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Circular Immersive Parametric Design Workflow for Sustainable Construction Materials Development

TRACK 4:
Sustainable Innovations in the Built Environment Ecosystem in Africa

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Abstract

Universities can play an essential role in educating students on Building and Information Modelling before they enter the construction industry. Educating students is related to technological constraints against which researchers and BIM providers face as they accelerate the process of compatibility and data exchange in BIM workflows. Revit is a leading BIM platform and works with Enscape, Unity, and other software for translation. Subsequently, virtual environments have been implemented successfully in residential and commercial projects However, in Sub-Saharan Africa, the potential for BIM and virtual reality (VR) are still unexploited for the realization of construction projects. The use of new technologies could increase the willingness of construction professionals to use BIM. This paper presents an innovative workflow towards sustainable construction material application through VR-enabled BIM for architecture, engineering, and construction (AEC) industries towards improving circularity. Students applied BIM and VR in a Building Design course.

Therefore, this study introduces a workflow for circular immersive parametric design (CIPaDe). The CIPaDe Workflow includes stages of 1) material selection for load-bearing and non-loadbearing elements 2) geometry exploration and 3) unit and systems design applying modular design, design for disassembly, and design for deconstruction principles. There is sufficient evidence that the use of BIM and VR in AEC education environments is desirable and beneficial. The proposed CIPaDe, BIM-into-VR-based workflow is expected to improve students' learning performance, provide an environment similar to the real world, increase the visualization of models before they were built, and enhance their creativity.

Keywords: Virtual Reality, Sustainability, BIM, Design Review, Immersive Virtual Reality

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Introduction

Universities around the world are adopting Building Information Modelling (BIM) for their built environment courses and consider it a necessary component of professional practical training (Pillay et. al., 2018). Design education usually involves the use of freehand and software, creators go through the processes of sketching, shaping the forms, detailing, and final renderings (Drampalou et. al., 2022). The design process is full of iteration and commences with the exploration of concepts which leads to two-dimensional sketches. Subsequently, the geometry became defined and the repetitive actions of sketching and considering the ways to communicate design intentions resulted in a final render that

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represented the design in the best possible way. In current times, the use of software in the design process has introduced tools for more efficient and sustainable design, early material selection, and mass simulation that contribute to decision-making at the early stages of design. In addition, adopting BIM technologies at the early design stage allows for additional information into building models such as time, cost, manufacturers, details, sustainability, and maintenance information (Ogwueleka & Ikediashi, 2017).This paper seeks to provide an educational framework for adopting immersive exercises and BIM during sustainable building design education in universities. The following sections presented are the literature review, methodology, findings, discussion, and conclusion.

Literature Review

A lack of skills, education, and knowledge of BIM are the biggest barriers to the full implementation of BIM in South Africa. Furthermore, the results also show that educational and skill development initiatives are widely considered to be the answer to the existing barriers to BIM adoption (Kekana et al., 2015).There are many BIM tools in the Architecture, Engineering, and Construction (AEC) industry. The top ten BIM software sourced from three websites; Plannerly, Parametric Architecture, and LinkedIn showed that Autodesk Revit was the most popular software. Other useful software included Plannerly, Trimble Connect, Revizto, BIMcollab, Dalux, Autodesk Construction Cloud formerly known as BIM 360, Graphisoft Archicad, Solibri Model Checker, BricsCAD BIM and others, Table I.

Table I: Popular BIM Software from three websites. Access date February 2024

SN	Plannerly	Parametric Architecture	LinkedIn
1	Autodesk Revit	Autodesk Revit	Autodesk Revit
2	Plannerly	Graphisoft Archicad	Plannerly
3	Trimble Connect	SketchUp	Trimble Connect
4	Revizto	Rhino	Revizto
5	BIMcollab	Vectorworks	BIMcollab
6	Dalux	AutoCAD	Dalux
7	Autodesk Construction Cloud / BIM 360	Plannerly	Autodesk Construction Cloud / BIM 360
8	Graphisoft Archicad	Trimble Connect	Graphisoft Archicad
9	Solibri Model Checker	Revizto	Solibri Model Checker
10	BricsCAD BIM	BIMcollab	BricsCAD BIM

In higher education students have explored immersive experiences in design-related subjects. In a previous study, participants were asked to imagine teaching and learning situations twenty years ahead, in a future where Virtual Reality (VR) technology and the design studio are harmoniously integrated, findings showed that VR use combined with a lesser amount of real-world interactions was perceived as undermining student maturity or growth. This hints at implications in the design process, pedagogy, curriculum, teacher and student dynamics, and role repositioning, showing that

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integrating VR may have ramifications stretching far beyond the design studio context (Bernando & Duarte, 2022). However, the design of technology education does not only satisfy the students' needs but also the requirements of teachers, industries, and market trends and soft systems methodology is an effective approach in designing courses regarding hands-on technologies, and the use of immersive technologies improves the learning performance for acquiring fundamental knowledge and application know-how (Wu et al., 2021).(Cho & Park, 2022) proposed an immersive virtual reality simulation for environmental education based on the virtual ecosystem model and presented two applications developed based on simulation. Their research encouraged students' active participation and motivation to solve environmental problems while experiencing the results of interaction related to environmental factors in a virtual environment. VR has been used in conjunction with project-based learning for a self-directed approach to designing and implementing a product using 3D software whilst also using virtual reality to evaluate their design. The hypothesis was that the use of VR with a project-based learning approach to facilitate the attainment of desirable goals in the engineering design project, improved achievement of course learning outcomes and promoted effective communication. In the findings, the VR approach significantly affected the distribution of cumulative project grades, particularly the implementation component. In addition, the course outcomes related to project design were better achieved in the VR approach. The communication and problem-solving skills were improved in the VR approach as compared to the traditional approach (Frasson et al., 2021, Halabi, 2020).Frasson et al. (2021) proposed a framework for based on VR technology and contemporary head-mounted displays incorporating game-based techniques and adaptive design in education for educational applications to transform learning procedures into entertaining, engaging, enjoyable, and effective experiences. The use of VR enabled users to engage in the Energy SIM simulation tool (Anifowose et al., 2023). VR could encourage students in sustainable material selections. This study explored sustainable material selection in a design exercise that incorporated the use of VR for project reviews.

Research Methodology

The students began by sketching their modular panels for a shading wall. This was an iterative session and the focus was on the shading wall on the south-facing side of the building. Students selected traditional materials for the shading wall and there was geometry exploration for a modular design which would be repeated to fit the size of the shaded wall designed. Thereafter students produced their building and shaded walls in Revit and there were VR sessions to view the designs. Lastly, a cradle-to-gate life cycle analysis was conducted to evaluate the impacts of the design choices, Figure 1.

Figure I: *Research methodology*

Source: Author (2024)

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Results

For the strategy development part students were asked to name three sustainable strategies they could apply from the class readings and library list, Figure 2. The choices included a windmill, thermal storage, rainwater collection, sustainable materials, renewable energy, orientation, use of roof light pipes to increase natural light, use of glass and glass coating to increase energy efficiency, smart glass, passive heating, recycling, waste control, green plants, and solar panels. Some of the concepts

Integrated recycling and green plants. For the strategy development exercise, students were asked to name three sustainable strategies they could apply from the class readings and library list, Figure 2.

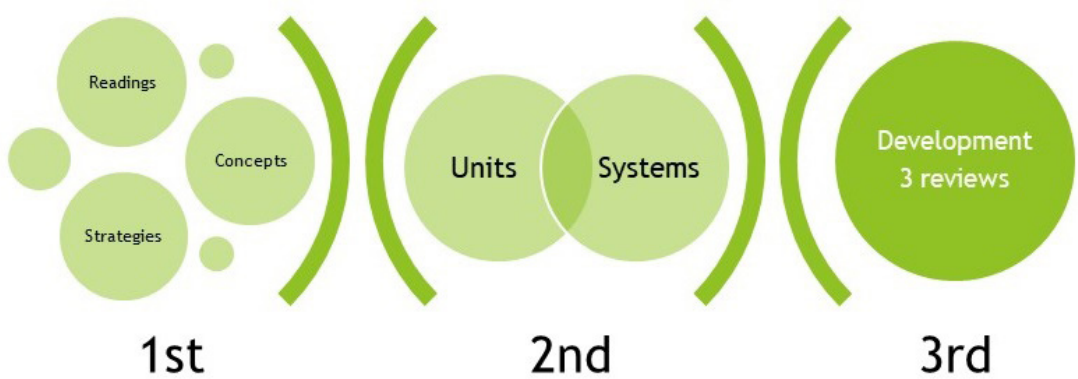

Figure 2: *Design Process*

Source: *Author (2024)*

In the Fall 2023 Building Design course, the students' definition of sustainability was as follows– 1) the ability to function for a long time without negative impact 2) routine 3) the ability to maintain 4) the ability to make something last forever 5) energy efficient practices 6) green building 7) the ability to work well 8) longevity 9) using minimal resources 10) ability to keep track consistently.The lectures commenced with class reading focused on sustainability. Sustainable design choices by the students included a windmill, thermal storage, rainwater collection, orientation, renewable energy, use of sustainable materials, use of light pipes, coating the glass to increase energy efficiency, smart glass usage, passive heating, soundproofing of the classroom near railway, recycling and waste control, and lots of green areas including green walls.After the class readings focused on sustainability, the design stage commenced with the concept development, Figure 3. The sketches included play with forms and green plants in the building. Three examples of concepts by the students include 1) a bright, colorful, art, fun, and expressive sketch. This initial sketch combined forms from an apple, a keyboard, a Dorito, and a dinosaur, Figure 3a. 2) an atrium design with a café, the goal was to bring nature inside and develop a greenhouse-type roof, Figure 3b. 3) an array of books that open up representing the idea of the task of designing an educational office building, Figure 3c.

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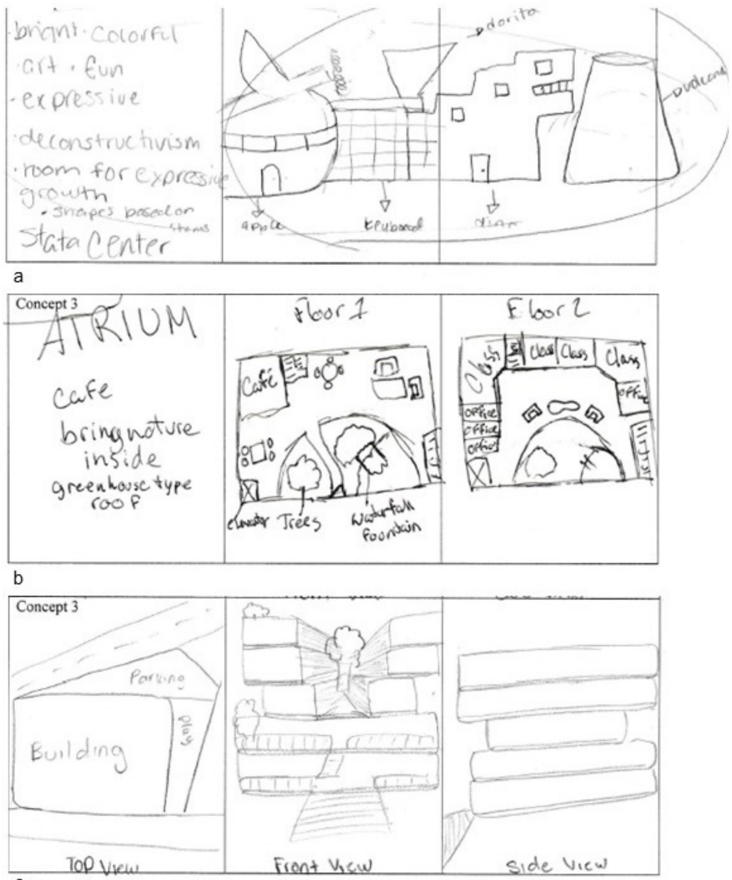

Figure 3: Concepts

Source: Student (2024)

The sustainable assessment focuses on material selection for the south-facing walls of the design project, Figure 3. Materials could be chosen from the Embodied Carbon in Construction Calculator (EC3) tool a free cloud-based tool that allows benchmarking, assessment, and reductions in embodied carbon, focused on the upfront supply chain emissions of construction materials Table II.

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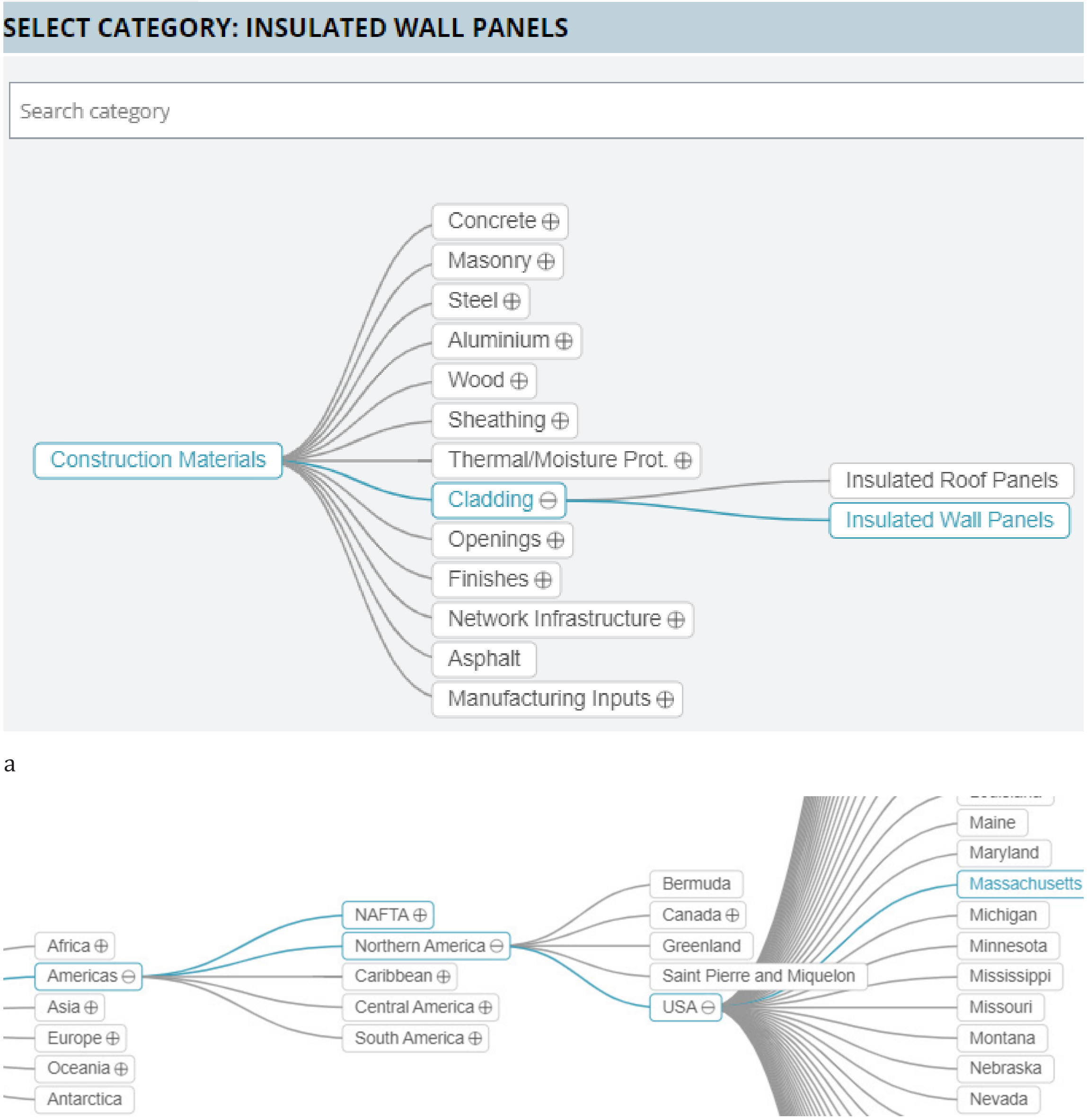

a

b

Figure 4: *Embodied Carbon in Construction Calculator*

Source: *Author (2024)*

Table II: Student material selection for the shading system

SN	Product Name	Mass per m³ (kg)	Density ()	Reported GWP/m³ (kgCO2e)
1	Classic sawn	500	500 kg/m³	42.18
2	Softwood lumber	458.13	1010 lb/m³	55.56
3	US redwood lumber			50.89
4	Clay			

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5	Drywall
6	Wood
7	Concrete
8	Steel
9	Cement

Table III: Default material for insulated panel walls in EC3 tool

SN	Product Name	Declared Unit (DU)	Thickness range min (m)	Reported GWP/DU (kgCO2e)
1	Metal Composite Material (MCM) Panels	1080 ft^2	0.004	3629
2	Aluminum exterior cladding	100m^2		11170
3	Insulated Metal Panels	100m^2		14370
4	Roll Formed Metal Wall and Roof Panels	100m^2		1652
5	Roll Formed Aluminum and Steel Cladding	100m^2		2491

The chosen products were compared to the default industry insulated wall panels in the EC3 tool, Table III. The first product of a metal composite material panel was declared in square feet (1080 ft^2) while others were declared as 100 square meters. The two quantities are equivalent therefore a direct comparison could be made, Figure 5. One product had a declared thickness and the study assumed the same thickness for other products to compare them with the student selections that were declared by volume.

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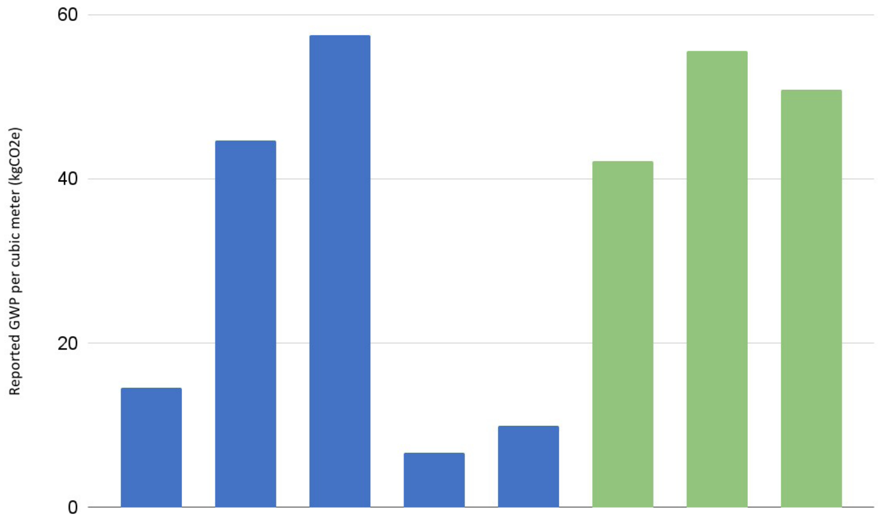
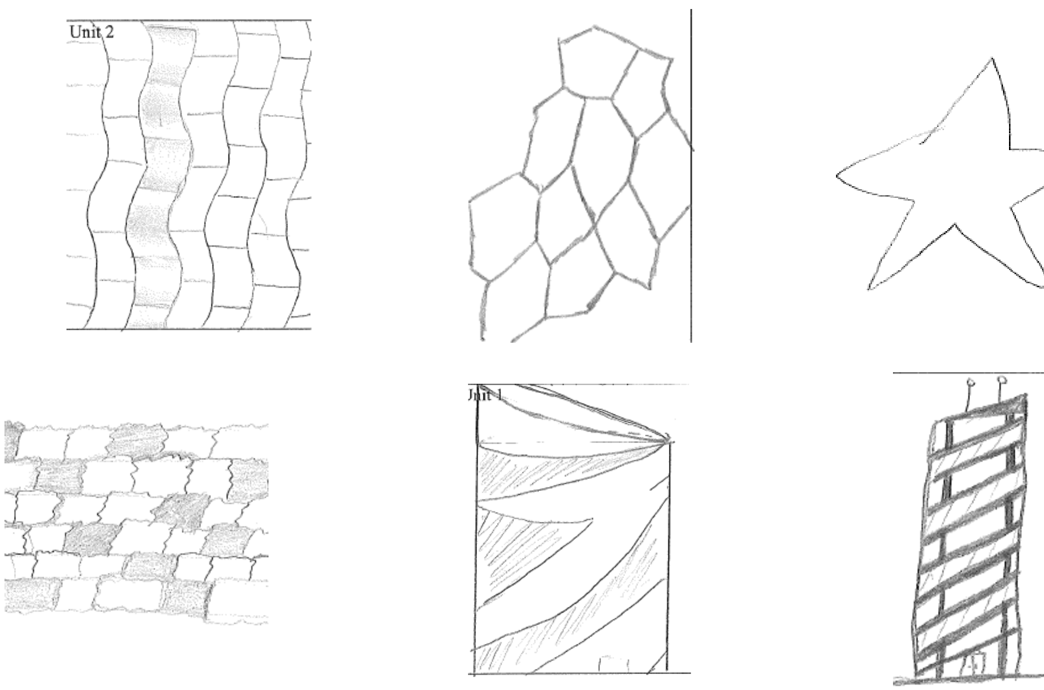


Figure 5: *Comparison of selected materials using the Embodied Carbon in Construction Calculator, student selection in green.*

Source: Author (2024)

Students were given forms for sketches of three possible units of their façade systems, Figure 6. Subsequently, they selected materials for their designed shaded wall systems in Figure 7.



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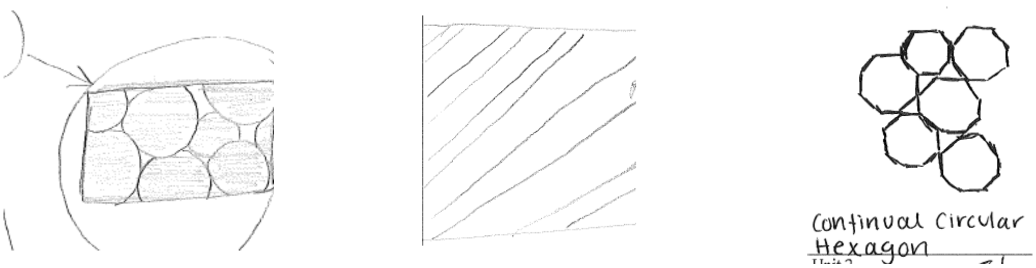

Figure 6: *Units*

Source: *Students (202*

Source: Students (2024)

VR sessions

Students assessed their projects as users and spent an average time of 5 minutes for 18 sessions in the VR environment, Figure 8. 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. In their report at the end of the semester, team members responded to questions on a user experience survey, and six students responded to inquiries on the VR sessions. Students strongly agreed that the VR sessions were innovative, new, interesting, exciting, attractive, practical, efficient, dependable, motivating, and enjoyable. 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. 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.

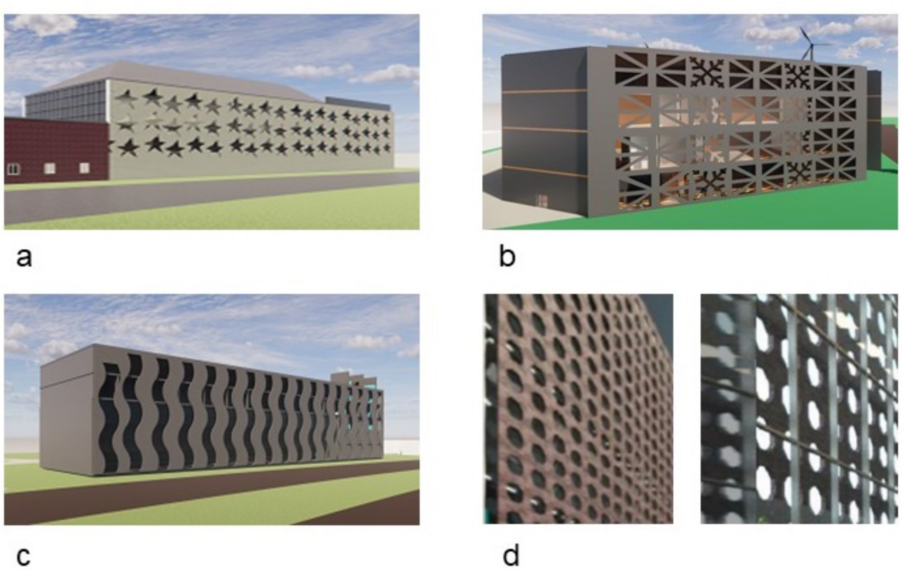

Figure 7: Shading systems

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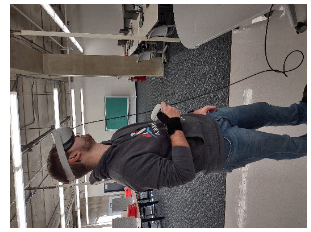

Figure 8: *VR sessions during the semester*

Source: *Author (2024)*

Cradle-to-Gate life cycle analysis

Four shading systems in Figure 7 were analyzed using the United States Environmental Protection Agency's Waste Reduction Model (WARM) Version 16. Data on the scrap metal from the city from 2010 to 2020 provided an annual average scrap metal amount of 82,558 kg, Figure 9. Dimensions of the student shading walls are shown in Table IV. The metal was compared by selecting the recycling process as the baseline generation and management of the waste material while the alternate management scenario for the scrap metal was source-reduced. This method proposed the direct reuse of the metals as shading system parts without recycling. The study assumed a thickness of 0.004m for all panels.

The best two products did not declare their weight for comparison with the WARM model. However, the Metal Composite Panels (MCP) provided a mass of 756 kg for 100 m^2 of product. The GWP after uncertainty adjustment per 100 m^2 was 3629 kgCO2e. Therefore, MCP represented virgin materials for the four designs and the environmental impacts were compared with utilizing the salvaged scrap metal in the city.

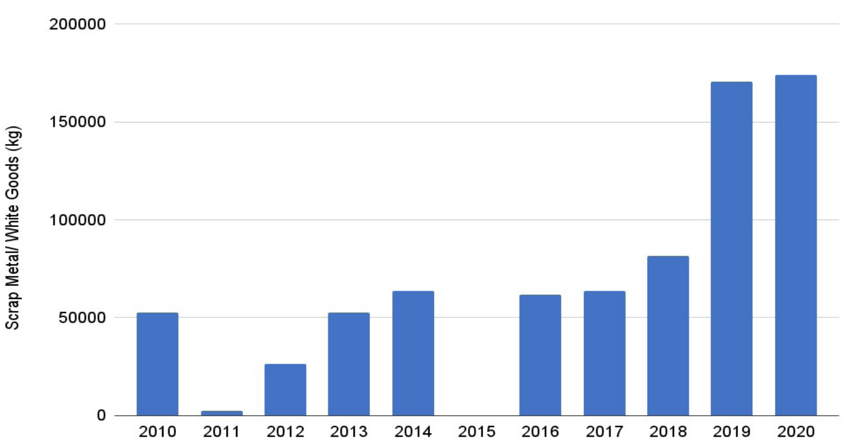

Figure 9: Scrap Metal/White Goods data from the city

Source: Author (2024)

Table IV: Sizes of students' shading systems and impacts when Metal Composite Panels are used as primary materials

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SN	Height (m)	Width (m)	Area (m2)	Mass (kg)	EC3 GWP (kgCO2e)
a -1	21.36	96.97	2071.63	15,661.5	75,179
b- 2	24.85	47	1118.18	8.453.5	40,579
c - 3	22.73	101.21	2300.28	17,390	83,477
d- 4	21.21	49.32	1046.14	7,908.8	37,965

Table V: Results from WARM for comparison between virgin materials and reusing metal

Design	Mass (tons)	Avoided GWP (MTCO2e)	Avoided GWP (kgCO2e)	Avoided energy (mBTU)	Avoided energy (mJ)
1	17.3	12.84	12,840	271.41	286,352.71
2	9.3	6.9	6,900	145.9	153,932.65
3	19.2	14.25	14,250	301.23	317,814.47
4	8.7	6.45	6,450	136.49	144,004.57

WARM results showed that possible avoided emissions and energy of the designs when virgin materials were substituted with salvaged material from the city, Table V. Avoided emissions due to material reuse for Design #1 were equivalent to annual emissions from 3 passenger vehicles or consuming 5,435.26 litres of gasoline or consuming 532 cylinders of propane. The range of avoided emissions was 6,450 to 14,250 kgCO2e. The range of avoided energy was 144,004.57 – 317,814.47 mJ. Design #4 was the most sustainable, Figure 10.

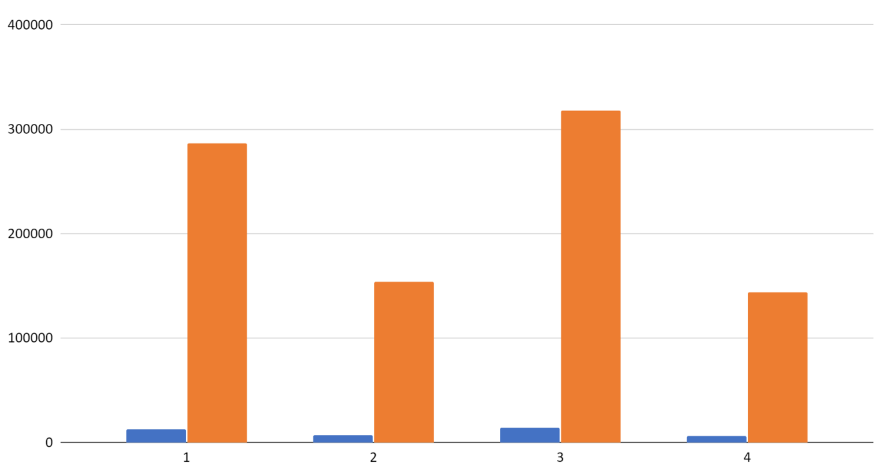

Figure 10: *Avoided emissions and energy due to reuse of scrap metals*

Source: *Author (2024)*

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Discussion

In the presented study, students' project in a building design course was structured to enable sustainable material selection and VR engagement in the design process. The EC3 tool was selected as the material source for global warming potential comparisons. Default external cladding materials had lower GWP than student selections while the maximum GWP was found in the default selections too. This study demonstrates a workflow for sustainable design, material selection, and VR usage in a design studio. The results of this study demonstrate that default materials in the EC3 tool could be selected for building use based on design intent. The cradle-to-gate analysis showed that reusing scrap metal for the shading systems could avoid emissions and energy used in recycling. Additional exercises for considerations while selecting materials are needed to better understand how design choices influence GWP and energy.

Conclusion and Further Research

The workflow for sustainable material selection included material selection, geometry exploration, unit and systems design, design iterations with virtual reality sessions, and a cradle-to-gate life cycle analysis. The results of the study demonstrate that default materials in the Embodied Carbon in Construction Calculator (EC3) could be more sustainable than designer choices. Recommendations include conducting a material selection activity as a studio exercise. Although the declared units in the EC3 appear in different units, they could be equivalent and represented in imperial and metric units. Cradle-to-gate life cycle analysis showed that there were positive impacts of substituting materials with scrap metal from the city. The range of avoided emissions was between 6,450 and 14,250 kgCO2e and the range of avoided energy was between 144,004.57 and 317,814.47 mJ. Four design projects were compared focusing on shaded wall designs in their projects. Designs #2 and #4 were the most sustainable due to their sizes. Further tests of the proposed workflow are needed, especially towards designing for sustainability.

Acknowledgment

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