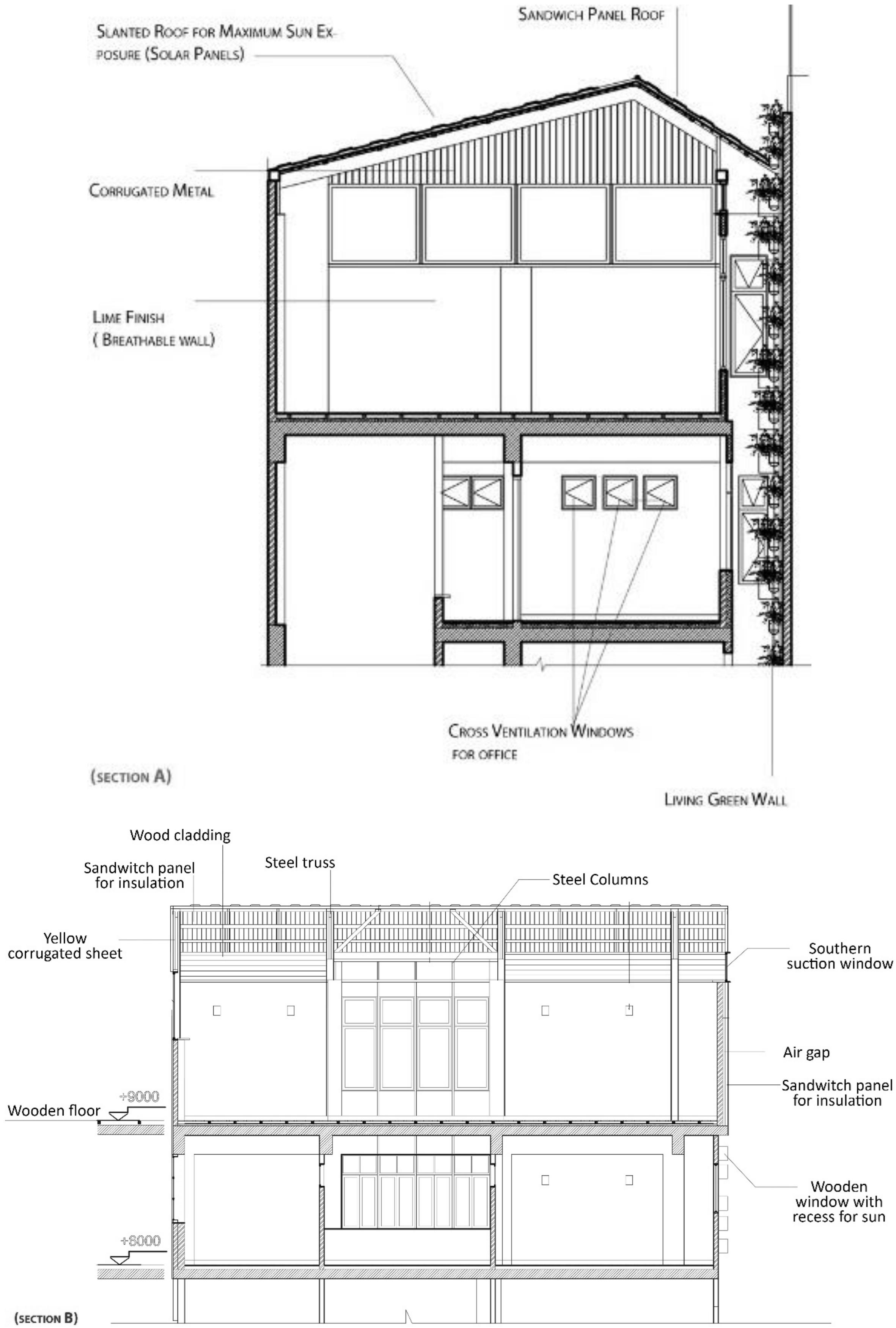


Figure 6: Cross section (section A) and longitudinal section (section B) showing materials (Source:[50]).

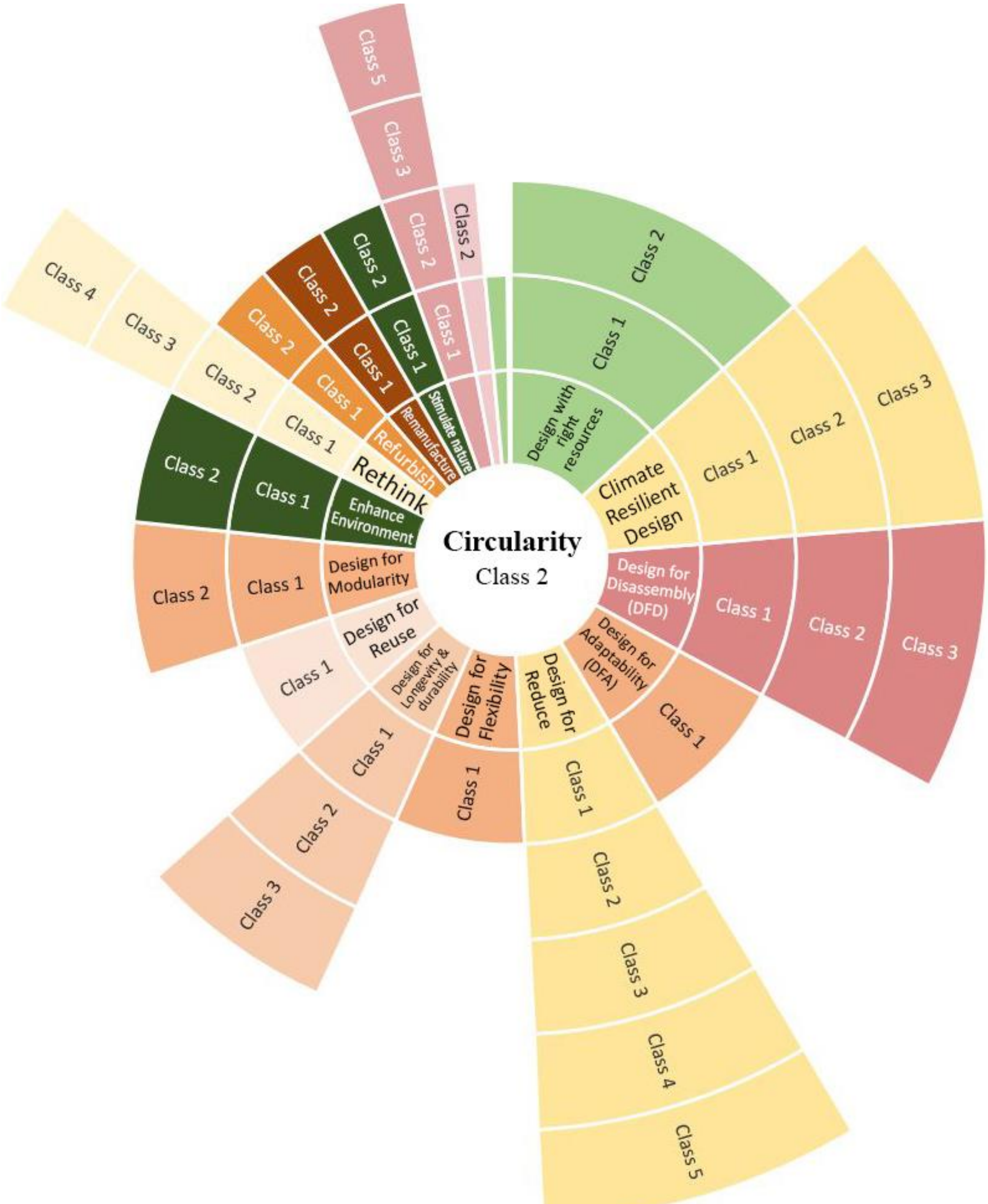


Figure 7: Detailed classes of circular design strategies obtained by the original design.

2.3.2. Design Workshop Planning

A one-day workshop was planned to follow a three-step format. First, a pre-workshop introduction was conducted to demonstrate the proposed circular design methodology and the workshop's goals. This information included maps of the focus area showing potentials of surrounding areas, recent photos from the surroundings (Fig. **8**), a brief, program requirements, and as-built drawings. The tools provided were two A3 boards demonstrating the circular design process and circular design strategies wheel, cards showing several design actions, and an Excel sheet representing the Hol. C-Calculator. Second, the team started experimenting the tools to solve the design problem following CE concepts. The use of digital tools in this workshop was restricted to the simplest tools to save time, thus only artificial intelligence (AI) and digital marketplaces were allowed. Third, a post-workshop discussion and feedback was performed. Fig. (**9**) presents the workflow of the design workshop.

Figure 8: Different shots showing the existing discarded wood in nearby locations to the project.

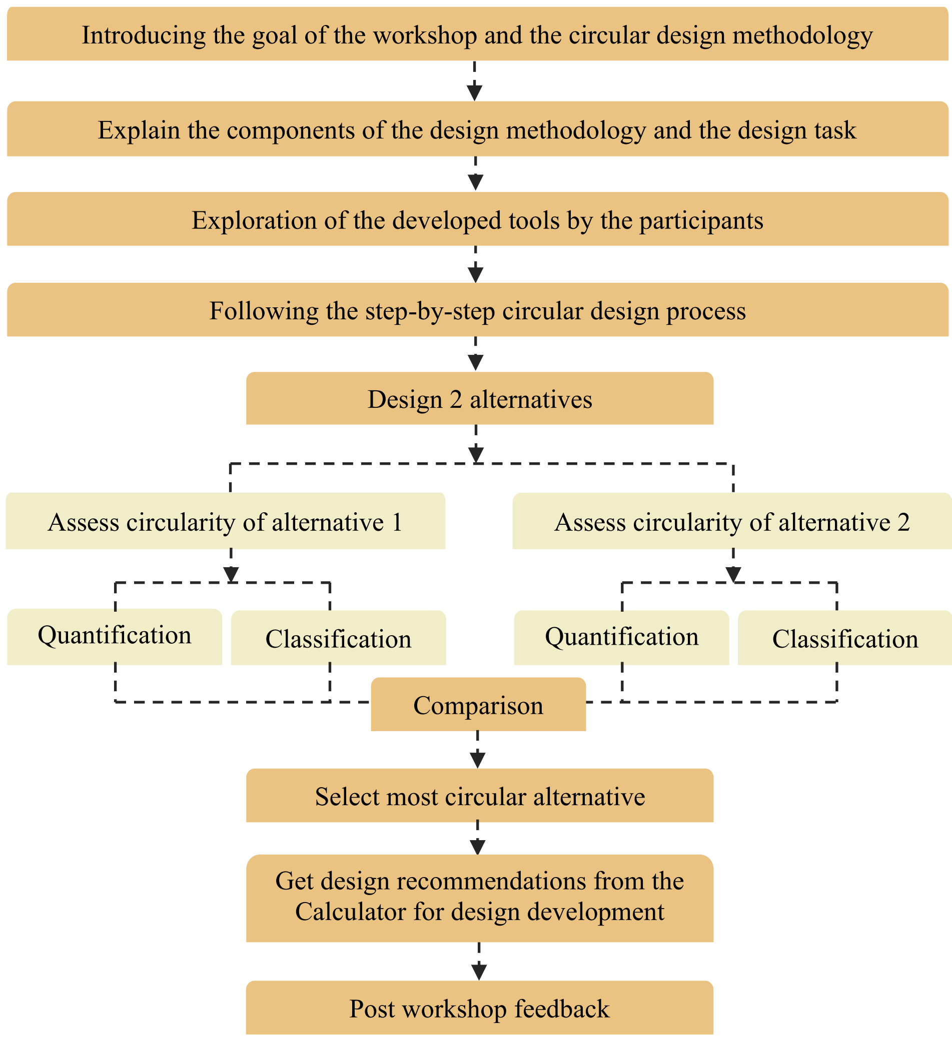


Figure 9: A diagram showing the plan of the design workshop.

The workshop was planned to generate two conceptual design alternatives using free hand sketches. Comparing these alternatives may allow architects to determine the one that best aligns with CE objectives and offers higher circularity performance. The given brief to the participants presented the main function of the building as a community kitchen. However, the client required additional spaces to serve as communal workshops. The spaces required to be taken into consideration are as follows. The ground floor needs to include functions as welcoming, meeting, communication, teatime, receiving, and storing. The first floor needs to include cuisine and nutrition workshops. The extension needs to accommodate community-based drawing and painting workshops besides a theatre. Nevertheless, the footprint of the building is limited. To support the design task, participants were given site maps and as-built drawings showing the original situation of the building (Fig. **10-11**).

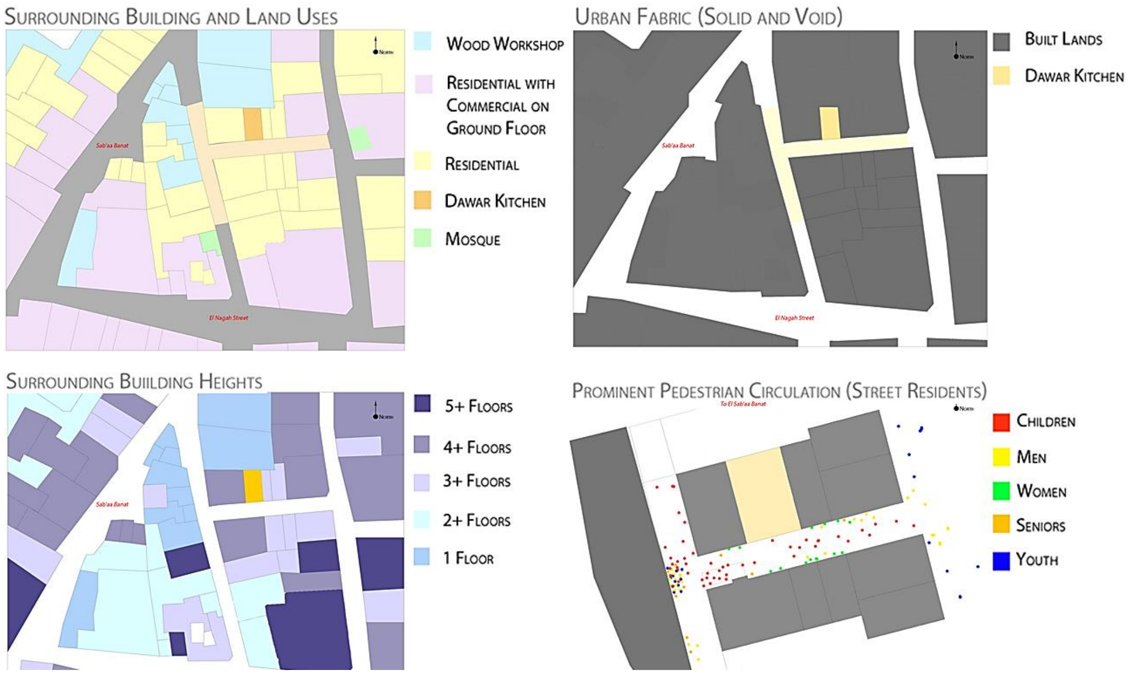


Figure 10: Site analysis showing the potentials and restriction of the context (Source: [50]).

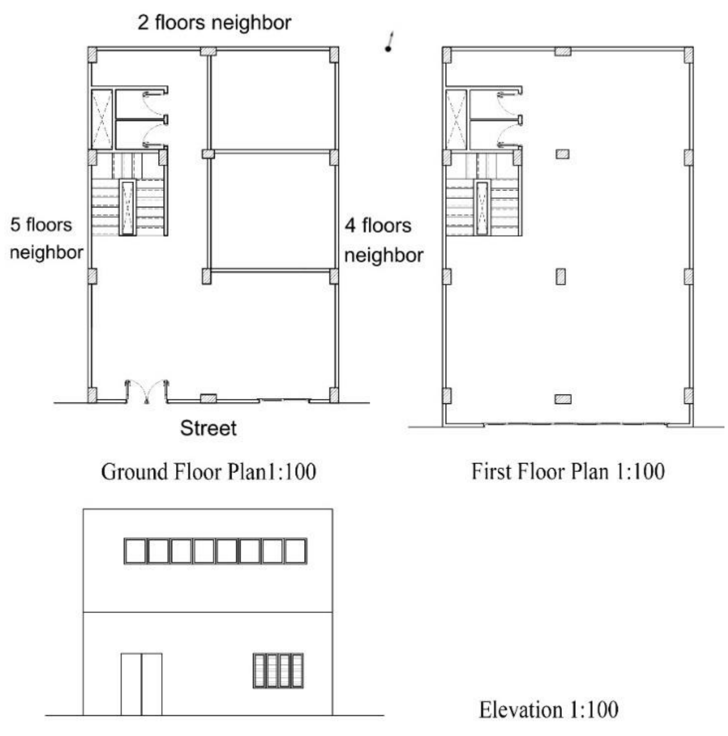


Figure 11: Drawings provided to the design team as prepared by the researcher.

3. Results

This section provides a deeper analysis of the design workshop results. It starts with documenting the implementation of the circular design methodology. It further presents participants' opinions about circular design, through analyzing their quotes to capture their thoughts and to understand their interaction with the methodology. The emphasis is on understanding their experiences, particularly in terms of usability and effectiveness of the developed methodology.

3.1. Methodology Implementation Results

The workshop held on 16 September 2024 at the Department of Architecture, Faculty of Engineering, Cairo University. Prior to the workshop, the researcher outlined the goal of the workshop and the key components of the framework, and the design problem to work on in around 10 minutes. The workshop started with co-exploration of the developed methodology; this led to developing a common understanding of CE objectives. They viewed the step-by-step circular design process and spotted major changes. The participants questioned the meaning of some steps included in the given design process like 'material passports' and 'harvest map'. A pack of 92 design action cards were provided and shortly introduced then the team took approximately 20 minutes to discover them in an explorative way to recognize the relation between circular design strategies and the design actions cards. Some had inquiries about the content of some cards, particularly technical-related card, and some raised questions about the meaning of some design actions such as 'developing disassembly plans'. The participants recognized the repetition of some cards like 'Transportability' and recognized its impact on multiple circular design strategies.

Afterwards, the team started by categorizing the cards to provide better structure and a way of navigating besides identifying possible waste streams through site analysis and using Mrkoon digital marketplace. This step took around 25 minutes to classify the given cards to reduce complexity in dealing with large number of cards and to detect suitable available waste in order to serve as a basis for design. Classification of cards is categorized, according to their type of support, into 6 groups: space and form, facades, materials, furniture, details, and design documentation. The participants then got inspired by finding alternative building material in the form of plastic tiles like Lego, known as Replox. One of the team identified it on the back of one of the cards as a best practice supporting 'design for flexibility' strategy through mobile furniture. For reaching more inspiring building components, two participants identified other discarded elements using the digital marketplace 'Mrkoon', as mentioned in some cards, that are possible to be used. Fig. (**12**) demonstrates the selected elements that ranges from glass, metal plates, steel truss, steel bars, wooden boxes, corrugated sheets, and tyres. Using the data in the brief, key terms from the selected design action cards, and mapped materials, the team members used AI for getting inspiration during conception. They spent approximately 10 minutes in navigating the architecture version of ChatGPT to get some inspirational images for the building facade implying circular concepts like modularity and reused materials as the corrugated sheets.

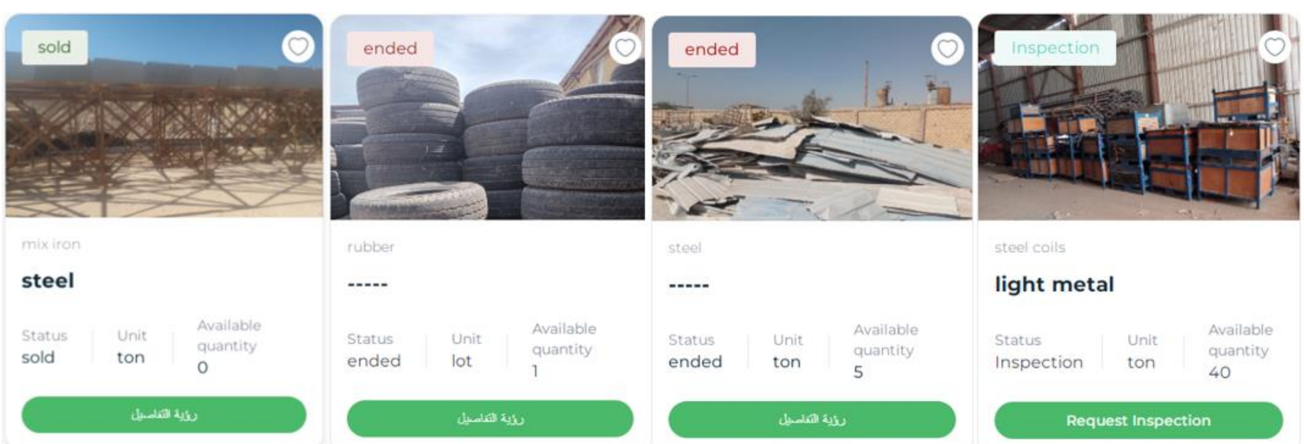
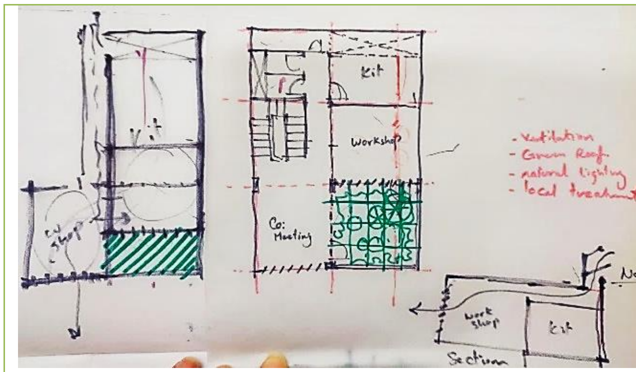


Figure 12: Overview of the selected stagnant and scraps from Mrkoon digital marketplace. (Source: accessed 9 September 2024).

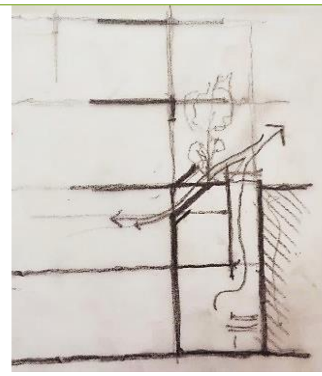
Searching possible design actions using the cards is revisited iteratively during the workshop. After the workshop participants select a combination of solutions and their implementation areas, two proposals are developed. Both share the similar ideas in the space design, furniture, details, and materials; however, the major difference is in the façade design. Fig. (**13**) provides an overview of the cards selected by the team during the design process that resulted into two alternative designs.

Figure 13: Overview of the selected cards by the team members.

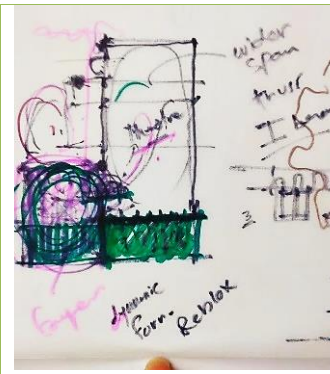
Design of the two alternatives shares modularity in designing spaces and utilizing the concept of shared spaces to accommodate different functions within the same space. Fig. (**14**) shows sketches designed by the participants including relevant keywords to circular design. Both alternatives are based on mobile furniture emphasizing adaptability and flexibility. A shaft for cross ventilation, known as wind catcher, is added facing the Northern orientation to enable natural ventilation for spaces facing the attached neighbor walls. The upper floor is designed to accommodate the theatre using movable furniture made of Reblox plastic bricks. To facilitate non obstruction, a wide span structure is design by recycling the found steel truss. Wooden pallets from the surrounding waste and discarded tyres are selected to be reused as mobile furniture, this supports accommodating different functions. The roof is designed to be accessible green roof with shading pergolas made of reused wooden beams from the residual of the surrounding wooden workshop. The façade design of alternative 1 is based on creating modules to enable creating greenery void within these modules. Solid modules are treated with corrugated sheets overlayered by reused wooden beams from the nearby existing waste. These wooden beams were selected to resemble local traditional shutters in the surrounding buildings and to act as louvers on the Southern façade to reduce heat absorption. Alternative 2 maximizes the green impact of the design by using smaller modules of Replox to form the entire façade. To increase diversity of greenery designs and get benefited from found resources, wooden boxes are reused as found online using Mrkoon platform. They are integrated within the façade modules for plantation. Using these plastic bricks, higher percentage of green modules is created in a staggered form through the whole façade. After conception, participants used cards with a focus on detailing to sketch connections between building elements, for instance, fixation of reused corrugated sheets to design movable walls.



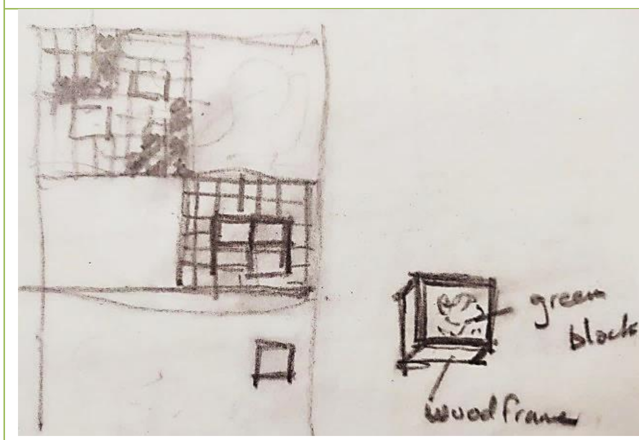
Modular design with green spaces – adding local treatments as louvers and wind catcher for cross ventilation



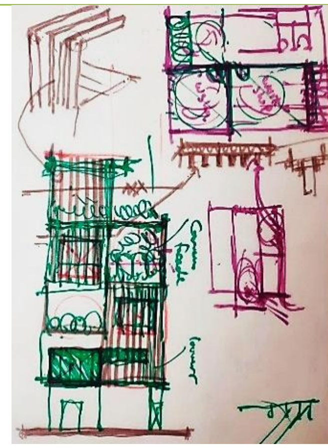
Applying the wind catcher on the Northern orientation



Open plan theatre using reused steel truss and mobile furniture



Proposal 2 of the façade using plastic bricks and reused wooden boxes for creating green facades within modules



Proposal 1 of the façade including reused corrugated sheets and wooden louvers

Reused wooden louvers on the corrugated sheet of the exterior wall to reduce heat

Figure 14: Selection of sketches that show circular design thinking as presented by the team members.

To demonstrate how the developed Hol. C-Calculator can be implemented, and a design proposal can be assigned a circularity score and class, the two proposals are assessed, and the resulting scores are compared. Firstly, assessment is done by inserting data required in the provided excel sheet showing the proposed calculator. Inserted data are simple measurements that are calculated from conceptual drawings provided by the team members. Secondly, assessment is done by comparing indicators of the two designs and comparing the changes introduced by each strategy as appeared in the sunbursts. Fig. (**15**) shows the sunburst resulted by using the calculator as applied to proposal 1, while Fig. (**16**) shows the result of proposal 2. Both alternatives got circularity class 3, however, proposal 1 got C-Score equals 502 out of 723 points representing 69%, while proposal 2 got C-Score equals 483 out of 723 representing 67%. The two proposals highlight the substantial impact that reclaimed materials can have in promoting circularity. It is evident that using material which cannot be readily reused or recycled - as in the case of the recycled Reblox facade of proposal 2 - receives a significantly lower score than using a modular design with reusable and reversible connecting components – as in the case of reusing corrugated sheets and wooden louvers. Proposal 1 has the highest score as it demonstrates the benefits of combining reusable reclaimed materials with a standardized, reversible modular design giving them second life. Modular units or linear elements with visible, accessible connections are particularly well-suited for circular design. The assessment of proposals emphasizes how material selection as well as overall design strategies affect circularity. Highly shared strategies in each proposal appear in a clockwise order from the right-hand side; both alternatives focus on design strategies as adaptability, flexibility, and disassembly, which ultimately improve the whole circularity score.

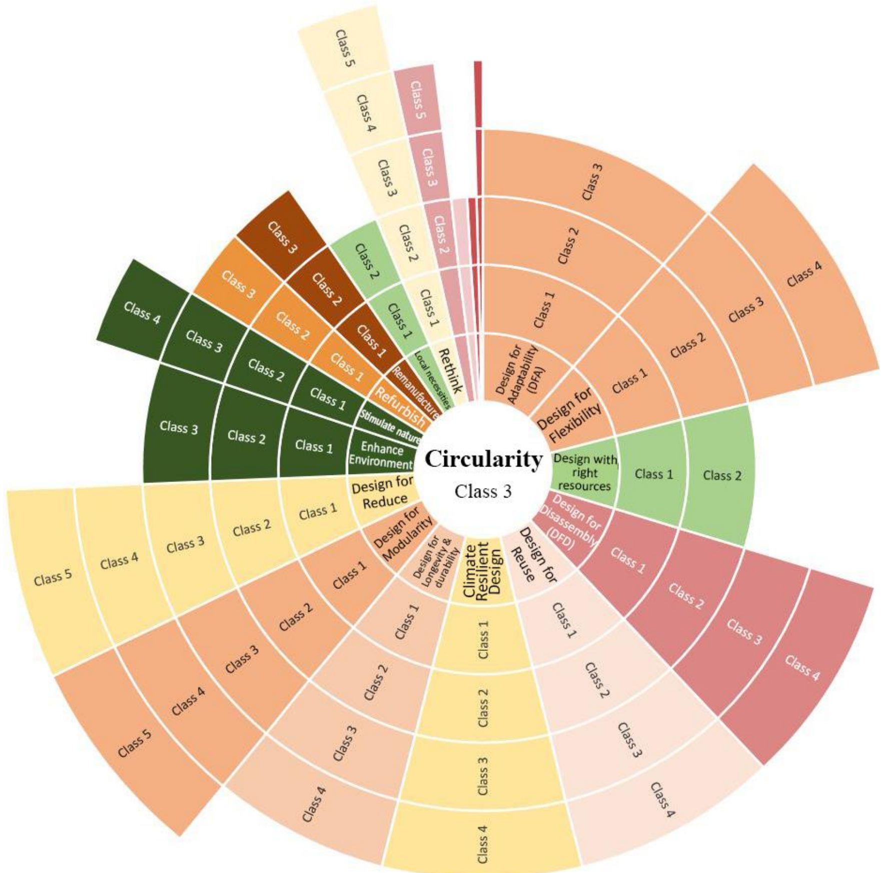


Figure 15: The sunburst obtained for Alternative 1- Corrugated sheets and wooden strips.

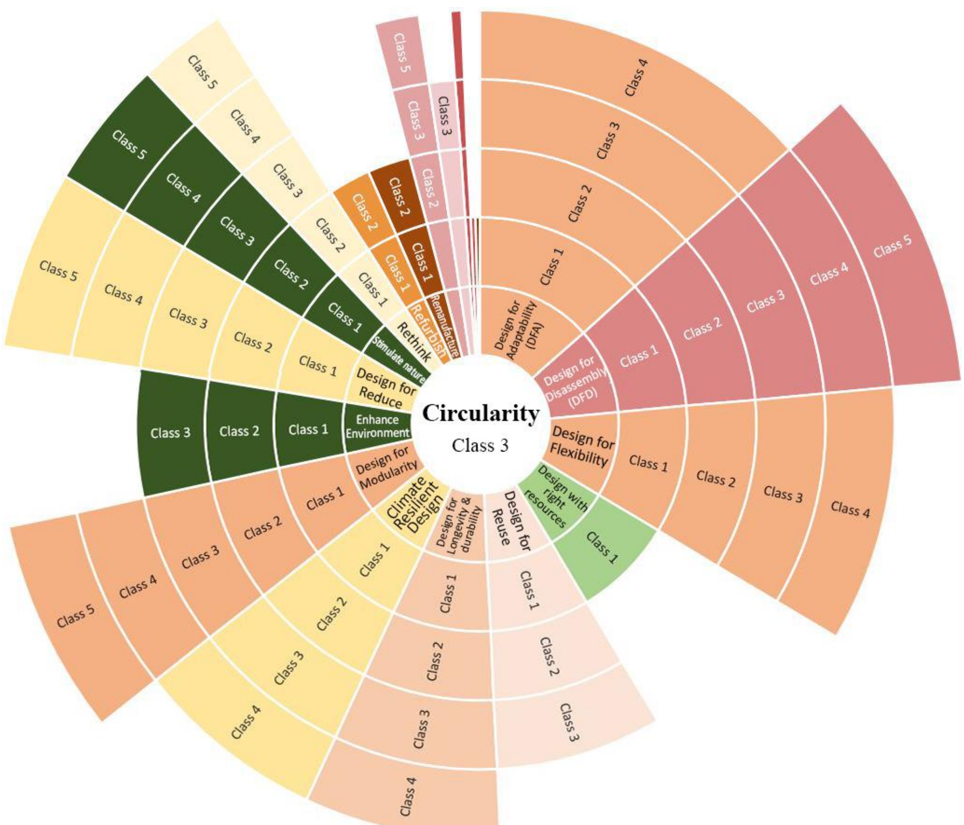


Figure 16: The sunburst obtained for Alternative 2-Reblox.

The workshop ended with setting recommendations for developing the most circular alternative (proposal 1). These recommendations are extracted from indicators with lower scores. Further circular design strategies and design actions that can be revisited to increase building circularity and their possible applications are listed as follows:

1. Strategy 1: Stimulate human nature, Action 2: Increasing greens on the northern facade of the building.
2. Strategy 11: Design for Adaptability, Action 2: Minimize façade pattern (bay size).
3. Strategy 12: Design for Flexibility, Action 9: Use folded panels on roller for easier interior customization without disassembly.
4. Strategy 4 Actions 3 and 7 – Strategy 6 Action 2 - Strategy 7 Action 1 - Strategy 8 Action 4 – Strategy 15 Action 1 – Strategy 16 Action 1 and 3 – Strategy 17 Action 1 - Strategy 19 Action 2: Replace bricks of outer walls and core with recycled materials as plastic bricks.
5. Strategy 20: Design connected building products, Action 1: consider specifying sensors and connecting technologies as RFID to building elements.

A side-by-side comparison is set to clarify each design proposal, and consequently to demonstrate the impact of the applied circular design methodology. Table **2** outlines key differences between the original design and the two alternatives developed by the participants. The table summarizes concepts applied in each design proposal that align with CE principles, actions undertaken, corresponding circularity score and class, tools used, competencies, and roles of architects followed.

Table 2: A comparison between the original design and alternatives designed using the circular design methodology.

Aspects	Original Design	Alternative 1	Alternative 2
Major circular design strategies	Design the right resources, climate resilient design, design for disassembly, design for reduce, design for longevity and durability, rethink, and design for recovery	Design for adaptability, design for flexibility, design for disassembly, design for reuse, climate resilient design, design for longevity and durability, design for modularity, design for reduce, enhance environment, stimulate nature, refurbish, remanufacture, rethink, design for recovery, and design connected building products	Design for adaptability, design for flexibility, design for disassembly, design for reuse, climate resilient design, design for longevity and durability, design for modularity, design for reduce, enhance environment, stimulate nature, rethink, design for recovery, design for recycle, and design connected building products
Actions taken	Reuse waste, green wall, sun shading, cross ventilation, and lightweight bolted walls	Reuse waste, green wall, sun shading, cross ventilation, lightweight bolted walls, adaptable walls and furniture, modular design, open plan, louvers, and green roof	Reuse waste, green wall, sun shading, cross ventilation, plastic brick walls, adaptable walls and furniture, modular design, open plan, and green roof
Circularity score	322.7 (45%)	502 (69%)	483 (67%)
Circularity class	Class 2	Class 3	Class 3
Tools applied	Classic design tools (sketches)	AI, digital marketplace, and assessment tool	
Competencies and roles of architects	Competencies: collaborations, mapping waste, solve aesthetics and structural problems with limited resources – Roles: waste miners, connect waste to design requirements, and superuse scout	Competencies: CE understanding, using digital tools, collaborations, mapping waste, solve aesthetics, structural problems with limited resources, design for multiple use cycles, develop disassembly plan, and circular impact assessment – Roles: waste miners, connect waste to design requirements, upcyclers, superuse scout, and deconstruction expert	

Using the developed circular design methodology enabled architects, non-experts to CE, to explore CE principles from multiple perspectives. They managed to apply different design actions in a systematic manner.

These actions resulted in increasing the circularity of the original design by generating two alternatives. The methodology provided access to digital tools that facilitated the design process during the preliminary, conceptual, and design development (evaluation) phases. Throughout the process, participants experienced a broader range of competencies and roles of architects in CE than those experienced by the original architect. The following subsections provide further details about the impact of the applied circular design methodology.

3.2. Workshop Feedback and Participant Reflections

Following the workshop, participants engaged in a feedback discussion to evaluate whether the methodology met its intended objectives. Overall, architects who used the methodology had positive experiences. It generally promotes thinking and discussion on circular design choices. Architects often rely on their experience and do not follow steps in the design process to save time. This structured sequence of tools can act as a guide, helping them explore innovative concepts within a definite basis related to the CE.

The developed circular design methodology is regarded as both instructive and inspiring as the participants appreciated its design with embedded instructions that enhanced their understanding of applying CE in practice. To get insights into the potential of the methodology applied in the workshop, two qualities central to design tools are explored: usability—ensuring they are easy and enjoyable to use—and effectiveness in assisting non-expert architects to CE in achieving circular designs. Representative quotes from the participants are selected to illustrate key insights and to highlight the benefits of the developed design methodology. Participants mentioned that it is flexible, easy to understand and implement, unexpectedly fun, quick, and instructive as one mentioned that "*it is clear as steps*". Participants mentioned that "*architects tend to use some of these design strategies without deep knowledge concerning its theoretical relation to CE*." Thus, the developed circular design methodology enables distinguishing this theoretical base.

The wheel of design strategies and their subsequent actions cards offer a concise explanation of how they can support each other in order to apply circular concepts. The circular design strategies wheel highlighted some strategies that are not commonly visited by architects in their everyday practice like 'design connected building products', which need more recognition to ensure comprehensive application of CE principles. One of the team members highlighted that: "*it is useful in realizing different design aspects related to circular economy from the very beginning and knowing the relative weight of each element to be able to determine which of them will benefit the design at most*." In this sense, at the end of the conceptual design phase, participants rethought their choices according to the circularity impact of circular design strategies. One of the team members mentioned "*Should we count the number of cards we used from each color?*" They questioned the possibility of increasing some green-colored cards to get higher circularity score. This reveals how the participants gained the knowledge behind the circularity differences between circular design strategies.

Overall, participants appreciated the cards for guiding discussion and fostering idea generation within circular design. They found the cards to be a structured and practical tool for presenting information effectively. One mentioned that "*The cards help guide someone towards circular design and encourage them to experiment*" and other highlighted "*I think the design action cards are the most important because they push you to take action immediately and think directly in terms of design*." However, the team had difficulty in considering and distinguishing some technical-related cards such as 'lifecycle coordination' and 'assembly sequence'. Nevertheless, the cards effectively facilitated a solid understanding of CE, enabling discussions on strategies and translating information into concrete ideas.

The exploratory nature of the methodology was well received, as it encouraged meaningful discussions and founded for a common language using CE-related vocabularies. During the workshop, team members used the same vocabularies in communication; key terms are extracted from the circular design strategies and circular design action cards. For instance, one of the team members asked others to check whether they apply modularity, open plan, and adjustability cards. This unified objectives between different members and maintained that alternative generation is around CE in an easy manner.

Participants recommended using the Hol. C-Calculator in teaching as a user-friendly assessment tool for early design stages. "*I feel it's very effective as a teaching tool because it puts everything in front of the students and opens up* *points, they might not have been aware of*." Comparing the two alternative designs with the original one revealed that the methodology encouraged a broader approach and enabled its users to consider different dimensions forming circular design. Different circular design strategies are easily considered from the first trials, such as adaptability, flexibility, and design for local treatment. On the contrary, the original design got lower score and lower circularity class as it focused on few strategies like designing with reused and recycled reclaimed materials. Overall, using calculations of the two design alternatives it can be stated that a score of 60% is considered good and a score above 70% represents an excellent example of circular design and serves as an ideal target for circular building projects. Since exceeding 60% on the proposed calculator is challenging, this threshold can be used as a benchmark, indicating a high level of circularity.

For future use of the calculator, assessment value ranges proposed in calculations can be refined and adjusted after multiple applications on many case studies in the future. Moreover, it is recommended while using the proposed circularity calculator to neglect concrete-related calculations in case of the inability to replace concrete with alternative materials in most cases. The reason behind that is that they mostly represent the highest percentage in constructing a building, leading to lessen efforts made in selecting alternatives for other finishing materials.

During the entire workshop, it is noticed that participants have practiced several emerging roles for architects in CE as well as experienced multiple key competencies. Three undertaken roles are waste miners, architect as connector that connects waste to design requirements and being a Superuse scout. The team members gained six key competencies through the design process; these are learning CE strategies, mastering vocabularies, and experimenting different design out waste scenarios, using AI tools in circular design, mapping waste resources, solving aesthetic and structural problems with limited supplied components, designing for multiple use cycles and being able to establish future visions, and experiencing circular impact assessments.

At the end of the workshop, participants gave some recommendation for future possible application. They believed it can show better results on other case studies with lower restrictions regarding scale and context. Furthermore, they mentioned that it can be applied in experimental design courses with undergraduates, where students can use the calculator easily to assess and refine their designs. In this sense, they believed the developed methodology in its gamified sense can serve as a pedagogical method. To support this, one of the team members elaborated on its potential by saying that *"the presence of information in the form of physical tools like cards are better than formal learning methods, as after a period of time, I still remember the circular design strategies and actions"*. For further modification, one of the team members suggested digitalizing a calculation method during detailed design phase. She mentioned: "*Maybe add a digital way of applying this methodology during detailed design phase as a BIM plugin that calculates the circular economy impact of each selected material and connections used in real-time means."*

3.3. Mapping Design Dynamics and Patterns of Interaction

A graphical format in the form of bar chart is used to visually track design activities, illustrating how they evolve. This helps document the iterative nature of the design team's process and identify patterns across different iterations throughout the design process. Macmillan *et al*. [51] have developed this method to record several design processes. Thus, this method is used in this study to map the interaction of the design team with the developed circular design methodology. By annotating the bar chart, as illustrated in Fig. (**17**), offers a quick overview of the team's activities and the key drivers influencing the design process, this is to observe the nature of the circular design process.

The first observation is a clear pattern of progressing through activities one step at a time while frequently reverting multiple steps in a single leap. While step-by-step progression has been emphasized, there are instances of backward leaps to reach a design solution. Participants moved backward and forward between design activities within the same phase. For instance, mapping available materials then identifying possible design action cards followed by revisiting mapping other possible discarded materials. Moving backward to previous steps also clear during design development and improving details, in which participants returned to check circular design actions related to details design. The team even stepped back several steps to check the impact of circular design strategies through the strategies wheel to check if they are missing any possible intervention. This emphasizes the reciprocating characteristic of the circular design process. The progression gradients of the iterations are also analyzed, as shown in Fig. (**18**).

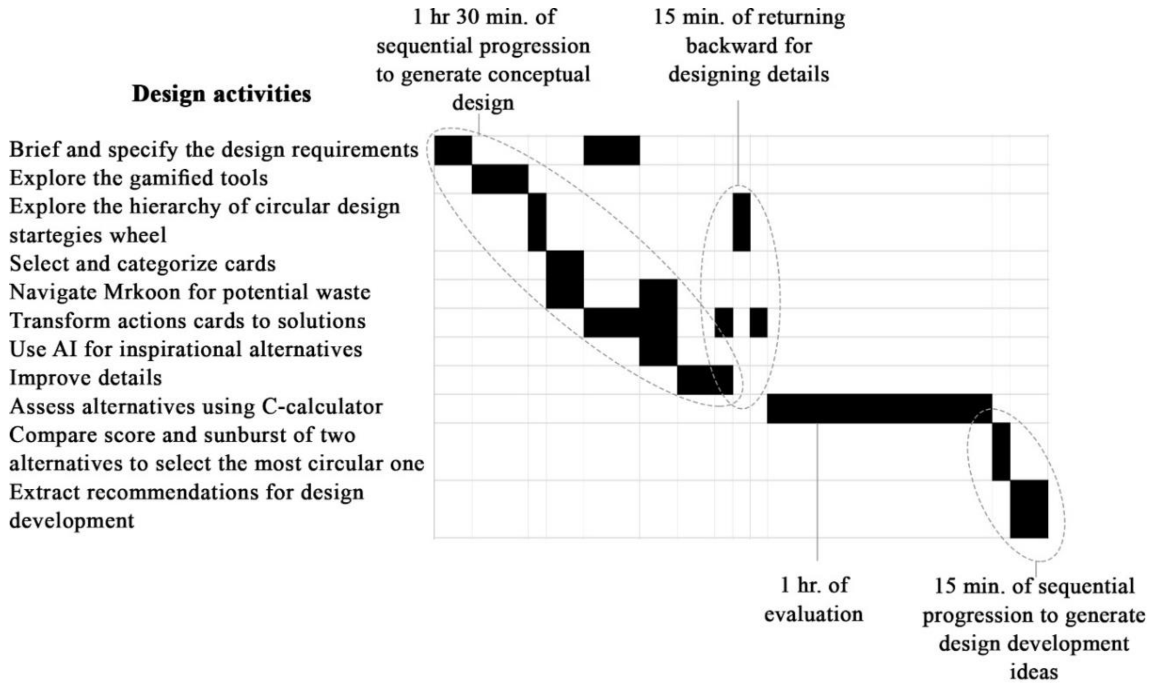


Figure 17: Flow of design activities over time throughout the workshop.

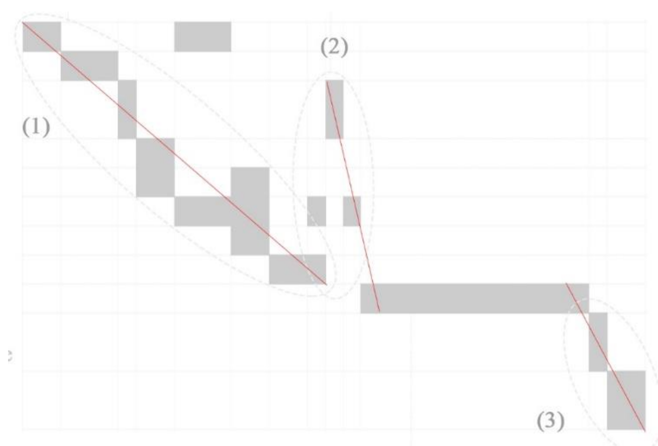


Figure 18: Gradient of design activities through different phases.

It is observed that the gradients are often shallow during the first design phase (1) through a set of activities but become steeper in the second iteration during the design development (2). This suggests a learning process, where the initial phase builds understanding about circular design strategies and actions, making the next iteration more efficient. Supporting tools like strategies wheel and actions cards promote this learning process. Also, selecting the most circular design and generating recommendations for further development follows a steep flow (3) due to the usage of Hol. C-Calculator and sunburst diagram.

4. Discussion: A Methodological Framework Leading to Circular Design Process

Reflections on the potential of the proposed methodology to promote circular design is further explored in the discussion. Also, guidelines for future application are listed in this section.

4.1. Reflections

Circular design methodology is the method that ensures compliance with circular design strategies using enabling tools and circularity indicators. The developed circular design methodology responds to the research question, as it enabled circular thinking and facilitated generating ideas with a focus on CE in an easy manner, even for non-experts, using a time saving process. The circular design process, circular design strategies wheel, and design actions cards help to construct a common knowledge among the team members. The Hol. C-Calculator provided real-time feedback on the impact of changes on circularity indicators of different CE strategies.

The proposed methodological design framework in its sense of gamification provides a structure for the design process. Applying this methodology during conceptual design can be highly beneficial for: (1) identifying the most appropriate circular design approach for a specific project; (2) steering the design process toward circularity goals; (3) transforming circularity objectives into practical and feasible design actions, from concept to detailed design; (4) facilitating communication among diverse team members through gamification; and (5) evaluating and demonstrating the incorporation of CE principles using the proposed Hol. C-Calculator. The success of implementing the proposed methodology depends on:

1. Design culture and structure: The decision-making process and the individuals involved significantly impact the methodology's effectiveness. Encouraging open dialogue and broad participation enhances its overall usefulness.
2. Workshop set-up: To ensure an open discussion, multiple participants should be presented, ideally the entire design team. Additionally, proper introduction and guidance—whether by a facilitator or a written guide—are crucial for the effective use of the design methodology.

By revisiting drivers to circular design and how to overcome existing challenges. The developed methodology includes informational, technical, and technological drivers. Covered informational drivers are providing clear road map for circular design in the built environment, redesigning the process through structuring the design process using meta methods, operationalizing training, and awareness workshops, measuring circular design, providing best practices, incorporating circular design strategies into various design actions. Regarding technological drivers, it includes technological tools that promote circular building design and material sourcing as digital inventory of materials (digital marketplaces). Eventually, included technical drivers are the presence of a flexible design process, establishment of collaboration, design tools, and metrics systems, the presence of user-friendly analysis tools and guides to simplify the adoption of CE, and the presence of tools that align definitions/understanding, including practical examples and aid in educating architects.

This research enhances an understanding of the research problem regarding the need to operationalize CE in designing the built environment and to stimulate design thinking towards circular design. Stimulating design thinking is doubled by gamification impact. Findings of this research show the ability of the proposed circular design methodology to address more efficient approaches in dealing with circular design than classical methods. The experimental case study designed in this research indicates the relatively good impact of adopting the developed circular design methodology in solving design problems towards circularity. This provided additional evidence of the benefits of adopting CE while designing in informal areas. Findings show that circular design contributes to creating affordable solutions, besides finding fresh ideas.

4.2. Guidelines to Use the Circular Design Methodology

The presence of a certain experimental and gamified methodology scales up developing circular concepts by allowing its replicability and transferability to other conditions. Therefore, this study serves as a base for future studies that can increase incrementally the research in this area. The research questions how non-expert architects to CE, be methodically stimulated and systematically guided towards adopting circular design. This is answered through experimenting a previously developed circular design methodology in a design workshop. To enable wider dissemination of this design methodology, guidelines (Fig. **19**) were set to facilitate its future adoption.

Figure 19: Step-by-step guidelines for future application.

Based on the evaluation of the workshop, it is suggested that a session with the developed design methodology should take minimum four hours and is best organized in a group of architects to allow brainstorming using CE-related vocabularies. These recommendations may change according to the scale and requirements of the design problem. Participants should leave the session with a broader perspective on circularity in architectural design, a clear understanding of their role within the CE system, and innovative ideas for transforming the built environment. A trained facilitator with expertise in the CE is essential to effectively guide the workshop; someone who is familiar with the four CE loops, principles, and best practices. The session is suggested to follow the step-by-step guidelines including the following:

1. Understanding tools: Present the circular design methodology using the tabletop board, the 20 circular design strategies wheel, and give instructions on the hierarchical order of the given strategies. It is crucial to clarify how the design action cards connect to the 20 strategies. Some cards may appear repetitive because a single design action can apply to multiple strategies. For instance, the ‘slow’ strategy ‘design for reuse’ includes ‘disassembly’ as a design card which also appears under the ‘closing’ strategy as ‘design for disassembly’ at the product’s end-of-life. Both cards are included because designing for disassembly to facilitate reuse in various scenarios differs from designing for easy disassembly to give building products second life at the end of its service. Both are essential to consider during circular building design. Moreover, the card ‘Transportability’ exists in more than one design strategy. In general, designing circular buildings needs participants to realize the relationships among different design cards: to uncover how one design action may enable another one; and how many cards can work together to enable circularity.
2. Site analysis: Analyze the site with specific reference to available waste and browse digital marketplaces for possible waste and discarded elements that can serve as a basis for the design.
3. Filtration: Hand out the design action cards to enable the participants to explore different possible actions. Participants may benefit from pre-selecting certain cards to reduce the total number of cards that they have to go through according to the relevance of the cards for a specific design problem. Afterwards, categorize the selected cards according to type of support, for instance space design, façade design, furniture, details, design documentation, and materials, to facilitate reaching the required cards in accordance with the design task and the design phase.
4. Conception: After gaining a basic understanding of the cards, encourage participants to explore how the principles can be applied in their specific context. The cards can then be put on the table in groups where each stack of cards relates, allowing team members browse through them throughout different design stages. It is expected to convert combinations of design action cards into design alternatives.
5. Assessment and design development: Use the Hol. C-Calculator by inserting required data for each design alternative to establish a comparison between them. Choose the most circular option with the highest circularity score and rethink how to develop the design by checking actions with the lowest scores of each design strategy. If any design action appears to be missed after inserting the data in the calculator, the team can reconsider it during the design development. Actions with lower scores or missed actions can stimulate a second-round of generating ideas to promote circularity of the design.

5. Conclusion

This paper presents the key conclusions derived from the validation of a circular design methodology, highlights its principal contributions to the existing body of knowledge, and concludes with recommendations for future research directions.

5.1. Concluding Summary

This study focused on validating a circular design methodology previously developed by the authors. A design workshop was selected to test the proposed framework, due to the significance of workshops as a participatory and practice-oriented approach when studying design support methods. A one-day workshop was carried out with non-expert architects to CE, resulting in multiple insights. The most interesting finding was the positive experience reported by the participants while experimenting the methodology. They mentioned that it is flexible, easy to understand and implement, unexpectedly fun, quick, and instructive. They believed that it could be an educational tool to be tested with students. The wheel of design strategies and the corresponding action cards offered a clear overview of how they can complement one another while conveying insights into the circularity difference between design strategies. The methodology unified objectives around CE and established common language between the team members using CE-related vocabularies. Using the Hol. C- Calculator in this workshop, a score of 60% is considered good and a score above 70% represents an excellent example of circular design. The pattern of the undertaken design activities by the participants emphasized the reciprocating characteristic of the circular design process.

The developed circular design methodology, with its gamification tools, responds to the need for supportive methodologies to designing circular buildings. It enables circular thinking and facilitates idea generation with a focus on CE in an easy manner, even for non-experts to the CE. The findings are in agreement with the fact that gamification is associated to stimulating design thinking and delivering complex information. The gamified circular design methodology assists architects in four ways: first, it facilitates the creation of a cohesive and thorough circular design using a step-by-step, board-based design process; second, it presents all the design strategies that should be considered when developing a circular design; third, it offers a wide range of circular design actions for each strategy, enabling architects to systematically combine and customize selected design options; fourth, it provides an assessment method to evaluate the circularity of a design proposal and guide design development.

The findings raise questions about the future implementation of the developed methodology in practice. Therefore, the research concluded a set of guidelines for future application. Eventually, 12 steps were set as guidelines for the future application of the circular design methodology, with a recommendation to be applied in groups to encourage collaborative brainstorming. It provided steps to be followed, using the gamified tools, to facilitate its application even for non-experts. These guidelines provide practical dissemination of the circular design in architectural practices.

5.2. Contribution to Knowledge

This study offers a key contribution to CE practice. As a practical contribution, this study presents a validated methodology for generating and developing circular building designs. This makes circular design knowledge accessible to architects unfamiliar with CE, thereby bridging the gap between theory and practice in the circular-built environment. This study develops a guidance on applying a practitioner-focused gamified design methodology for circular building design. Accordingly, this can advise architects throughout early design stages. For more practicality, classification and quantification assessment used by the Hol. C-Calculator at the end of the design workshop enabled the identification of the most circular design alternative. It also delivered feedback in the form of recommendations to further promote the circularity of the design proposal.

5.3. Research Limitations

The present study is subjected to two limitations regarding calculations considered for evaluating the design proposals. First, regarding the cost implications, the study claims that the proposed design alternatives outperform the original winning design in terms of circularity. However, the original objective of the project was to provide a low-cost solution. This study is limited to circularity evaluation without cost calculations. If cost calculation is considered, this may draw different conclusions. Second, regarding concrete-related calculations, in Section 3.2, the authors suggest that concrete-related calculations should be neglected when its replacement is not feasible, as concrete often constitutes the largest mass of a building. The circularity score, in this first experiment, is handled by including concrete in the circularity calculations, that’s why the obtained scores and classes are considerably moderate. Therefore, future applications of the methodology can neglect considering it in case of basing the design on standard raw concrete material.

From another perspective, the findings of this study are subjected to a generalizability limitation. The context and scale of the intervention where the circular design methodology has been tested is constrained by particular settings. The tested project was located in an informal area where certain amount and types of waste and resources - mainly wood, aluminum, and plastic – were available. The building scale was relatively small, and the primary task involved extending an existing structure. The building also represents a certain building typology, namely a community center. Given these constraints, the potential of the developed circular design methodology and the obtained circularity scores may differ by changing the previously mentioned variables. Therefore, further experiments across different design contexts and building typologies are necessary to broaden the generalizability of the research findings.

5.4. Recommendations

Finally, the research formulates a set of recommendations that would help in providing a better atmosphere in architectural circular design. This research recommends testing the proposed circular design methodology in practice and in architecture schools to refine it. Architects should grasp the circular design concept and apply its enabling methodologies in their practice. Since the design process is strongly linked to design education, the contemporary educational system and the field of architecture design must incorporate training methods that align with new paradigms like CE. Additionally, design education pedagogy needs to evolve to address emerging topics such as circular design. The validated circular design methodology can lay the ground for curriculum development to promote circular design education in higher education. The proposed step-by-step guidelines can be followed in architecture schools. Architecture students must be educated on the fundamentals of circular design approaches and use the presented tools while designing to attain circular buildings. Further research is required to introduce gamification in circular design education and to investigate its impact as a teaching tool.

To sum up, future research could test the validated circular design methodology in practice to identify possible improvements. Validating the discussed design methodology should be an iterative process, in which different components of the methodology need to be evaluated individually. Each element should undergo separate validation exercises, for instance, digital tools are distinct artifacts that require validation on their own through diverse applications.

Eventually, the future logical progression in this research trajectory is suggested to involve digitalizing the validated circular design methodology through the integration of AI. AI is increasingly recognized as an accessible and efficient tool, particularly valuable during the early stages of the design process. Training AI models can enable the automation and facilitation of design decision-making. Future research could therefore focus on the development of an AI-driven circular design assistant - an intelligent system capable of generating design solutions that align with CE principles. Moreover, this AI model could be equipped to evaluate design alternatives using the Hol. C-Calculator validated in this study, thereby facilitating informed, data-driven design choices that support architectural circular design.

Conflict of Interest

The authors declare that there is no competing financial interests or personal relationships that could have appeared to influence the work reported herein.

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