

Circular Immersive Parametric Design Workflow for Innovative Materials

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ABSTRACT: There is sufficient evidence that the use of Building Information Modeling (BIM) and Virtual Reality (VR) in Architecture, Engineering and Construction (AEC) education environments is desirable and beneficial. This study introduces a workflow for circular immersive parametric design (CIPaDe). The proposed CIPaDe, BIM-into-VR-based workflow is expected to improve students' learning performance, provide an environment similar to real-world, increase the visualization of models on a larger scale, and enhance their creativity. The CIPaDe Workflow includes stages of 1) material selection for non-loadbearing elements 2) geometry exploration and VR sessions 3) life cycle assessments (LCA). Secondary materials for LCA were selected from declared products on the Embodied Carbon Construction Calculator (EC3) Tool. The goal was to arrive at a design with minimal embodied carbon and energy. The intersections of material choices for innovation and sustainability provides the opportunity to test its impact through embodied energy investigations and operational energy impacts. Emerging designs are the basis for comparisons between recycling and virgin materials. The results show that the novel workflow utilizes BIM and VR to promote circularity and provide environmental benefits.

KEYWORDS: Circular Design, Materials, Building Information Modeling, Sustainability, Virtual Reality

INTRODUCTION

A major challenge of the AEC industry is the inefficient approval process due to the slow adoption of modern technologies such as Building Information Modelling (BIM), Virtual Reality (VR), Augmented Reality (AR), and cloud computing (Hartmann et al., 2009; Khan et al., 2021; Mehrbod et al. 2019). The design process for AEC is iterative and relies strongly on individual experience (Ahmed 2018), and there is a developing ecosystem of content for millions of available VR headsets and devices. Much of this content include games or game-like social experiences and many other diverse activities. As this VR mediums become more popular and mainstream, there is need for the Architecture, Engineering and Construction (AEC) industry to adapt to the growing awareness of the technology. The recent exciting commercial developments refreshes interest in the promise of these technologies to support the iterative design process. Three-dimensional (3D) design programs allow designers to explore their ideas in the digital (Aprilliandini 2020). The use of VR in the AEC design process was explored using a BIM program. A design activity that incorporates VR gives users the ability to move from a two-dimensional (2D) spectator experience to an actor in the 3D environment that is the object of study. VR designing offers many advantages, it is easy for the users to handle, they quickly form ideas at scale, they collaborate in real-time and they communicate their ideas (Drampalou 2022). It is essential that VR use is embraced by the AEC to enhance the design process, discover new ways of expression, and develop new ways of adopting available technologies.

Despite the potential advantages of adopting modern technologies, there are considerable challenges to implementing VR applications. The use of gaming engines such as Unity 3D and Unreal which are frequently utilized for VR development require a significant level of expertise limiting the adoption of VR systems in the field (Globa et al. 2023). This study suggests leveraging the commercially available Enscape software application and the MetaQuest VR headset to construct an alternative approach for VR adoption in the design process for the AEC industry that takes less time.

Previous studies have demonstrated that the adoption of VR supports the design review process by identifying design errors and improving communication, collaboration, and decision-making. It provides an interactive, engaging, immersive, and realistic presentation of space (Liu et al. 2020). For instance, students conducting design reviews in a classroom environment using VR determined a higher number of design mistakes and performed significantly better than those using 2D drawings, (Kandi et al. 2020).

The concept of circularity promotes the use of materials for as long as possible in closed loop systems. CE means that products no longer have a life cycle with a beginning, middle, and end, therefore this can reduce waste and add value to their ecosystem (Ellen Macarthur Foundation, 2024). The CE is based on three principles, driven by design: 1) eliminate waste and pollution, 2) circulate products and materials (at their highest value), 3) regenerate nature. CE is constructed on the 9R framework: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover (Kirchherr et al., 2017). The CE tackles climate change and other global challenges like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources (Ellen Macarthur Foundation, 2023).

The world is becoming less circular, moving from 8.6% in 2019 to 7.2% in 2023 as reported by the circularity gap report. (de Wit et al, 2018; Fraser et al. 2023). It is imperative that designers explore digital strategies to increase circularity. VR can be used to simulate the building process and identify potential issues that could help construction companies avoid costly mistakes and reduce material waste (Soman et al. 2024). (Lee & Leite 2023) sought to promote circularity by an immersive experience integrating physical and digital worlds that allowed users to interact with digital objects which were overlaid with the actual world resulting in a more effective learning experience. VR has become prevalent in our daily lives and have been integrated into meeting the principles of circular economy (Bucea-Manea-Țoniș 2021). VR could be used as a tool towards engaging individuals in sustainability especially circular economy, a prototype showing the transition from a linear to a circular economy led to an affirmation from testers of feeling more engaged and motivated to live more sustainably (Aune & Ghattas 2023).

This manuscript reports a design activity of building design students paired in teams and designing an education building. Two VR sessions were part of the design process and students discussed their experience during the immersive process. Teams submitted their reports including their perception of the VR sessions. Findings showed that students could actively engage with their content by providing feedback in situ.

1.0 RESEARCH METHOD, EXPERIMENTAL SET-UP, AND PROCEDURE

1.1 Research methods

This research study adopted a mixed research method and implemented a case study to investigate the potential of VR activity for design iteration exercises in building design education using an educational office building design as an example. The cohort was made up of 20 students in ten teams. The design activity commenced with material selection, design of units, two design reviews with VR sessions and a final report. Responses to the VR sessions in the report were analyzed to determine the effectiveness of the new immersive approach, Figure 1. This study follows LCA stages described in ISO 14040 (ISO 14040 2006).

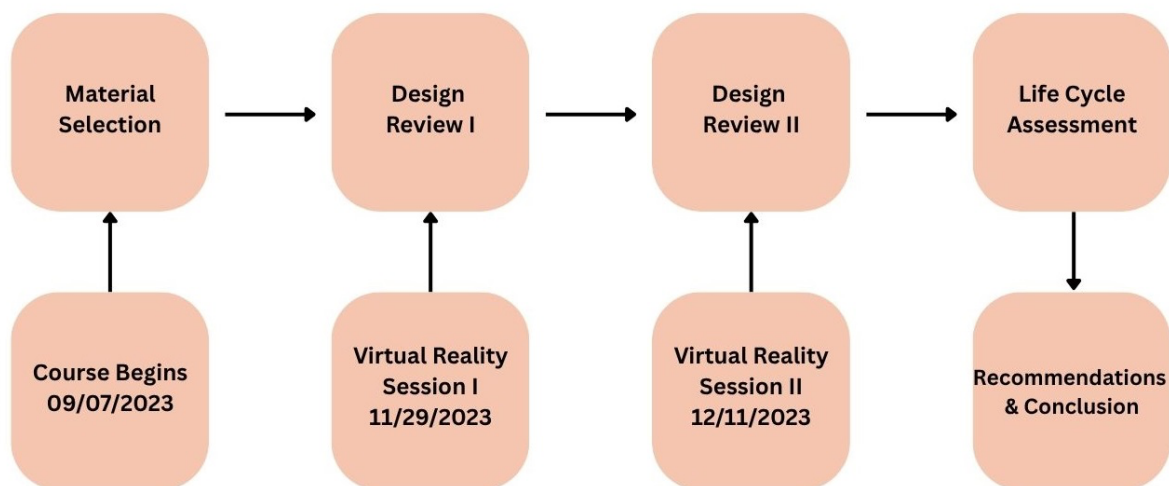


Figure 1: Research method for VR sessions. Source: (Author 2024)

1.2. Course pre-survey

The students were given an 8-question pre-survey comprising questions focused on their understanding of sustainability and experience with VR headsets. 85% of the students responded, their responses to the question – “What does sustainability mean to you?” comprises - routine, able to function for an extended period of time without having a large negative impact, the ability to maintain something that will last forever, sustainability is being able to maintain at a certain level, sustainability are energy efficient practices and materials that last, having little to no carbon output, Green Building / Green Energy that doesn't compromise the environment, the ability to be maintained at a certain rate or level, the reuse of energy efficiently whilst limiting and reducing waste, sustainability means meeting the needs of today without compromising the ability of future generations to meet their own needs, to be able keep up with the work that you have and do it well, a way to describe the longevity of a system to continue performing the desired action, making a conscious choice to use the minimal effective resources, and reduce waste as much as possible, sustainability would be the use of materials or practices that won't hurt the future generations, able to keep track in a consistent manner, fulfilling the needs of current generations without compromising the needs of future generation, sustainability to me means living a way of life that allows one to keep doing so without negatively affecting things or people around them or impacting the resources around them. 53% of the students had use a VR headset before the course and 100% of them used the headsets for games, 91% used them less than once a week and 9% had used them only once. 35% of the students were familiar with the term parametric; 33% were familiar with Revit Software, 30% were familiar with AutoCAD, 11% were not familiar with any BIM software, 7% were familiar with Sketchup and other software mentioned include Tinkercad, Chief Architect, Keycreator and Envisioneer.

1.3. Design case study of an educational building

In one semester for a building design course, students were asked to design an educational building and the sustainability inquiry was limited to a south facing shaded wall. Student teams were required to design a parametric patterned wall for the purpose of substituting traditional materials with reused sustainable materials. The goal was to divert as much waste from landfills as possible. The designs of three teams (six students) are presented in this study. The teams designed shaded walls applying different forms of geometry. The design process was divided into two parts- building as a whole and the shaded wall. Students designed units for their wall before proceeding to produce them in Revit BIM software, Figure 2.

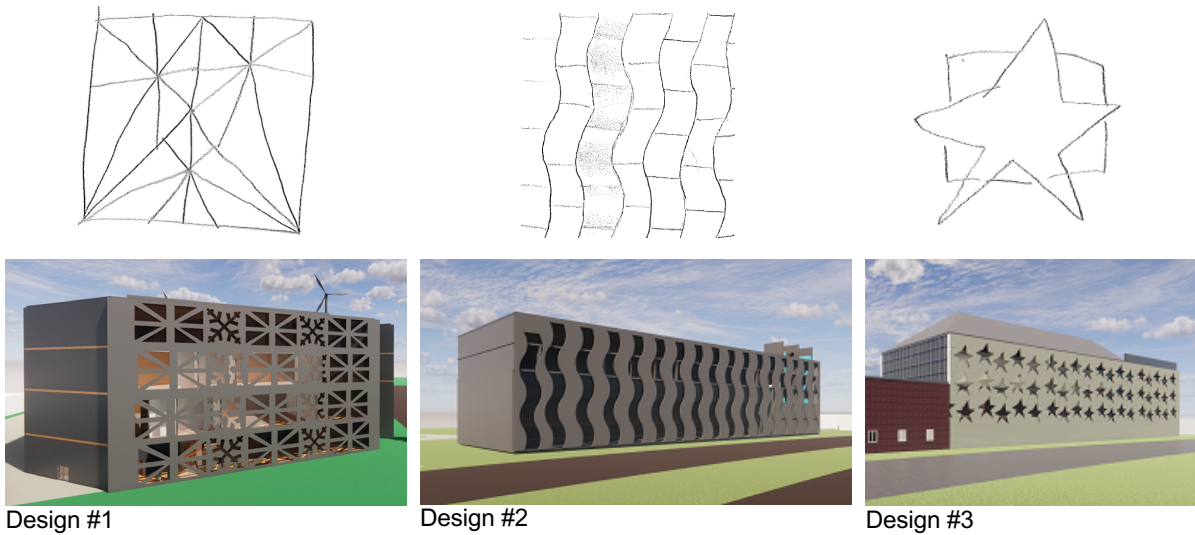


Figure 2: Design of South-facing shaded wall by teams showing sketches and walls. Source: (Author 2024)

1.4. Material selection

Teams were asked to select materials from the Embodied Carbon in Construction Calculator (EC3) tool for their shaded walls. The data given for the materials would be used for a life cycle assessment (LCA). Design #2 team selected NOREX Panels from EC3 for the shading material. This was used as the alternate throughout.

1.5. Virtual reality sessions

There were two VR sessions during the design process. The goal was for students to experience their design and report its impact on them as users. The equipment used were a personal computer (PC) Lenovo gaming laptop, air link cable from Facebook, and a Meta Quest 2 VR headset. The headsets required Oculus software and further steps included downloading of airlink software, begin VR, plug usbc cable. On laptop, settings, system> quest link > access PC/VR > launch quest link > launch rift. Students produced their project in Revit. The instructor explored Unity, Twinmotion and Enscape softwares and Enscape was the easiest to use, however students did not have laptops that met the requirements to run Enscape. Therefore, the instructor’s gaming laptop was used for the VR sessions, Figure 3.

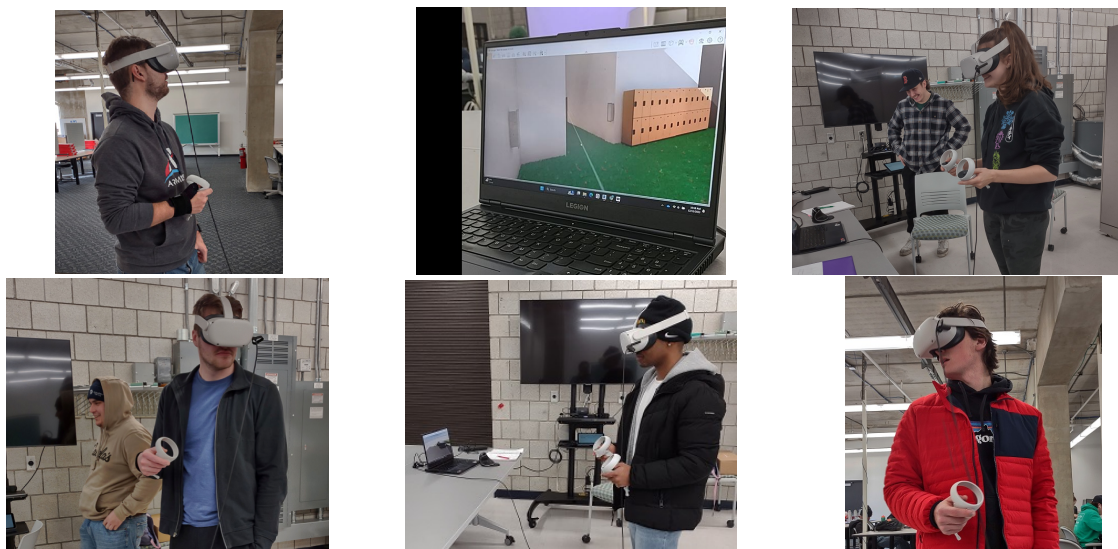


Figure 3: Students during virtual reality sessions. Source: (Author 2024)

2.0 RESULTS

2.1. VR design observations

Students assessed the projects as users and spent an average time of 5 minutes for 18 sessions in the VR environment. The range of time spent was 2 – 10 minutes. Students voluntarily critiqued their design when immersed in the building environment. The most mentioned areas for improvement were the walls (8), windows (7), staircases (6), and building pads (6). Other areas included furniture, ceilings, and handrails Table 1. Thirteen out of twenty students participated in the VR session and nine out of ten teams were represented in the VR sessions, one student declined to participate sessions.

Table 1: VR sessions and action points observed. Source: (Author 2024)

Session 1 Time (minutes)	Student observations	Session 2 Time (minutes)	Student observations
5	Add floor; adjust furniture arrangement; floating objects	5	Set height of crane; building pad; notices furniture placed; exclaims that VR exercise is cool!
4	staircase on the roof; adjust window; create building pad		
2	Improve furniture arrangement in a laboratory		
7	Adjust ceiling at stairs; Provide additional windows; seats were cramped; create circulation space; impressed with the geometry of the parametric wall: noticed curves and height of spaces		
5	Adjust roof; floating walls; building pad; open slab above stairs; noticed crowded light fixtures; stated that there was much work to be done	10	Add walkway to roof garden; add doors; elevator and stairs; at library open floor above the stairs; correct wall heights;
5	Add windows; doors; furniture; floor; handrails; change location of doors	3	Add building pad; add ceiling; move spiral stairs away from wall
5	Remove slab over stairs; add windows		
3	Adjust wall heights	4	make window bigger; adjust window height; building pad
2	change form; increase corridor; adjust wall heights;		
8	Increase sizes of classrooms		
	staircase is assuring; generated design idea for hallway space;		
	add doors and windows; drop ceilings in bathroom;		
	appreciates seeing building in 3D; suggests future use and project it could be used in; says it would be useful for deaf and accessible housing tenants	7	Observed atrium; narrow hallway; add slabs;
		7	considered shape of bathroom
		5	Would change the direction of solar panels; cover stairs; add lockers; add handrails
		5	remove windows at roof level; likes white walls; add building pad
		5	noticed lines on walls, concerned about details and fire rating

2.2. Perception of VR sessions

In their report at the end of the semester, team members responded to questions on a user experience survey, six students responded to inquiry on the VR sessions. Students strongly agreed that the VR sessions were innovative, new, interesting, exciting, attractive, practical, efficient, dependable, motivating, and enjoyable, Figure 4. They agreed that it was organized, clear, pleasant, good, valuable, easy to learn, creative, and understandable. A few students strongly disagreed that the sessions were friendly, dependable, easy and easy to learn.

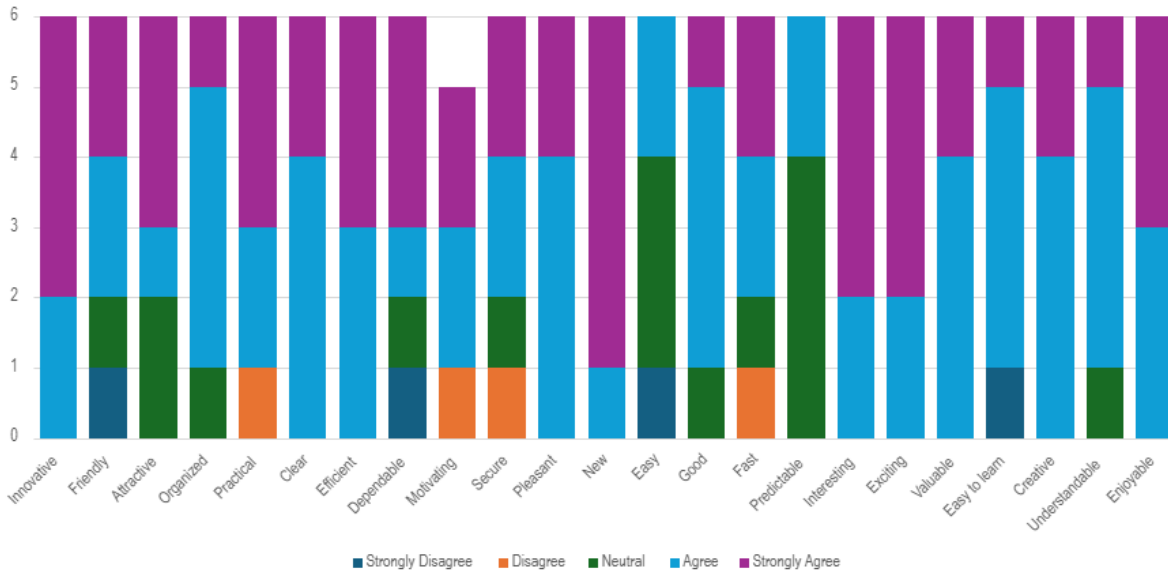


Figure 4: Students' responses to a user experience survey. Source: (Author 2024)

3.0 LIFE CYCLE ASSESSMENT

3.1. Process

The LCA was conducted following steps defined by the International Standards Organization (ISO) standards for measuring environmental impact (ISO 14040 2006). The LCA includes the following steps: goal and scope definition, inventory analysis, impact assessment, and interpretation Figure 5. The goal was to evaluate the environmental impacts of using the selected material from EC3 tool and the alternate scenario of using recycled material from the city through a cradle to gate approach. The assumptions for the study were that transportation distances were similar for both scenarios.

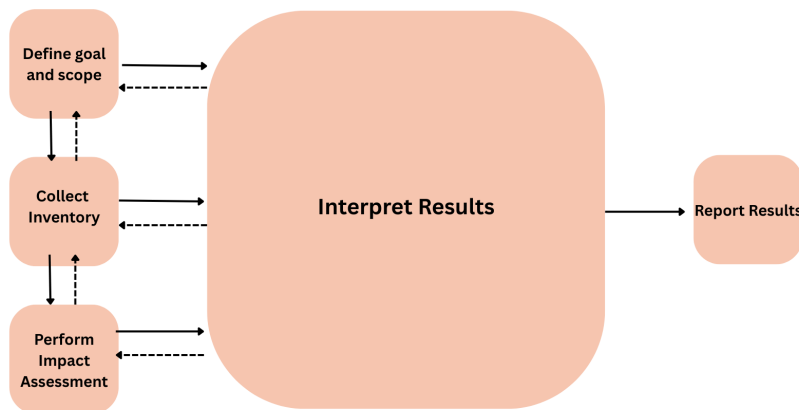


Figure 5: Diagram of the LCA process. Source: (Author 2024)

This study utilizes the United States Environmental Protection Agency's Waste Reduction Model (WARM) as the main data source for calculating greenhouse gas emissions and avoided energy. Additional data was obtained from the City of Fitchburg waste data from 2010 to 2020. The annual average availability of scrap metal was 74,933.5 kg (82.6 tons), Figure 6.

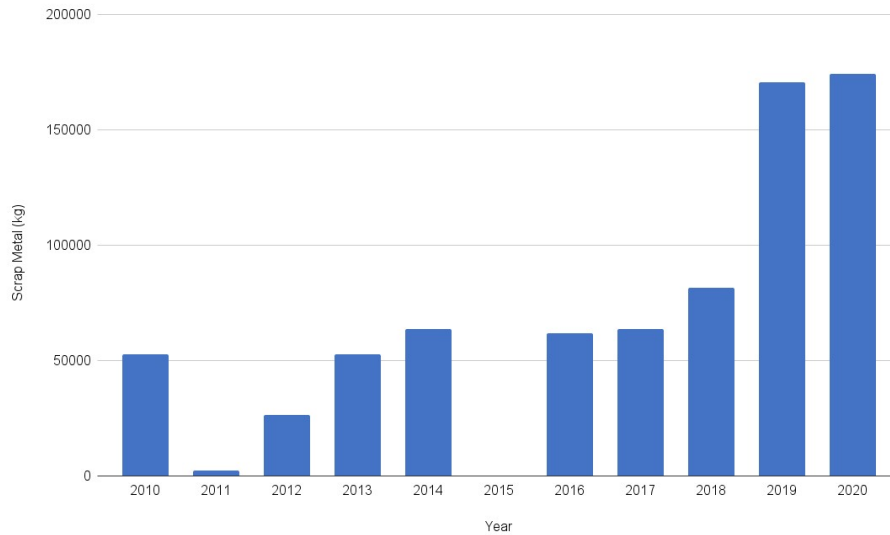


Figure 6: Scrap metal data from the city of Fitchburg, 2010 to 2020. Source: (Author 2024)

3.2. Functional unit modules

Three designs of exterior shades were used to compare the annual quantity of metal reused from. Student unit designs were in modules of 800 x 800 mm (331.5 x 31.5 inches), Figure 7. This was the functional unit to compare it with alternative traditional materials found on the EC3 tool for the same product. The total area of shaded walls from the designs were 1,118.18 m², 2,300.28 m², and 2,071.63 m² respectively.



Figure 7: Waste data in tons 2010 to 2020 (scrap metal (blue), newspaper (orange), cardboard (grey)). Source: (Author 2024)

The alternate traditional material from EC3 tool was NOREX Panels with a declared unit of 100m² and the mass per 100m² was given as 2500kg. The adjusted global warming potential (GWP) per 100m² was given as 4550 kgCO₂e (EC3, 2023). The thermal resistance was given as 4.46 (km²)/W, thickness 88mm, insulating material was polyisocyanurate and the facing material is steel. The panels are insulated metal panels with a polyisocyanurate (PIR) core designed for highly efficient buildings. The study assumed similar mass and thickness from NOREX Panels for the designs. The total surface areas for Design #1, #2, and #3 were 1,118.18m², 2,300.28m², and 2,072.63 m² respectively. Applying the 100 m² declared unit to the designs, using the NOREX panels for the design would result in GWP of 50,877 kgCO₂e; 104,663 kgCO₂e; and 94,259 kgCO₂e respectively. The mass was the basis of a second analysis carried out in WARM to validate the avoided energy. If 100 m² weighs 1240 kg then the total weight of panels per design was 13,865 kg; 28,523 kg; and 25,688 kg.

In WARM tool, the baseline scenario of recycling for steel cans was selected. The weights of the panels were converted from kilograms to tons and input in WARM to obtain the GWP when recycled materials are the secondary materials, the GWP were 25,410 kgCO₂e; 52,250 kgCO₂e; and 47,070 kgCO₂e respectively, Table 2.

Table 2: Environmental impacts of using recycled material. Source: (Author 2024)

Design	Area(m ²)	EC3 GWP (kgCO ₂ e)	Mass (kg)	Mass (tons)	WARM-GWP (kgCO ₂ e)
1	1,118.18	50,877.27	13,865.45	13.87	25,410
2	2,300.28	104,662.53	28,523.42	28.52	52,250
3	2,071.63	94,258.95	25,688.15	25.69	47,070

4.0 DISCUSSION

4.1. VR session

In the presented study, VR sessions were introduced into a sustainable design project and the students strongly agreed that it was new, innovative, interesting, exciting and enjoyable. In addition, students self-critiqued their

designs and suggested ways to improve the spaces in their designs. They suggested solutions for walls, ceilings, windows, doors, staircases, railings, floors, and furniture. This study demonstrates how VR sessions can elicit interest from individuals in a design activity and communicate understanding of forms through immersion. The results of this study demonstrate that within a time range of 2 – 10 minutes spent per individual during a session, students could gain insights into the nature of their design. Responses from the reports showed that the students thought that the VR sessions could be easier.

4.2. Impacts

Available data from the city for 10 years showed an annual average of 74,933.5kg (82.6 tons). This amount could serve as secondary materials for the three buildings. Students were required to select a possible material for their south-facing shade walls. Data for the declared unit of a selected wall was used to calculate equivalent GWP for alternate recycled steel. The resulting environmental impacts showed that 50% of the GWP could be reduced by reusing recycled steel as secondary materials for panels in the south-facing building envelopes.

CONCLUSION

The ability of VR sessions to improve sustainability-focused design sessions is comparable to results from previous studies. The results of this study demonstrate that VR sessions of approximately 5 minutes long are helpful in communicating spatial understanding and encourage participation of students. Students described the VR sessions as new, innovative and interesting. The materials selected to design exterior shading wall from the EC3 tool was compared recycled steel from the city and findings showed that 50% of the global warming potential could be reduced when recycled material is used. This study shows that technology could improve circularity education. Enscape software provides fast and interesting user experience of BIM to VR workflow. Further applications of VR in circularity are needed especially for the use of evaluating more building elements.

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