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Earthen Builder Simulation: Representing Natural Materials and Embodied Carbon With Computational Play

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Abstract. Natural building materials are critical to the future of a decarbonized built environment. Involving low-carbon and readily available materials such as clay-rich soils and plant fibers in building processes employ a range of techniques, and hence, a range of environmental and visual features, from rammed earth to cob and light straw clay. However, despite their advantages, natural materials are not represented in mainstream construction, perceived mistakenly as poor in their performance, low-tech, and are missing representation in training for building professionals. This research develops a digital representations-study of natural material futures and their associatedembodied carbon. It links, for the first time, computational play, and criticaldata with traditional recipes of designing with natural materials. A digital tool for sustainable engagement was developed by utilizing a geological database of locally available soil-based repositories. As an exploratory design tool, it was tested through 24 playtests for its mechanics, graphical user interface, and perception shifts among designers and researchers. The final outcome seeks to establish a digital foundation for a more comprehensive earthen materials knowledge tool and life-cycle assessment. As a final deliverable, this work aims to unveil the strength of simulative material representations in heightening the knowledge base of an overlooked, historic, and sustainable practice.

Keywords: Earthen materials; Media arts; Computational play; Life-cycle assessment; Embodied carbon; Sustainability design.

1 Introduction

Diagrammatic representations visualizing cradle-to-grave life-cycle assessments (LCA), building nutrition labels, and material diets for climate-neutral construction have been developed with the aim to cultivate a deeper understanding of decarbonized building materials [1-3]. Some of these representation studies have been furthered as established LCA tools, calculating the greenhouse gas emissions of modern building materials encompassing processing, transportation, and operational energy such as One Click LCA and the Embodied Carbon in Construction Calculator (EC3) by the Building Transparency organization (Fig. 1) [4-5]. While these tools hold great promise and importance in designing sustainable architecture, they have yet to adopt additional, non-commodified and radically low-carbon building materials which are readily available in and around their construction site. This includes transforming soils, agrowastes, and other bio-based additives into earthen construction systems such as adobe bricks, rammed earth, light straw clay, and compressed earth blocks – low-carbon building materials locally sourced from their environment [6-7]. In addition to absent construction methods, current LCA tools lack the responsive, playful engagement needed to help users train and understand their design and material's locational context. As a result, this research investigates how the intersection of computational pedagogy and natural materials can help users (1) explore building material origins, (2) simulate low-carbon architecture, and (3) democratize knowledge in sustainable design practices.

Following this line of inquiry, foundations of computational game theory were explored to provide users with an accessible simulation that demonstrates a low- carbon built environment. Traditionally, computational games have been defined as algorithmic approaches of simulating achievement-based end goals [10]. Computational games such as SimCity and Minecraft provide players with decision metrics from user actions that inform on either their urban or building material contexts [8-9]. Through the game theory framework, it has been proven that combining playful aesthetics with real-world problems delivers a perceivably low-stakes approach of engaging users into a virtual Anthropocene [10, 28-29]. Therefore, computational play is at the center of this research, offering users a virtual environment that simulates datasets into spatial contexts and reflects user decisions based on their input.

This study introduces "Earthen Builder LCA," a gamified simulation demonstrating the use of locally sourced earthen materials. Serving as a computational play experience, it aims to foster sustainable engagement among designers and the general public by presenting low-carbon structural possibilities. The simulation's development process utilized game mechanics and allowed for outcomes from playtests to inform the minimum viable product (MVP) – serving as a foundation for a more comprehensive earthen materials life-cycle assessment.

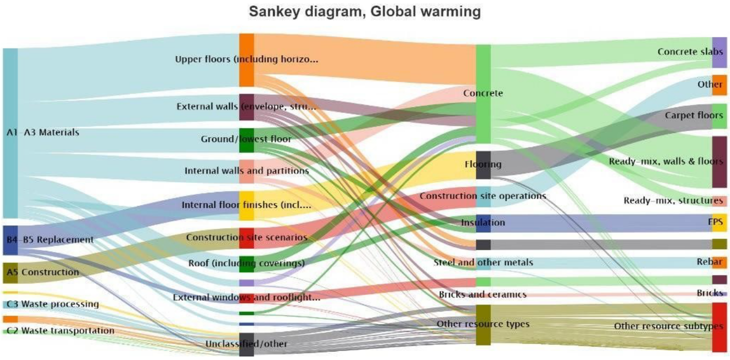


Fig. 1. Diagram of a current life-cycle assessment algorithm covering modern construction systems. From "Building life cycle assessment software for Level(s)," One Click LCA.

2 Background

Building with natural materials suffers from both inaccurate perceptions and a lack of representational resources to its knowledge base. This section provides an overview of natural materials and their embodied impact, current life cycle assessment models, and how computational play and its precedents can address natural building materials within a virtual context.

2.1 The Case for Natural Building Materials, Perception, and Life Cycles

Natural materials are low-carbon building materials locally sourced from their environment. Their applications include soil and fiber-based materials mixed and applied in construction systems such as rammed earth (monolithic load-bearing earth-aggregate wall applied in compression), to slightly reinforced assemblies such as cob (monolithic load bearing earth-fiber wall applied in sculpture), and fiber-rich earth composites such as light straw clay (earth slip-coated straw infill). Natural earth-fiber materials in building construction have been a historic practice overlooked by the rapid processing and use of modern materials – a significant climate change contributor [7,11]. Life cycle assessment (LCA) models for building construction, which are analyses for measuring a building's environmental impact from its material production (cradle) to its transport on location (site) and end of use (grave), have beenused to document natural materials as carbon-neutral alternatives compared to life-cycles of modern building materials such as Portland cement and steel production[7,11-13,27]. Furthermore, the use of natural materials has proven mechanical and thermal properties yet is omitted in mainstream construction practices due its inaccurate perception of being low-tech [14-16]. As a result, accessible representationis crucial in overcoming the existing knowledge and perception barriers regarding building with locally-sourced natural materials for sustainable impacts. Strides have been made in visualizing carbon impacts of natural materials such as diagrammatic material guides and collections [17-18]. Thus, this study presents an opportunity in furthering this work by developing a dynamic interface for engaging users with natural materials.

2.2 Related Work on Computational Play in the Context of Architectural Design and Materiality

Simulation and computational play provide a contemporary learning practice that represents, informs, and visualizes user decisions within a virtual space [19]. Tools such as "House Builder" and "Cities: Skylines" all provide informational and playful experiences that assist users with learning about new knowledge bases within an architectural and urban context [30-31]. This subsection explores how games and activities — from modernist Buckminster Fuller and his developed World Game, to the current computational era Minecraft simulation — can set a foundation for assessing earthen material impacts and their geography within a virtual context.

2.2.1 Buckminster Fuller's World Game

Buckminster Fuller, an American architect and systems theorist, is relevant for his work on computation and cooperative design – using play as a method of understanding human collective survival (Fig. 2) [17,20]. In the World Game, Fuller sought to "document and represent a generalized inventory of world resources. Fuller intended for the inventory to reveal the impact of energy and resource scarcity at the scale of the planet [17]." Through collaboration and computational simulation of resources displayed onto a Dymaxion map, participants were asked to seek "stability and equilibrium" for equitable and sustainable distribution of world resources [17]. From the simulation, three metrics were visualized: resources, distribution, and impact.

Like Fuller's activity, this research asks, how can the visualization of locality-based natural materials contribute to carbon-neutral building practices for the collective survival of humanity? Since both a knowledge and information accessibility barrier exists, how can these resources be simulated for a higher level understanding?

Fig. 2. Buckminster Fuller's World Game™. From "A Brief History of the World Game™ Workshop," 2019, World Game Workshop and "Buckminster Fuller's World Game," 2015, Columbia University GSAPP.

2.2.2 Minecraft

The sandbox game, "Minecraft," serves as the most relevant precedent to understanding materiality from soil to form through a low-poly architectural context (Fig. 3) [9]. In the game, the 'Creative Mode' provides users with all the material textures pre-applied to blocks, architectural elements, and furniture to place and build in-game. While 'Minecraft: Creative Mode' invites an educational argument, the game empowers users to rapidly design a world of synthetic building realities without restraint or consideration for its environmental outcomes. As a result, can playful approaches inspired by games such as “Minecraft” inform these worldly notions of building through climate impact contexts? Based on the game mechanics of the building sandbox, can users design on a level of scale where the material possibilities feel endless? Can these approaches then be combined to visualize environmental decisions that translate into the material world?

Fig. 3. Minecraft terrain view and village environment. From “Minecraft game adds Ordnance Survey GB terrain data” by Matthew Wall, 2013, BBC and “5 Best Minecraft Village Seeds” by Emily Eubanks, 2023, Sportskeeda.

3 Aims and Methods

“Earthen Builder LCA” is a response to the knowledge barrier regarding earthen materials and their availability in a local context [21]. The purpose of this project was to develop an accessible experience that engages multiple disciplines in designing and visualizing potential structural outcomes with low-carbon soil-based mixtures serving as pre-applied sustainable building materials. The intention of integrating a playful methodology was to engage a broader user-base in designing with natural materials through a publicly accessible computational tool. This was accomplished by calculating the data of cradle-to-site carbon footprint metrics from the Inventory of Carbon & Energy database, photographing earthen materials from the Columbia GSAPP Natural Materials Lab, including clay soils and fibers such as straw, fique, flax, and hemp, and compiling locational soil data from the USDA soil survey. All of these components were then streamlined into accessible game mechanics, allowing for ubiquitous understanding of earthen materials through gamification.

3.1.1 Methodology

The CRISP-DM (Cross-Industry Standard Process for Data Mining) methodology was followed in developing the pilot MVP of representing the soil and carbon data through a virtual simulation (Fig. 4). In this methodology, a six-step framework is established in discovering and validating datasets and downscaling them into high-level models for product deployment [22]. Through this methodology, a downscaled virtual space was created to inform users on sustainable data-driven decisions through the power of

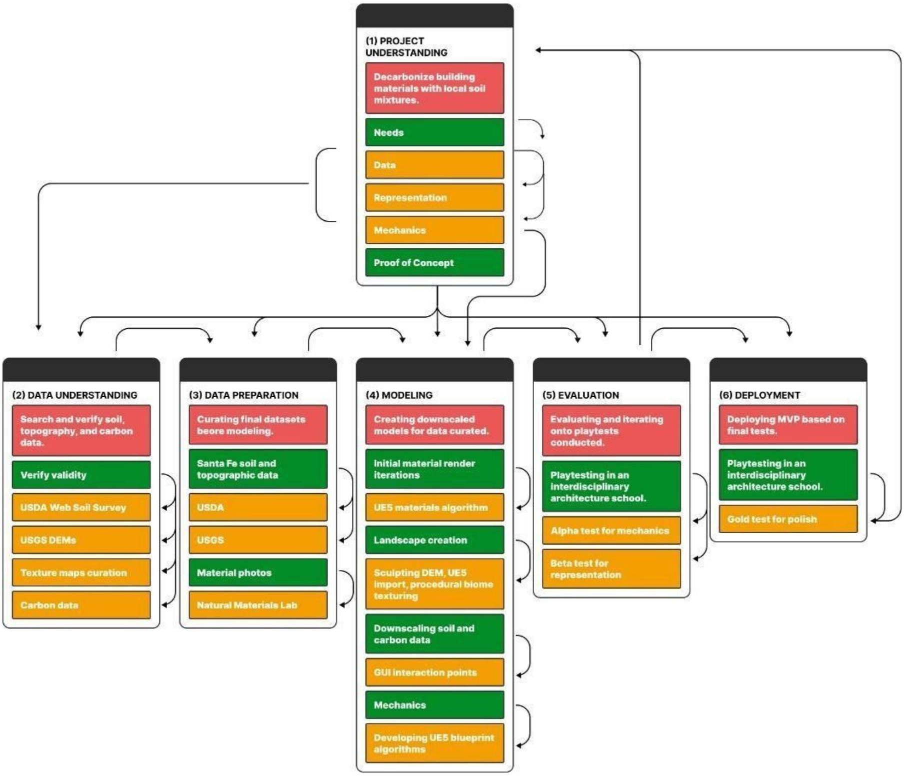


Fig. 4. The project methodology of downscaling the soil and carbon datasets into a virtual simulation consisted of six distinct stages: (1) project understanding, (2) data understanding, (3) data preparation, (4) modeling, (5) evaluation, and (6) development.

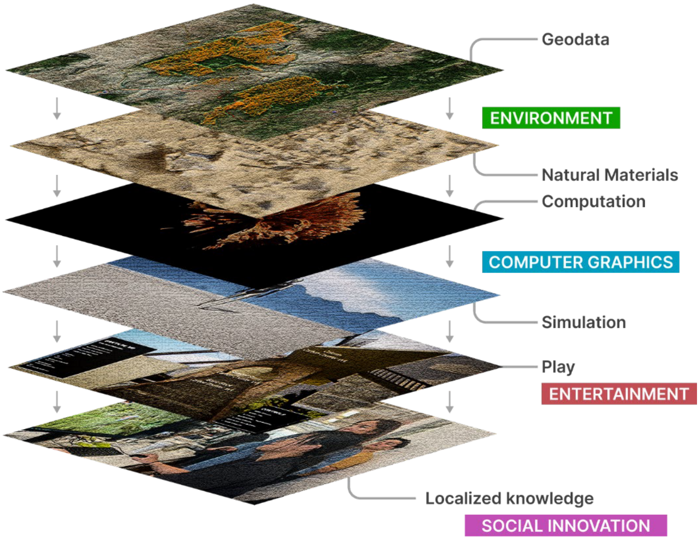


Fig. 5. The project layers map demonstrating the four disciplinary components factored into the final outcome.

computational play and addressing the pedagogy of design technology (Fig. 5). The project's process was initiated by demonstrating a video proof of concept presented to an architecture school committee and identifying its three core components for product development: data, representation, and mechanics.

The project's primary datasets were the US Department of Agriculture (USDA) national web soil survey updated once every year by the Natural Resources Conservation Service and digital elevation satellite imagery collected by the US Geographical Survey (USGS). The embodied carbon data was collected from an inventory report compiled by a UK university center [23]. These datasets were then visualized as a landscape terrain and as graphical user interface interactions for users to be informed on the materials' data in their chosen locality and begin building with it. As a result, a data-informed spatial interface was fully realized, and user tested through its first (alpha) and second (beta) iterations to inform its final (gold) stage for product deployment.

The MVP serves as a foundational milestone for what is demonstrated in the proof of concept (POC). In the POC, the user selects from a world library of localities to design in. Within these localities, the user is presented with a location's soil data and options to mix varying materials to apply them to the architectural elements they will be building with (Fig. 6). As they create their structures, the embodied carbon of their design decisions is presented along with any adjustments they may need to lower their design's carbon footprint (Fig. 7).

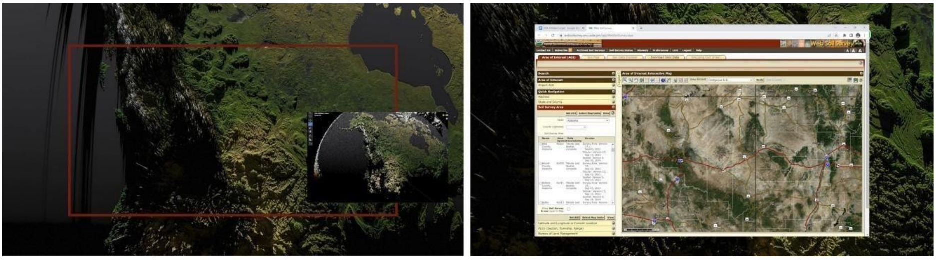


Fig. 6. The 'World View' allows users to select which locality to build in. Each locality selection is presented with the soil type that can be used as a suitable building material.

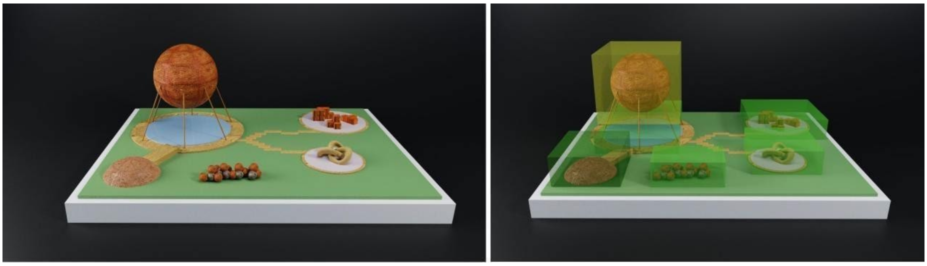


Fig. 7. The 'Terrain View' presents users with a range of possible earthen mix-designs, building elements, and

In the pilot MVP, Santa Fe, New Mexico is presented as the first point of intervention to design in with the locality's soil mixtures pre-applied to the inventory of architectural elements. This is in addition to the soil horizon level in which these elements are sourced and their associated carbon footprint. The product's development process included representing materiality within the context of a locality's soil data and programming the tool through the Unreal Engine 5 (UE5) software to serve as a playful design interface. Initial development tests were conducted in Unity and Rhino Grasshopper. However, using UE5 allowed for higher-fidelity graphical representation and mechanics compared to its counterparts. The interface was playtested on 24 instructors, researchers, and graduate students in an architecture and planning school encompassing architecture, computational design, and urban planning backgrounds. Discussed in this section is the methodology of representing earthen materials as a speculative digital twin to understand our own physical habitats including material texturing, real-world landscape rendering, and downscaling datasets into a simulative spatial reality.

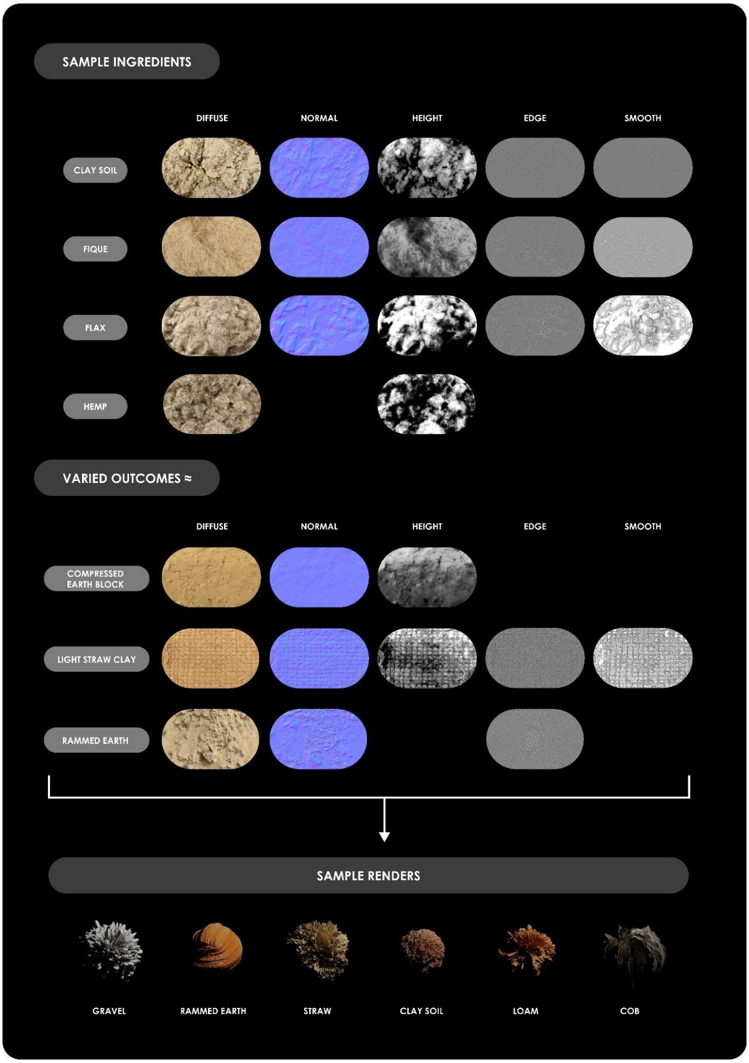


Fig. 8. Demonstrated are the samples of the original soil materials digitized through photo documentation. These material maps were rendered into the Unreal Engine 5 software where the models were texturized.

3.1.2 Curating Material Textures

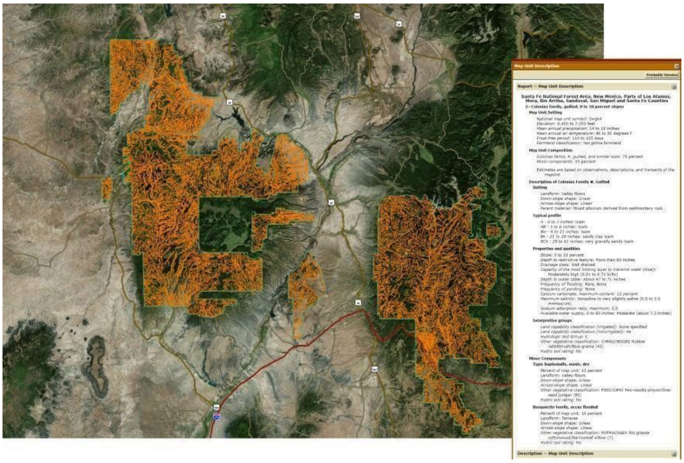
The first step in visualizing materiality through a virtual environment was to document original soil and fiber-based textures. The Columbia GSAPP Natural Materials Lab, which specializes in earth-fiber materials, served as the primary source for curating a materials portfolio: clay soils, fique, flax, hemp, light straw clay, and iterations of rammed earth were photographed (Fig. 8-9). These materials were then digitized into varying texture maps: normal, albedo, diffuse, edge, height, and smoothness to be rendered as material abstractions and onto the inventory of build materials provided to the user in the simulation.

Fig. 9. (From left to right per row). Gravel, rammed earth, loam, clay soil, cob, and straw material textures were developed in a 3D rendering system.

3.1.3 Soil and Topographic Data

Known for its clay-rich environment, Santa Fe, New Mexico was selected as the first locality that users could design in. Santa Fe's soil data was identified on the USDA's publicly available web soil survey with its soil horizon levels and climate conditions listed (Fig. 10, 13). Since climate plays a significant role in the texturization of natural materials, representing this through the UE5 materials algorithm with contrast shading and height map displacement was essential in providing users an accurate design experience for understanding compositional change per location.

The topography of the landscape was downloaded as a BIL file (produced from satellite/aerial imagery) from the USGS EarthExplorer interface, digitized as a digital elevation model (DEM) in the TerreSculptor software, and rendered into UE5 spanning a 129,024 meter-map to-scale with a procedural semi-arid biome texture applied (Fig. 11). This large-scale map would contribute to the sandbox aesthetic of the tool where the user could endlessly design around them at free-will [24].



Report — Map Unit Description

Santa Fe National Forest Area, New Mexico, Parts of Los Alamos, Mora, Rio Arriba, Sandoval, San Miguel and Santa Fe Counties

2—Colonias family, gullied, 0 to 10 percent slopes

Map Unit Setting

National map unit symbol: 2wgk4
Elevation: 6,400 to 7,050 feet
Mean annual precipitation: 14 to 18 inches
Mean annual air temperature: 46 to 50 degrees F
Frost-free period: 110 to 125 days
Farmland classification: Not prime farmland

Map Unit Composition

Colonias family #, gullied, and similar soils: 75 percent
Minor components: 25 percent

Estimates are based on observations, descriptions, and transects of the mapunit.

Description of Colonias Family #, Gullied

Setting

Landform: Valley floors
Down-slope shape: Linear
Across-slope shape: Linear
Parent material: Mixed alluvium derived from sedimentary rock

Typical profile

A - 0 to 3 inches: loam
AB - 3 to 6 inches: loam
Bw - 6 to 21 inches: loam
Bk - 21 to 29 inches: sandy clay loam
BCk - 29 to 61 inches: very gravelly sandy loam

Properties and qualities

Slope: 0 to 10 percent
Depth to restrictive feature: More than 80 inches
Drainage class: Well drained
Capacity of the most limiting layer to transmit water (Ksat): Moderately high (0.21 to 0.71 in/hr)
Depth to water table: About 47 to 71 inches
Frequency of flooding: Rare, None
Frequency of ponding: None
Calcium carbonate, maximum content: 12 percent
Maximum salinity: Nonsaline to very slightly saline (0.5 to 2.0 mmhos/cm)
Sodium adsorption ratio, maximum: 2.0
Available water supply, 0 to 60 inches: Moderate (about 7.2 inches)

Interpretive groups

Land capability classification (irrigated): None specified
Land capability classification (nonirrigated): 4e
Hydrologic Soil Group: C
Other vegetative classification: CHNA2/BOGR2 Rubber rabbitbrush/Blue grama (42)
Hydric soil rating: No

Minor Components

Typic haplustalfs, mesic, dry

Percent of map unit: 15 percent
Landform: Valley floors
Down-slope shape: Linear
Across-slope shape: Linear
Other vegetative classification: PIED/JUMO Two-needle pinyon/One-seed juniper (80)
Hydric soil rating: No

Bosquecito family, occas flooded

Percent of map unit: 10 percent
Landform: Terraces
Down-slope shape: Linear
Across-slope shape: Linear
Other vegetative classification: POFRW/Salix Rio grande cottonwood/Narrowleaf willow (7)
Hydric soil rating: No

Description — Map Unit Description

Fig. 10. The soil data displayed from the USDA database based on the selected locations.

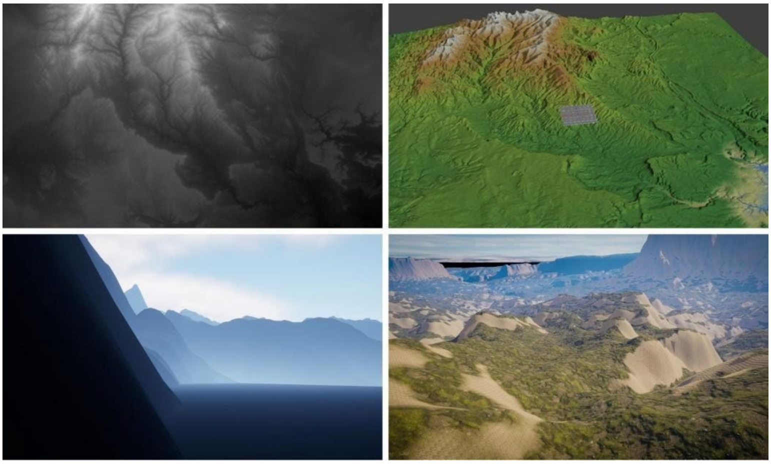


Fig. 11. (Top) Demonstrated is the process of digitizing the digital elevation model into a 3D terrain landscape asset. (Bottom) The landscape was then rendered into the simulation engine with the semi-arid procedural biome applied.

3.1.4 Carbon Data

The embodied carbon data for the material calculations were collected from the cradle-to-site Inventory of Carbon & Energy report [23]. As noted by the report, "this Inventory contains a summary of approximately 1800 records of embodied carbon and energy for 34 classes of materials used in construction [23]." The calculations were then assigned to the building elements to serve as a sustainable metric for the user's design decisions (Table 1). In the table, each building element lists the anticipated materials needed to mix and create the necessary assets based on published guidelines from an agency specializing in natural building construction [25-26]. It is important to note however, that since the carbon data was limited to embodied carbon measurements within select European countries excluding Sante Fe, U.S. as a result, the materials data only served as a schematic estimate for providing feedback to user decisions.

Table 1. Embodied carbon calculations based on materials required.

Building Element	Constituent Materials	Constituent Embodied Carbon Values [$kgCO_2/kg$]	Total Embodied Carbon [$kgCO_2/kg$]
Arch	Soil	0.023	0.765
	Limestone	0.032	
	Timber (mold frame)	0.71	
Block	Soil	0.023	1.333
	Sawn wood (mold frame)	0.86	
	Fiber	0.45	
Brick	Soil	0.023	0.505
	Limestone	0.032	
	Fiber	0.45	
Column	Limestone	0.032	0.032
Door	Soil	0.023	1.743
	Sawn wood	0.86	
	Primary glass (only processed source)	0.86	
Foundation	Soil	0.023	0.915
	Limestone,	0.032	
	Sawn wood	0.86	
Pillar	Limestone	0.032	0.032
Roof	Soil	0.023	1.855
	Limestone	0.032	
	Fiber cement panel	1.09	
	Timber	0.71	
Stairs	Soil	0.023	1.123
	Limestone	0.032	
	Sawn wood	0.86	
	Mortar	0.208	
Tall & Wide Beam	Timber	0.71	0.71
Wall	Soil	0.023	0.765
	Limestone	0.032	

	Timber (frame)	0.71	
Window	Sawn wood	0.86	2.27
	Primary glass	0.86	
	Secondary glass	0.55	

4 Results

The results from the development process were recorded and tested among 24 users, covering the navigation, mechanics, and how the playtests informed the final stages of the computational simulation, as described below.

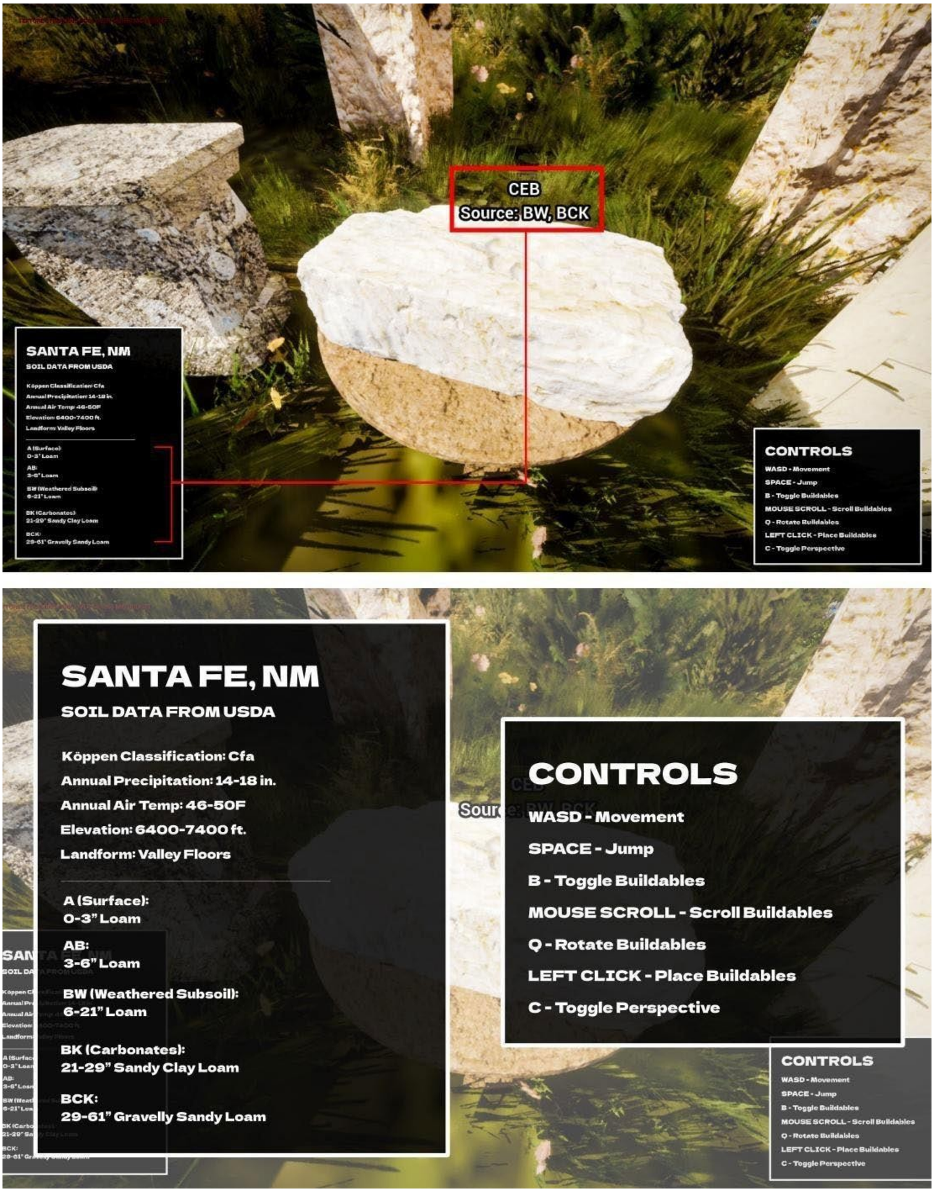
4.1 Navigation

The player character was assigned standard 'WASD' and/or arrow key mechanics to navigate the user through the tool's open world. Upon entry into the simulation, the user is presented with a 'Materials Oasis' of building elements available to them with the soil mixtures pre-applied (Fig. 12-13). The Santa Fe USDA soil horizon level data in which the mixtures are sourced are listed as a hover UI element once the user collides with the building elements in the oasis (Fig. 13).

SANTA FE, NM
SOIL DATA FROM USDA
Köppen Classification: Cfa
Annual Precipitation: 14-18 in.
Annual Air Temp: 46-60F
Elevation: 6400-7400 ft.
Landform: Valley Floors
A (Surface):
0-3" Loam
AB:
3-6" Loam
BW (Weathered Subsoil):
6-21" Loam
BK (Carbonates):
21-29" Sandy Clay Loam
BCK:
29-61" Gravelly Sandy Loam

CONTROLS
WASD - Movement
SPACE - Jump
B - Toggle Buildables
MOUSE SCROLL - Scroll Buildables
Q - Rotate Buildables
LEFT CLICK - Place Buildables
C - Toggle Perspective

Fig. 12. The 'Materials Oasis' presents users with all of the items available in their inventory with the soil mixtures pre-applied.



SANTA FE, NM

SOIL DATA FROM USDA

Köppen Classification: Cfa
Annual Precipitation: 14-18 in.
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Elevation: 6400-7400 ft.
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A (Surface):
0-3" Loam
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3-6" Loam
BW (Weathered Subsoil):
6-21" Loam
BK (Carbonates):
21-29" Sandy Clay Loam
BCK:
29-61" Gravelly Sandy Loam

CONTROLS

WASD - Movement
SPACE - Jump
B - Toggle Buildables
MOUSE SCROLL - Scroll Buildables
Q - Rotate Buildables
LEFT CLICK - Place Buildables
C - Toggle Perspective

Fig. 13. Once the user collides with the buildables, a hover-text UI appears to display where the soil mixture was sourced within its locality. Additional data is presented from the locality including the Köppen Classification (climate zone), annual precipitation, annual air temperature, elevation, and landform type.

4.2 Mechanics

The mechanics of the tool were developed using blueprint class algorithms in UE5 for the PC. A freeform base builder algorithm was scripted that allows users to place architectural elements onto the open world: walls, foundations, roofs, doors, windows, beams, arches, bricks, and simple blocks. Some of these assets were rendered in and retexturized from open-source UE5 and Sketchfab libraries. The inventory of building elements was assigned to the player character where the user could toggle their buildables and apply the mouse scroll to view all their available elements. From there, users could rotate buildables and move through the landscape to place the objects in their chosen positions and view its embodied carbon (Fig. 14). Players also had the option to design from both the first and third-person perspective adhering to the users' range of desires and to represent the scale of the placed objects in relation to their landscape and player character.

Fig. 14. Demonstrated is a user building in third and first person and viewing the embodied carbon of each placement decision through a collision/hover UI action.

4.3 Product Iteration and Playtests

24 playtests were conducted in an architecture and planning school through the first (alpha) and second (beta) iterations to inform its final (gold) stage for product deployment [32-33]. The user sample consisted of researchers, instructors, and students with architecture, computational design, and urban planning backgrounds. In these playtests, three components were observed through observational and qualitative data collection: (1) subject understanding, (2) ease of use, and (3) perception shifts of designing with natural materials.

Before the playtest began, participants were briefed about the study and were asked about their level of knowledge in earthen materials, embodied carbon, disciplinary background, and expertise in using game technology (Fig. 15-16). Of the 24 participants, 88% held very little to no knowledge on earthen materials, 8% had an intermediate understanding, and 4% had advanced expertise. For knowledge in embodied carbon 79% expressed having very little to no knowledge, 17% expressed having an intermediate understanding, and 4% held advanced expertise. 59% of those who playtested were architectural researchers or designers, 33% were computational designers, and 8% were urban planners. For expertise in using game technology, 84% expressed having very little to no proficiency, 8% held intermediate proficiency, and

8% held advanced expertise. Having a high percentage of those who didn't frequently use game technology would help inform the user accessibility of the simulation. The playtests lasted between 15-30 minutes. After 15 minutes, the players could choose to opt out or continue exploring the simulation. This would help inform the users' level of engagement with the experience. In the first stage of testing, 50% chose to continue to the 30-minute mark, with 50% in the second stage, and 84% in the final testing stage. Following the final playtest which involved 18 participants, users were asked the subsequent questions, concluding the playtest study:

1. Do you feel your comprehension of locally sourced earthen building materials has enhanced?
2. Do you feel your comprehension of embodied carbon and life-cycle assessment has enhanced?
3. Did employing a playful interface enhance your engagement with designing for low carbon architecture?
4. Would you use this tool to design potential low-carbon structures for future projects?

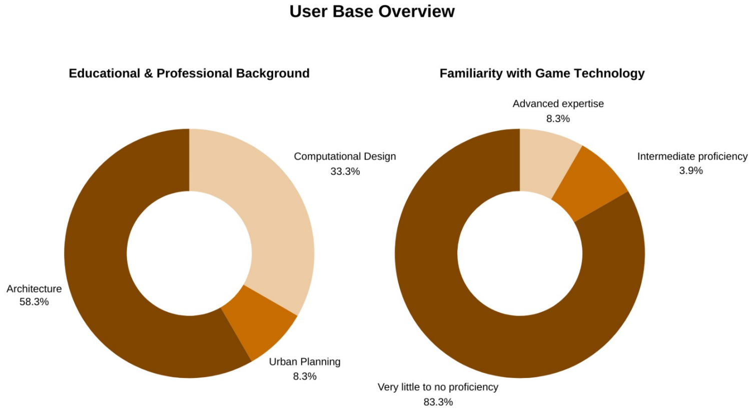

Fig. 15. Demographics on the participants involved in the playtests assessing their academic and professional backgrounds.

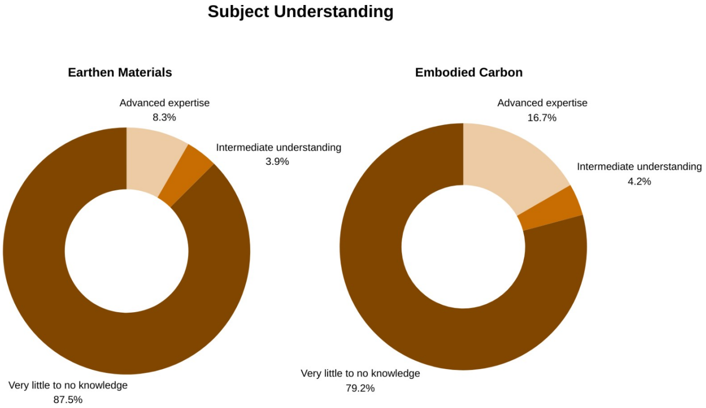

Fig. 16. Demographics on the participants involved in the playtests assessing their familiarity with game technology and subject understanding of earthen materials and embodied carbon.

4.3.1 Alpha Stage Testing and Iteration

In the alpha stage, two playtests were conducted to observe how users interacted with the mechanics of the simulation (Fig. 17-18). In this stage, users played as the default UE5 character and were assigned three building elements: blocks, foundations, and walls. A compressed earth block asset (CEB) was assigned to the block and foundation assets to serve as a low-fidelity representation of earthen materials applied to a virtual space. The only mechanics available to the users at that time were the toggle and placement options along with a blue-red hover box indicating where the build elements could be placed in proximity to the player's character. From this exercise, users noted that they enjoyed creating "playful abstractions with primitive objects," "running through the vast terrain," and appreciated "placing the objects at random" compared to other base builder games that utilize a grid-based system of snapping objects next to one another. As a result, adding a snapping system algorithmwas shelved to observe which build-system users preferred in the following playtest stages.

Fig. 17. Playtests were conducted in an educational environment among designers and researchers and recorded through a semi-structured interview.

Fig. 18. The first round of playtests was observed for their mechanics and user maneuverability of the simulation.

4.3.2 Beta Stage Testing and Iteration

In the beta stage, a mix of primitive and representational objects were added to the inventory of build elements. The material textures were iterated on, and the player character was replaced with a more representational humanoid designed in the Metahuman interface. Observing representation and perception shifts was crucial in refining the simulation for its gold stage. Four playtests were conducted, and users stated that while they enjoyed the photorealistic rendering of the virtual space, replacing the player character with a "less representational humanoid" could strike a balance between "realism" and "abstraction" in the playscape (Fig. 19). The Metahuman was eventually changed into a monochromatic gravel humanoid for the final version (Fig. 15). Users also noted that they wanted to be informed on where their building elements' materials were sourced from before being placed onto the landscape and if there was an option to design in the first-person perspective. As a result, the 'Materials Oasis' was added informing users on where their inventory was sourced within its locality along with a heads-up display of the soil data and toggling between third and first-person perspective for user preference.

Fig. 19. Beta playtests observing user reactions to data and character representation.

4.3.3 Gold Stage and Final Playtests

18 playtests were conducted in the gold stage of the simulation's development (Fig.

Variables Observed	**Alpha Playtests** **2 conducted for mechanics**	**Beta Playtests** **4 conducted for representation**	**Gold Playtests** **18 conducted for polish**
Input	Toggle and placement mechanics; 3 items; CEB texture map; Default UE5 player character.	Mix of primitive and representational items in the inventory; Metahuman player character; Material textures.	GUI embodied carbon data; Soil data GUI; Incomplete structures.
Outcome	Users enjoyed creating "playful abstractions with primitive objects," "running through the vast terrain," and appreciated "placing the objects at random" compared to other base builder games that utilize a grid-based system of snapping objects next to one another.	Users enjoyed the photorealistic rendering of the virtual space. Replacing the player character with a less representational humanoid could strike a balance between "realism" and "abstraction" in the playspace. Users wanted to be informed on where their building elements' materials were sourced from before being placed onto the landscape. Wanted a 3rd/1st person option.	The Metahuman was changed to a monochromatic gravel humanoid. The 'Materials Oasis' was added informing users on where their inventory is sourced from within its locality along with a heads-up display of the soil data. Toggling between third and first-person was implemented.
Iteration	Adding a snapping system algorithm was shelved.	The Metahuman was changed into a monochromatic gravel humanoid. The "Materials Oasis" was added informing users on where their inventory is sourced from within its locality along with a heads-up display of the soil data. Toggling between third and first-person was implemented.	Consider visualizing the environmental consequences of modern building materials in relation to its low-carbon counterpart. Considering a materials map of where specific soil mixtures were sourced from within its locality for its embodied carbon metric.

MVP established as a digital representations study for designing with low-carbon natural materials.

Fig. 20. The outcomes from each playtesting stage informed the next development phase until the MVP was accomplished. The pointer lines represent the flow of how specific user feedback impacted iteration and outcomes contributing to the final product.

20). In this stage, mechanics and perception shift iterations were observed based on the comments of the previous playtests. The embodied carbon data was added as a hover-GUI interaction and three of the early playtester's incomplete structures were implemented within the simulation to serve as a call to action. With these structures, users could complete and/or add to it to seek the lowest embodied carbon or design their buildings from scratch. The outcomes of these playtests included exterior (Fig. 21), interior (Fig. 22), and experimental builds (Fig. 23) based on user needs in the simulation. Most catered towards the free-placement system as noted in section 4.3.1 (Fig. 18). Playtesters such as architects were more interested in the "texture mapping of soil-based materials" applied to building elements and urban planners appreciated the "sustainable outcomes of the tool" with some suggesting a design experience for planning earthen material realities at an urban scale.

Fig. 21. Exterior designs created by urban planners and architects.

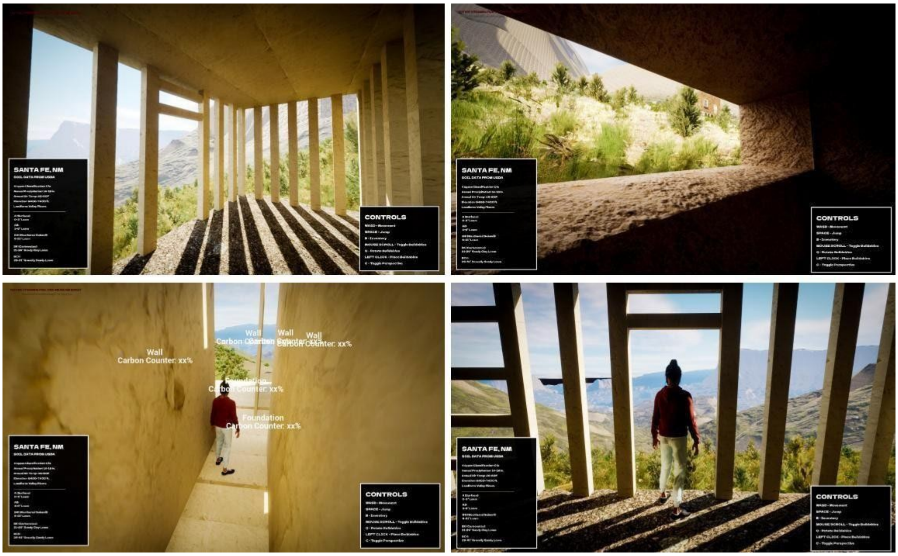

Fig. 22. Interior designs created by architects.

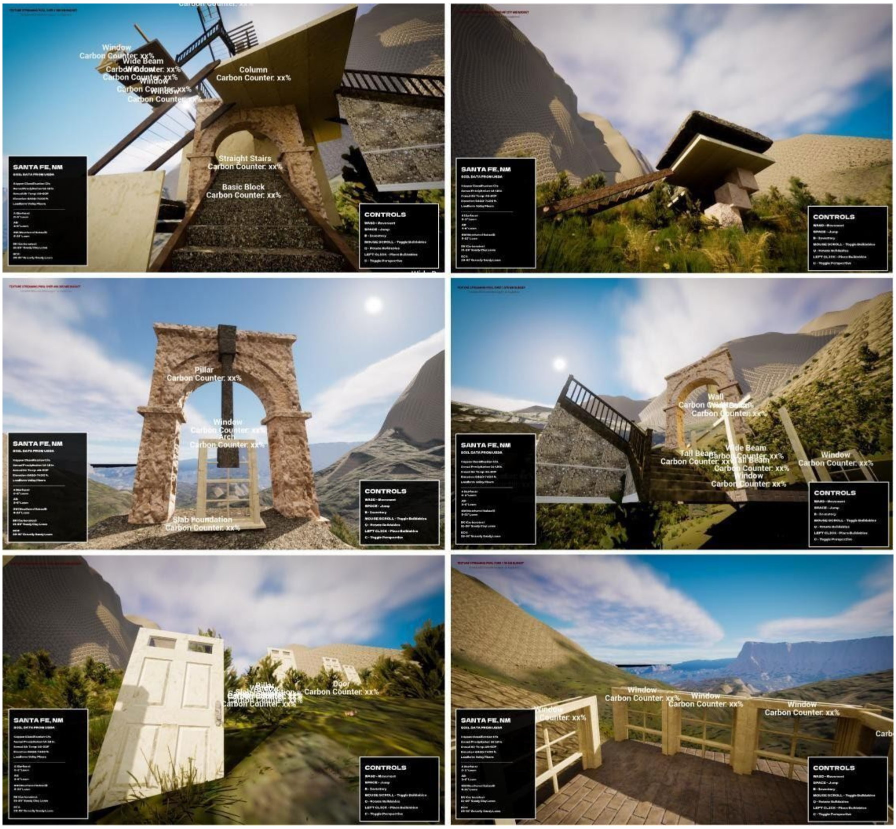

Fig. 23. Experimental designs created by computational designers, architects, and planners.

4.3.4 Study Results

Upon completion of each playtest in the final gold stage, users were prompted with a quick questionnaire to measure the effectiveness of the 15-30 minute experience on an agree-to-disagree likert scale. These questions centered on the effectiveness of conveying information on the geography of earthen materials, understanding building materials' carbon impact metrics, gamification, and future use (Fig. 24-26). Of the responses, 72% agreed that their comprehension of locally sourced earthen building materials had enhanced, 22% were neutral, and 6% disagreed. 50% agreed that their comprehension of embodied carbon and life-cycle assessment had improved, 39% were neutral and 11% were in disagreement. Employing a playful interface to enhance engagement with designing for low carbon architecture proved effective for 88% of participants, with 6% neutral and 6% in disagreement. For consideration of using the tool to design future projects for low-carbon architecture, 56% agreed, 38% were neutral, and 6% disagreed.

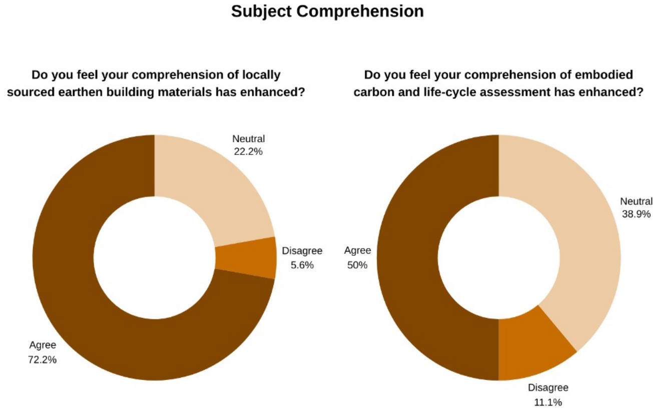

Fig. 24. Results from the playtest questionnaire assessing subject comprehension of earthen materials and embodied carbon.

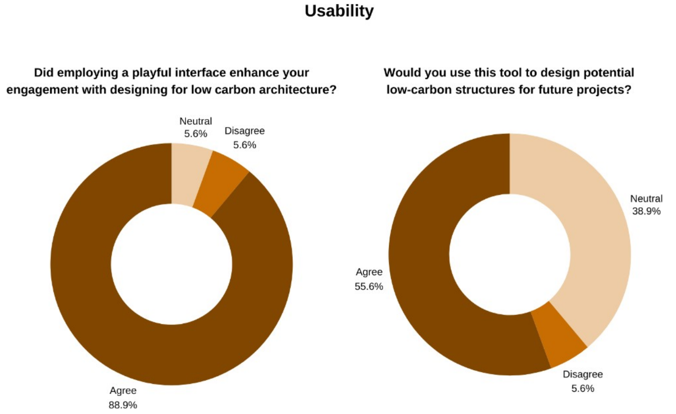

Fig. 25. Results from the playtest questionnaire assessing the user engagement and future use of the virtual simulation.

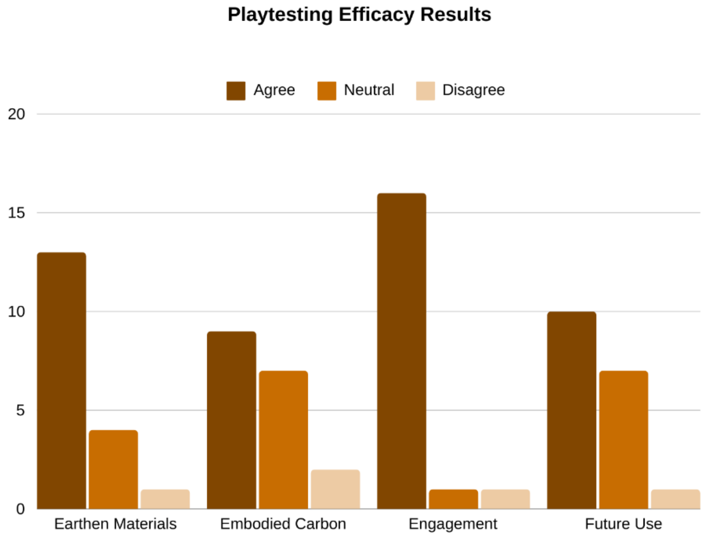

Fig. 26. Comparative analysis of the efficacy measured from the playtest results.

4.4 Findings

The data collected demonstrates the potential of using computational play to enhance the pedagogy of low-carbon architecture. The majority of participants demonstrated an improved understanding of earthen materials and embodied carbon. Since the understanding of embodied carbon was lower (50%) compared to the comprehension of earthen materials (72%), many participants suggested that adding a life-cycle map could help demonstrate the carbon emissions produced from the processing and transport of earthen materials compared to conventional building materials for modern construction methods. This would assist users in understanding the carbon impact of each material used in their design, effectively contextualizing the embodied carbon metric applied onto each building element. Integrating a gamified approach proved extremely useful (88%) in engaging users into learning about sustainable building practices with more than half of participants (56%) expressing desire for future use of the simulation as a tool to speculate earthen structures in a variety of world locations. Overall, many expressed that adding more information to help guide users in understanding the life-cycle assessment and additional building elements could help ensure the continued use of the simulation as a tool for designing with earthen materials.

4.5 Information Architecture of MVP as a Result of Playtests

The insights gathered from the playtests helped inform the final iteration, leading to the MVP of the simulation. The steps are as follows:

Player Journey:

1. The player selects the locality to design in.
2. Upon entry into the location (Santa Fe, NM), the player is presented with a 'Materials Oasis' of architectural elements with the soil mixtures pre-applied to the inventory of building elements. The player can view these mixtures by colliding with the build elements in the oasis.
3. The GUI demonstrates the soil and weather data available in their chosen locality to inform the texturization of the building elements.
4. The player scrolls through their inventory of buildables and places them onto the environment to view its embodied carbon and begin designing diverse earthen structures.
5. The player also has the option to complete three incomplete structures placed onto the landscape to achieve the buildings' lowest embodied carbon, contributing to their learning of sustainable design.

Simulation Features:

- The player uses standard 'WASD' and/or arrow key mechanics to navigate through the tool's open world.
- The to-scale digital twin of Santa Fe's landscape contributes to the sandbox aesthetic of the simulation where the user can freely design onto the terrain.
- Toggling and rotating build elements assigned to the player characters allows for the user to place and design their structure freely. This contributes to the playful experience of the simulation.
- Colliding with build elements placed onto the open world allows for the player to view an architectural element or building's embodied carbon.
- Each architectural element placed onto the terrain closely reflects the material composition of its soil depending on the locality it was collected from.

5 Conclusion and Future Work

This research develops a virtual space that represents low-carbon materiality within a data simulation for designers and researchers to (1) geolocate earthen materials through an accessible virtual context, (2) understand its visualized materiality, and (3)design sustainable data-driven decisions. 24 playtests were conducted and assessed, demonstrating that streamlining these objectives into a gamified interface engaged users into the pedagogy of decarbonized design technology. Users demonstrated an increased interest in designing in additional localities with suggestions of a crowd-sourcing interface to contribute to the dataset of soil mixtures pre-applied to building elements. Further development of this project can seek to (1) visualize the environmental consequences of modern building materials in relation to its low-carbon counterpart and (2) provide a materials map of where specific soil mixtures were sourced from within its locality to clarify its embodied carbon metric. More localities can also be added to the simulation's library encouraging users to envision sustainable building practices within their respective communities. Opportunities including community-driven training and crowd-sourcing initiatives for material recipes can contribute to using the simulation as a method of enhancing low-carbon building practices for a more sustainable world.

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References

1. Moncaster, Alice, and Katie Symons. "A Method and Tool for 'Cradle to Grave' Embodied Carbon and Energy Impacts of UK Buildings in Compliance With the NewTC350 Standards." Energy and Buildings, vol. 66, Elsevier BV, Nov. 2013, pp. 514–23. https://doi.org/10.1016/j.enbuild.2013.07.046.
2. Carcassi, Olga Beatrice, Guillaume Habert, Laura Elisabetta Malighetti, and Francesco Pittau. "Material Diets for Climate-Neutral Construction." EnvironmentalScience & Technology 56, no. 8 (April 4, 2022): 5213–23. https://doi.org/10.1021/acs.est.1c05895.
3. Asensio, Omar Isaac, and Magali A. Delmas. "The Effectiveness of US EnergyEfficiency Building Labels." Nature Energy 2, no. 4 (March 27, 2017). https://doi.org/10.1038/nenergy.2017.33.
4. Vigovskaya, Alina, Olga Aleksandrova, and Boris Bulgakov. "Life Cycle Assessment(LCA) of a LEED Certified Building." IOP Conference Series: Materials Science andEngineering 365 (June 1, 2018): 022007. https://doi.org/10.1088/1757- 899x/365/2/022007.
5. Carlisle, Stephanie, Brook Waldman, Meghan Lewis, and Kathrina Simonen. "2021 Carbon Leadership Forum Material Baseline Report (Version 2)." Material Baselines2 (July 1, 2021). https://digital.lib.washington.edu:443/researchworks/handle/1773/47141.
6. Ben-Alon, L., Loftness, V., Harries, K. A., & Hameen, E. C. (2021). Life cycle assessment (LCA) of natural vs conventional building assemblies. Renewable andSustainable Energy Reviews, 144, 110951.
7. Reddy, B. V. Venkatarama. "Sustainable Materials for Low Carbon Buildings." International Journal of Low-Carbon Technologies 4, no. 3 (September 1, 2009): 175–81. https://doi.org/10.1093/ijlct/ctp025.
8. Kim, Min Soo, and Jungyeop Shin. "The Pedagogical Benefits ofSimCityin UrbanGeography Education." The Journal of Geography 115, no. 2 (March 3, 2016): 39–50. https://doi.org/10.1080/00221341.2015.1061585.

9. Méndez, Maria Do Carmo López, Angélica González Arrieta, Marián Queiruga Dios, Ascensión Hernández Encinas, and Araceli Queiruga Dios. "Minecraft as a Tool in the Teaching-Learning Process of the Fundamental Elements of Circulation in Architecture." In Advances in Intelligent Systems and Computing. Springer Nature, 2016. https://doi.org/10.1007/978-3-319-47364-2_71.
10. Greenwald, Amy, and Michael L. Littman. "Introduction to the Special Issue on Learning and Computational Game Theory." Machine Learning 67, no. 1–2 (May 1, 2007): 3–6. https://doi.org/10.1007/s10994-007-0770-1.
11. Ben-Alon, L., Loftness, V., Harries, K. A., & Hameen, E. C. (2021). Life cycle assessment (LCA) of natural vs conventional building assemblies. Renewable andSustainable Energy Reviews, 144, 110951.
12. Ben-Alon, L., Loftness, V., Harries, K. A., DiPietro, G., & Hameen, E. C. (2019).Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material. Building and Environment, 160, 106150.
13. Mateus, Ricardo, Jorge M.O. Fernandes, and Encarnação Teixeira. "EnvironmentalLife Cycle Analysis of Earthen Building Materials." In Elsevier EBooks, 63–68, 2019. https://doi.org/10.1016/b978-0-12-803581-8.11459-6.
14. Ben-Alon, L., & Rempel, A. R. (2023). Thermal comfort and passive survivability inearthen buildings. Building and Environment, 110339.
15. Araki, Hiroyuki, Junichi Koseki, and Takeshi Sato. "Tensile Strength of Compacted Rammed Earth Materials." Soils and Foundations 56, no. 2 (April 1, 2016): 189–204. https://doi.org/10.1016/j.sandf.2016.02.003.
16. Chandel, Shyam Singh, Vandna Sharma, and Bhanu M. Marwah. "Review of EnergyEfficient Features in Vernacular Architecture for Improving Indoor Thermal ComfortConditions." Renewable & Sustainable Energy Reviews 65 (November 1, 2016): 459–77. https://doi.org/10.1016/j.rser.2016.07.038.
17. Benjamin, David. Embodied Energy and Design: Making Architecture BetweenMetrics and Narratives. Lars Müller Publishers, 2017.
18. Mears, Alison, and Jonsara Ruth, eds. Material Health: Design Frontiers. Lund Humphries, 2023. https://healthymaterialslab.org/blog/announcing-material-health- design-frontiers-publication.
19. Torres, Maruja, and Joseli Macedo. "Learning Sustainable Development with a New Simulation Game." Simulation & Gaming 31, no. 1 (March 1, 2000): 119–26. https://doi.org/10.1177/104687810003100112.
20. Gabel, Medard. "Buckminster Fuller And the Game of the World." Encyclopedia ofthe Future 33, no. 10 (June 1, 1996). https://doi.org/10.5860/choice.33-5448.
21. Moriset, Sébastien, Bakonirina Rakotomamonjy, and David Gandreau. "Can Earthen Architectural Heritage Save Us?" Built Heritage 5, no. 1 (November 10, 2021). https://doi.org/10.1186/s43238-021-00041-x.
22. Schröer, Christoph, Felix Kruse, and Jorge Marx Gómez. "A Systematic LiteratureReview on Applying CRISP-DM Process Model." Procedia Computer Science 181(January 1, 2021): 526–34. https://doi.org/10.1016/j.procs.2021.01.199.
23. Hammond, Geoffrey, and Craig Jones. "Embodied Carbon." Edited by Fiona Lowrieand Peter Tse. The Inventory of Carbon and Energy (ICE). BSRIA, 2011. http://www.emccement.com/pdf/Full-BSRIA-ICE-guide.pdf.
24. Ekaputra, Glenn, Charles Ci Wen Lim, and Kho I Eng. "Minecraft: A Game as anEducation and Scientific Learning Tool." ISICO 2013 2013 (January 1, 2013). http://is.its.ac.id/pubs/oajis/index.php/file/download_file/1219.

25. Avrami, Erica. 2010. Preserving Haiti's Gingerbread Houses 2010 Earthquake mission report, December 2010. http://openarchive.icomos.org/2107/.
26. Rowell, Kevin. 2013. Materials Profile: Earth. Ed. by Dakotah Bertsch. The Natural Builders - Publications. The Natural Builders. (accessed: 5. September 2023).
27. Paula, Adilson C., Cláudia Jacinto, Chiara Turco, Jorge Emanuel Pereira Fernandes, E.R. Teixeira and Ricardo Mateus. 2022. Analysis of the effect of incorporating construction and demolition waste on the environmental and mechanical performance of earth-based mixtures. Construction and Building Materials 330 (1. May): 127244. doi:10.1016/j.conbuildmat.2022.127244, https://doi.org/10.1016/j.conbuildmat.2022.127244.
28. F. Laamarti, M. Eid, and A. E. Saddik, "An overview of serious games," International Journal of Computer Games Technology, vol. 2014, pp. 1–15, Jan. 2014, doi: 10.1155/2014/358152.
29. I. Kim, S. J. Hong, J. Lee, and J.-C. Bazin, "Overlay Design Methodology for virtual environment design within digital games," Advanced Engineering Informatics, vol. 38, pp. 458–473, Oct. 2018, doi: 10.1016/j.aei.2018.08.014.
30. R. Olszewski, M. Cegiełka, U. Szczepankowska, and J. Wesołowski, "Developing a serious game that supports the resolution of social and ecological problems in the toolset environment of cities: Skylines," ISPRS International Journal of Geo-information, vol. 9, no. 2, p. 118, Feb. 2020, doi: 10.3390/ijgi9020118.
31. A. Westre, Design games for architecture. 2013. doi: 10.4324/9780203750179.
32. Mirza-Babaei, P., Moosajee, N., & Drenikow, B. (2016). Playtesting for indie studios. Association for Computing Machinery. https://doi.org/10.1145/2994310.2994364.
33. Wallner, G., Halabi, N., & Mirza-Babaei, P. (2019). Aggregated Visualization of Playtesting Data. Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3290605.3300593.