Jordan Journal of Civil Engineering, Volume **20**, No. **4, 2026**
DOI: https://doi.org/10.14525/JJCE.v20i4.09

Jordan Journal of Civil Engineering

Journal homepage: https://jjce.just.edu.jo

Material Selection for Components of an On-Campus Study Pod

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ARTICLE INFO

Article History:
Received: 11/1/2026
Accepted: 9/7/2026

ABSTRACT

On-campus study pods offer private, flexible learning spaces designed to provide controlled thermal and acoustic environments within busy university settings. This study presents a systematic material selection process for the key components of a compact, modular, weather-exposed study pod designed for 2–4 students. Using the Ashby methodology, six application-specific performance indices were derived to optimize stiffness-to-weight, strength-to-weight, wear resistance, thermal insulation, thermal expansion compatibility, and cost efficiency. Realistic design constraints, including self-weight, occupancy loads, wind pressure, and deflection limits, were applied alongside outdoor durability, acoustic comfort, and sustainability requirements. The optimal materials identified are 5000-series aluminium alloys for the structural frame, a multilayer sandwich configuration (treated softwood/bamboo outer layer, rigid polyurethane foam core, and cork inner layer) for enclosure panels, plywood and polypropylene for seating and desks, and treated bamboo/plywood with polycarbonate options for roofing. Quantitative comparisons demonstrate approximately 42% mass reduction for the aluminium frame *versus* stainless steel, and 3–5 times lower heat transfer for cork/PU foam panels compared with untreated wood. The selected materials balance structural performance, thermal and acoustic comfort, recyclability, and economic feasibility while supporting circular-economy principles. Limitations and future validation pathways, including finite element analysis and prototype testing, are discussed.

Keywords: Material selection, Ashby method, Study pod, Sustainable design, Performance indices, Educational environments.

INTRODUCTION

In educational institutions, students are exposed to internal and external stresses due to pressures of achieving success, finances, exams, and future challenges (Iqra, 2024; Song et al., 2024). To address these challenges, universities provide on-campus study spaces for individual or group work. The COVID-19 pandemic further accelerated the demand for flexible and private spaces, transforming open-plan environments into hybrid hubs that prioritize health, privacy, and productivity (Mohamed & Ali, 2023). These facilities and services cater to students' needs, supporting their academic, health and social lives. Studies have reported that interaction with environmental landscapes and physical activity are associated with reduced stress levels (Khoudi, 2022). Selecting pod locations within the campus facilitates movement between university buildings and promotes walking, thereby contributing to active campus lifestyles (Gharaibeh et al., 2014). Therefore, well-designed on-campus study pods, integrated with their surrounding environments, aim to provide the thermal and acoustic comfort necessary to support focused study.

On-campus study pods for students have become increasingly popular in educational institutions, offering focused learning environments within open-plan campuses. These pods are not limited to studying, but can also be used for napping and relaxation as well (Papaioannou et al., 2023). Individual study spaces in libraries are typically designed with quiet areas, comfortable seating, good lighting, integrated power outlets, soundproofing, peaceful colours and good ventilation (Staines, 2012). The same design principles should apply to on-campus study pods, with additional advantage of nature interaction. The structures of these pods must withstand daily use, varying weather conditions, and student interactions while remaining cost-effective and environmentally responsible. Hence, the selection of materials for pod components—such as frames, panels, seating, and roofing—plays a pivotal role in achieving these goals (Grabiec et al., 2022).

Existing research on learning spaces and pods has primarily emphasized psychological benefits, functional design, and mental health promotion rather than systematic material optimization for small-scale, outdoor-capable campus applications. Mohamed and Ali (2023) developed multi-activity "Reviving Pods" for napping, meditation, and virtual communication, utilizing sustainable materials aligned with WELL Building Standards to support student comfort and academic performance. While effective in linking design to mental health outcomes, their work offers only general sustainability guidance without quantitative performance indices or trade-off analysis suited to weather-exposed, portable campus structures.

Outdoor classroom studies have proposed materials for seasonal adaptability and noise reduction. Şatiroğlu et al. (2023) recommended wood, aluminium, steel, plastic-based elements, and roofing options, such as treated wood or transparent glass shades, in modular designs. However, these focus on larger-scale school gardens rather than compact, individual study pods for open university campuses, and do not employ structured material selection methods to balance stiffness-to-weight, thermal performance, or durability under high-traffic use. Broader literature on urban furniture and modular learning environments highlights recycled materials, polycarbonate for transparency and impact resistance, aluminium frames for lightweight durability, and high-density polyethylene composites for seating (Bhattacherjee et al., 2021; Cole, 1999; Grabiec et al., 2022; Pickford & Ellis, 2015). These applications are predominantly indoor, library-based, or large-scale architectural projects.

Material selection in engineering design is a challenging process that involves balancing conflicting requirements by selecting the correct material to suit the needs of a particular application (Leary, 2011). Traditional approaches often prioritize strength (El-Naqeeb et al., 2022) and cost, but modern demands emphasize sustainability, recyclability, and lifecycle assessment (LCA). In this work, the Ashby material selection method (Ashby, 2010) is employed, which uses property plots to visualize trade-offs and performance indices that combine the material properties with the design objectives. To rank shortlisted candidates, a weighted-sum model is applied (Chukwuemeka et al., 2025) to identify optimal materials for an on-campus study pod. For structural applications, like pods, this method (Ashby, 2010) has been applied in designs ranging from furniture (Charles & Cran, 1989) to modular buildings (Brandt, 2008).

In educational settings, sustainability remains a key priority. Studies on the furniture of campus highlight the use of recycled materials to reduce carbon emissions (Pickford & Ellis, 2015; Sorrell, 2015). For instance, polycarbonate panels offer transparency and impact resistance, as seen in library pods (Cole, 1999), while aluminium frames provide lightweight durability (Bhattacherjee et al., 2021). Seating materials, like high-density polyethylene (HDPE) composites from recycled plastics, align with circular economy principles (Grabiec et al., 2022). Modular disassembly further minimizes waste and avoids permanent modifications, such as floor drilling. Challenges of optimizing such structures may include corrosion in outdoor environments, cost constraints, and selecting low-maintenance materials suitable for high-traffic campus use.

While the Ashby methodology has been widely applied to mechanical components, furniture, and large-scale modular buildings (Ashby, 2010; Brandt, 2008; Charles & Cran, 1989), its use for small-scale, deployable outdoor learning structures in higher-education campuses remains virtually unexplored. Existing pod-related studies primarily addressed functional layout, multi-activity use, and WELL Building compliance (Mohamed & Ali, 2023), or recommend materials qualitatively for outdoor classrooms (Şatiroğlu et al., 2023), but none derived application-specific performance indices or conducted systematic multi-criteria screening that simultaneously balances structural efficiency, thermal/acoustic comfort, wear durability, cost, and sustainability for compact, weather-exposed, portable on-campus study pods. This leaves a clear methodological and application gap in campus infrastructure design.

The novelty of this study lies in applying the Ashby methodology to a new and specific context: small-scale, deployable outdoor campus structures. While the method itself is well established, its use for modular outdoor learning pods has not been reported before. This work develops an application-specific selection framework by deriving an integrated set of indices (M1–M6) that simultaneously address structural stiffness, localized surface wear, and multi-layered thermal comfort. This approach moves beyond qualitative material suggestions. It provides a quantitative basis for designing resilient, portable educational hubs that prioritize both occupant comfort and structural durability in high-traffic environments.

This work applies the Ashby method in a tailored way for this specific application. First, it derives six performance indices that address stiffness to weight (M1), strength to weight (M2), wear resistance (M3), thermal insulation (M4), thermal expansion compatibility (M5), and cost efficiency (M6). Second, it embeds outdoor-specific constraints, such as wind pressure, relocation weight limits, and acoustic damping directly into the screening. Third, it treats sustainability as a primary filter rather than a secondary consideration. These steps produce a reproducible selection framework that other researchers can adapt to similar modular educational structures.

METHODOLOGY

Pod Design Overview

The proposed pod is a 4.00×1.78×3.00 m modular structure for 2-4 students, consisting of structural frames, enclosure panels, seating and roofing. The projection views of the proposed pod, showing the external dimensions in meters, are illustrated in Figure 1 (a).

Figure 1 (b) demonstrates a three-dimensional illustration of the assembled pod. The structural frames support the overall assembly and must be lightweight, corrosion-resistant, and easy to assemble. The enclosure panels provide privacy and weather protection; require transparency, impact resistance, and ultraviolet ray (UV) stability. The seating integrated benches or office chairs; need comfort, durability, and hygiene. The roofing shields from rain and sun; should be waterproof, insulating, and lightweight.

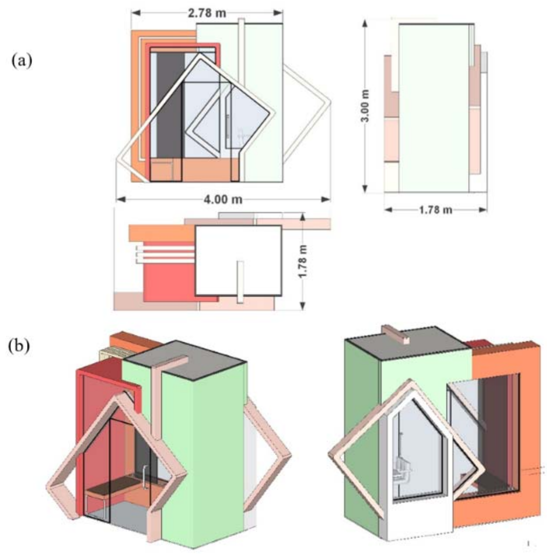


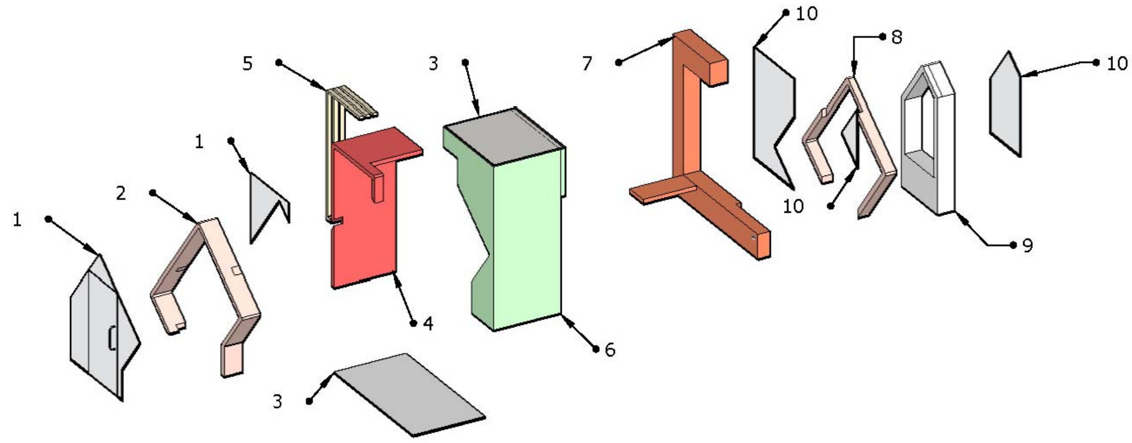
Figure 1. Projection views of the proposed study pod showing external dimensions in meters.
(a) Orthographic projections; (b) Three-dimensional assembled view

Material Selection Criteria

The primary function of material selection for the study pod is to provide a lightweight enclosure that ensures structural integrity, acoustic and thermal comfort, and long-term surface durability in a high-use academic environment. Maximum stiffness-to-weight and strength-to-weight ratios are therefore primary objectives for the load-bearing panels. Additionally, the materials must satisfy the following translated constraints: high scratch and wear resistance on contact surfaces, minimal heat transfer through the walls, low and matched thermal expansion to prevent warping or gaps at joints and glazing interfaces, ease of fabrication into flat and folded panels, and low material cost per unit volume.

Material Indices

The study pod consists of load-bearing panels (walls/roof), a transparent window (acrylic/glass), a desk surface, and acoustic/thermal insulation layers, as demonstrated in Figure 2. The inset table provides typical materials used for pod structures. The materials of pod components are classified into four categories: 1) structural frame, 2) enclosure panels, 3) seating, and 4) roofing materials. It is important to mention that the interior furniture does not appear in the figure, as it can be placed after the pod is constructed.



Part No.	Given Name	Category	Typical material(s)
1	Front façade	Enclosure panel materials	Clear glass window
2	Front façade frame	Structural frame materials	Iron metal section
3	Roofing and beading plate	Roofing materials	Polyester with fiberglass
4	Left Side panel	Enclosure panel materials	Iron metal section with polyester cover
5	Left Side frame	Structural frame materials	Iron metal section
6	Right Side panel	Enclosure panel materials	Iron metal section with polyester cover
7	Left Side frame	Structural frame materials	Iron metal section
8	Rear façade frame	Structural frame materials	Iron metal section
9	Rear panel	Enclosure panel materials	Iron metal section with polyester cover
10	Rear façade	Enclosure panel materials	Clear glass window
*	Furniture (bench and desk)	Seating materials	Woods, plastics and metals

* This item does not appear in the figure

Figure 2. Exploded view of the proposed study pod illustrating the main components and typical material categories for each part. Interior furniture is omitted as it is installed after assembly

For material screening, six performance indices (M1–M6) are derived to guide the selection process. Fixed parameters (e.g., pod dimensions, applied loads, deflection limits) are treated as constraints. The structural panels are designed to resist bending stiffness, and thus the performance index M1 is designated for stiffness-to-weight properties. The walls and roofs are subjected to bending due to self-weight and point loads, that may involve user leaning against the walls. Under these circumstances, the mass should be minimum for a given maximum deflection (δ). For a rectangular plate under uniform pressure (p), the deflection is:

$\delta = \frac{C_1 pL^4}{Et^3}$, solving for thickness, so that $t = \left(\frac{C_1 pL^4}{\delta E}\right)^{1/3}$

where, C_1 is a shape factor depending on the width to length ratio (*w/L*), *E* is the modulus of elasticity, and *t* is the thickness. The mass of panel can then be expressed as:

$$m = A.\rho.t = (wL).\rho.\left(\frac{C_1 pL^4}{\delta E}\right)^{1/3} \propto \frac{\rho}{E^{1/3}}$$

where, *A* is the area of the cross-section, and ρ is the density of material. Since w, L, p and δ are held constant, the mass is minimized by maximizing M1 as:

$$M1 = \frac{E^{1/3}}{\rho}$$

Additionally, the structural panels must also resist yielding under loading. Therefore, the index M2 represents the strength-to-weight properties to prevent deformation under impact or concentrated load (*F*). Failure stress (σ_f) is expressed as:

$\sigma_f = \frac{C_2 FL^2}{wt^2}$, solving for thickness, so that $t = \left(\frac{C_2 FL^2}{\sigma_f w}\right)^{1/2}$

where, C_2 depends on support conditions. Mass in this case can be presented as:

$$m = \rho.w.L.t = \rho.w.L.\left(\frac{C_2 FL^2}{\sigma_f w}\right)^{1/2} \propto \frac{\rho}{\sigma_f^{1/2}}$$

The mass is minimized by maximizing the index M2 as:

$$M2 = \frac{\sigma_f^{1/2}}{\rho}$$

The high touch panels must be designed to have high wear and scratch resistance. High touch panels, such as desk surfaces, door frames and edges, usually experience wear from pens, laptops and repeated contact. The performance index M3 is designated for wear and scratch resistance. The volume loss under these circumstances is minimized under sliding wear. Archard's wear law (Archard, 1980) states that:

$$V = \frac{KF_n L_s}{H}$$

where, *K* is the wear coefficient, *H* is the material hardness, F_n is the normal force and L_s is the sliding distance. In this equation, *K* is a system-level wear coefficient that depends on contact conditions and is not an intrinsic material property listed in standard material databases. For the purpose of material screening, *K* is treated as approximately constant across candidates under similar contact conditions, so volume loss scales inversely with hardness *H* alone. Thus, wear resistance is maximized by maximizing M3 as follows:

$$M3 = H$$

The thermal properties are important to minimize heat transfer through walls. Walls act as thermal barriers to prevent heat loss and/or gain and to maintain comfort. The performance index M4 represents the thermal conductivity. Heat flux (*q*) equals:

$$q = k\frac{\Delta T}{t}$$

For a panel of area *A* and thickness *t* fixed by structural requirements, the total heat flow $Q = q \cdot A = k \cdot \Delta T \cdot A/t$ is directly proportional to thermal conductivity *k*. Panel mass $m = \rho \cdot A \cdot t$ is proportional to ρ. Both heat flow and panel weight are reduced by minimizing the product of *k* and ρ, which also corresponds to the axes used in the Ashby thermal chart. This grouping is consistent with Ashby's thermal index for insulation panels:

$$m = \rho At \propto \rho k$$

The heat transfer and mass are minimized by minimizing M4 as follows:

$$M4 = k.\rho$$

M5 is the thermal expansion of materials. The target is to minimize the physical expansion among panels, frames and windows to avoid gaps and thermal stresses. The thermal strain mismatch ($\Delta\epsilon$) can be expressed as:

$$\Delta\epsilon = \alpha_1 \Delta T - \alpha_2 \Delta T = (\alpha_1 - \alpha_2)\Delta T$$

where, α_1 and α_2 are thermal expansion coefficients of two connected materials. In this study, the primary structural frame is 5000-series aluminium ($\alpha \approx 23$ µm/m·K) and glazing is glass ($\alpha \approx 9$ µm/m·K). The candidate panel and roofing material must have an α as close as possible to that of its neighbouring materials. M5 is therefore the absolute mismatch between the candidate material and a reference neighbour. Thermal stress is minimized by minimizing M5 as follows:

$$M5 = |\alpha - \alpha_{ref}|$$

M6 is the material index for economic feasibility, which should be minimized for scalable production. The cost per unit volume (C_v) can be determined by the cost per unit mass (C_m) and material density (ρ) as given by:

$$C_v = C_m . \rho$$

So, M6 is minimized as follows:

$$M6 = C_m . \rho$$

A summary of the material indices is listed in Table 1, which describes the objectives and goals of optimizing each index.

Table 1. Summary of material indices for the proposed study pod

Index	Objective	Expression	Goal
M1	Max. stiffness/weight (panels)	$E^{1/3}/\rho$	Maximize
M2	Max. strength/weight (panels)	$\sigma_f^{1/2}/\rho$	Maximize
M3	Max. wear resistance (desk/edges)	H	Maximize
M4	Min. thermal conduction	$k \cdot \rho$	Minimize
M5	Min. thermal mismatch	$\|\alpha - \alpha_{ref}\|$	Minimize
M6	Min. cost	$C_m \cdot \rho$	Minimize

Design Assumptions and Boundary Conditions

The proposed study pod is a modular structure, designed to accommodate 2–4 students. The structural loads include self-weight and distributed occupancy load of about 1.5 kN/m². Localized loads from users leaning are estimated at about 800 N. Wind pressure is taken as about 0.8 kPa, based on typical wind conditions in Amman for moderate exposure, in accordance with ASCE 7-16 (American Society of Civil Engineers, 2017). Deflection limits are set to $\delta \leq L/360$ for frames and roofing under service loads. This value is common for lightweight structures. Thermal conditions assume an indoor–outdoor temperature difference (ΔT) of about 20–30°C during summer. The target thermal transmittance (U-value) for panels is less than 1.5W/m²·K for better insulation. Frame members are assumed to span 1.78–4.0 m. Panels and roofing are supported at intervals of 1.0–1.5 m. These values represent typical outdoor campus conditions. They are used to define and apply the performance indices.

Selection Process

The material selection process was performed using Granta CES Selector EduPack 2013 (Granta Design Ltd., 2013), supported by its integrated material database and the Ashby methodology (Ashby, 2010). In the screening phase, the six performance indices (M1–M6) derived earlier were applied as limit and guideline constraints. Property limit filters were performed during selection process to eliminate unsuitable families of metals, technical ceramics, and high-performance composites. In the ranking phase, the shortlisted candidates were evaluated visually and quantitatively through a series of Ashby bubble diagrams. These charts, plotted directly in CES Selector, clearly highlighted trade-offs and identified a narrow group of high-performing, cost-effective materials. Final choices were confirmed by overlaying all relevant indices on a single chart and verifying that the selected materials lay within the top-right/low-cost envelope while satisfying all functional constraints. Supporting property data was sourced from the CES Selector 2013 database. These values are used strictly for relative ranking between material candidates, not for absolute project budgeting. To verify that the 2013 data remains representative, a spot-check was performed for the three key materials against current engineering databases (Matweb, 2024), 5000-series aluminium, bamboo/plywood, and polyurethane (PU) foam. The current approximate prices are 3.5–6.5, 1.8–4.0, and 3.0–6.0 USD/kg, as compared to CES 2013 prices of 1.5–2.5, 0.5–2.0, and 2.5–5.0 USD/kg, respectively. According to this data, the absolute prices have increased modestly, but the relative ranking order has not changed. Aluminium remains more costly than wood-based materials on a per-kg basis, and PU foam remains in the mid-range. Therefore, the M6 screening results are still valid for comparative screening purposes. A full sensitivity analysis of varying index weights by ±20% to ±30% is presented in Table 6, including one case where the top-ranked panel material changes under the largest cost-weight shift.

Reproducible Screening Procedure

To allow full reproducibility, Table 2 documents the complete screening procedure for each pod component. For each component, the table lists the initial material families drawn from the CES EduPack 2013 Level 2 database, all screening filters applied in sequence with the threshold values used, the families or candidates eliminated at each step, and the final shortlisted materials before ranking. Screening was performed in two stages. The first stage applied hard property limits (density, modulus, tensile strength, cost) as filter constraints to eliminate entire material families. The second stage applied guideline slopes on the Ashby charts to rank remaining candidates and identify the top performers visually. The final shortlist from Table 2 was then carried forward to the weighted-sum ranking in Table 4. The database property values used for screening are listed in Table 5.

Table 2. Step-by-step screening procedure for each pod component (CES EduPack 2013, Level 2 database)

Component	Initial families (CES Level 2)	Screening filters (in order) with thresholds	Eliminated at each step	Final shortlist before ranking
Frame	All metals and alloys, technical ceramics, composites (~3,000 entries)	Step 1: ρ ≤ 3,000 kg/m³ (portability); Step 2: E = 60–210 GPa; Step 3: σf ≥ 1.8 MPa; Step 4: elongation ≥ 0.06 (ductility for welding); Step 5: cost = 2–8 USD/kg; Step 6: M1–M2 Ashby chart — guideline slope 3, select upper-left envelope	Steps 1–5: ceramics, polymers, woods, composites, high-density metals (steels ρ > 7,000 kg/m³, titanium alloys cost > 8 USD/kg) eliminated; Step 6: stainless steel and zinc alloys eliminated by lower M1–M2 position; Al 1xxx (low σf) and 3xxx (moderate σf) eliminated by strength	5000-series Al alloys (5052, 5083, 5086): ρ ≈ 2,680–2,660 kg/m³, E ≈ 70–72 GPa, σf ≈ 190–310 MPa, cost ≈ 3.5–6.5 USD/kg
Enclosure panels	Polymers, foams, natural materials (woods, cork, bamboo), elastomers, paper/cardboard (~3,000 entries)	Step 1: cost = 1–5 USD/kg; Step 2: compressive strength ≥ 0.5 MPa (minimum handleability); Step 3: k ≤ 0.5 W/m·K (thermal insulator class); Step 4: M1 vs k Ashby chart — guideline slope 1, select upper-left (high M1, low k) region	Step 1: high-cost technical polymers (PEEK, PTFE, etc.) eliminated; Step 2: elastomers eliminated (compressive strength < 0.1 MPa); Step 3: metals and high-k materials eliminated (steel k ≈ 50 W/m·K, glass k ≈ 1 W/m·K); Step 4: paper/cardboard eliminated by low durability score in chart position	Cork (k ≈ 0.04–0.07 W/m·K, ρ ≈ 120–240 kg/m³, cost ≈ 9–14 USD/kg*); Rigid PU foam (k ≈ 0.02–0.05 W/m·K, ρ ≈ 30–80 kg/m³, cost ≈ 3–6 USD/kg); Treated softwood/bamboo (k ≈ 0.12–0.18 W/m·K, ρ ≈ 400–600 kg/m³, cost ≈ 0.8–2.5 USD/kg). *Cork retained despite cost > 5 USD/kg owing to its unique acoustic performance as inner layer only (thin application).

Seating and desks	Woods, polymers, non-technical ceramics, composites (~3,000 entries)	Step 1: ρ ≤ 2,000 kg/m^3; Step 2: tensile strength ≤ 30 MPa (comfort/safety — avoids overly rigid surfaces); Step 3: cost ≤ 8 USD/kg; Step 4: H vs ρ Ashby chart — guideline slope 1, select above-line materials (high H for given ρ)	Steps 1–2: metals, technical ceramics, high-performance composites eliminated (ρ > 2,000 kg/m^3 or σf > 30 MPa); Step 3: high-cost engineered polymers (ABS, PC) partially eliminated; Step 4: paper/cardboard eliminated by low H position	Plywood (H ≈ 10–30 MPa, ρ ≈ 500–650 kg/m^3, cost ≈ 1.8–4 USD/kg); Polypropylene (H ≈ 50–100 MPa Vickers, ρ ≈ 900–950 kg/m^3, cost ≈ 1.5–3 USD/kg); HDPE (ρ ≈ 940–970 kg/m^3, cost ≈ 1.2–2.5 USD/kg). Softwoods (pine, oak) retained as alternatives.
Roofing	Woods, polymers, foams, metals, composites (~3,000 entries)	Step 1: ρ ≤ 1,500 kg/m^3 (lightweight spanning); Step 2: cost ≤ 15 USD/kg; Step 3: C***f*** vs E^{1}Ł^2/ρ Ashby chart — guideline slope 1, select lower-left envelope (low cost, high specific stiffness)	Step 1: all metals (ρ > 1,500 kg/m^3), masonry, and technical ceramics eliminated; Step 2: high-cost polymers (PC partially retained for translucency function) eliminated on cost; Step 3: foams eliminated by low E^{1}Ł^2/ρ chart position	Treated bamboo/plywood (E^{1}Ł^2/ρ ≈ 60–100, ρ ≈ 600–800 kg/m^3, cost ≈ 2–6 USD/kg); Polycarbonate sheets (ρ ≈ 1,200 kg/m^3, cost ≈ 4–9 USD/kg — retained for translucent option); Polyethylene/PP opaque option (ρ ≈ 900–960 kg/m^3, cost ≈ 1.2–2.5 USD/kg).

Table 3. Summary of selected materials and their relevant information for constructing an on-campus study pod

Component	Selected Material	Key Properties	Advantages	Limitations	*Cost ($/kg)
Frame	5000 series aluminum alloys (e.g., 5052, 5083)	Density: ~2.7 g/cm^3 Young's modulus: 70-72 GPa Tensile strength: 190-300 MPa Good corrosion resistance	Lightweight, excellent weldability, high corrosion resistance, recyclable	Higher initial cost than steel; may require anodizing in very humid climates	3.5–6.5
Panels	1. Cork 2. Polymer foams (e.g., rigid polyurethane) 3. Softwoods (e.g., pine) or bamboo	**Cork:** k ≈ 0.04-0.07 W/m·K, density ≈ 120-240 kg/m^3 **Foams:** k ≈ 0.02-0.05 W/m·K, density ≈ 30-80 kg/m^3 **Softwoods:** k ≈ 0.12-0.18 W/m·K, density ≈ 400-600 kg/m^3	Excellent thermal & acoustic insulation, lightweight, natural aesthetics, sustainable	**Cork**: higher cost **Foams**: needs reinforcement **Woods**: requires weatherproof coating	Cork: 9–14 Foams: 3–6 Softwoods: 0.8–2.5
Seating	1. Plywood (birch or pine) 2. Polypropylene (PP) or HDPE	**Plywood**: density ≈ 500-650 kg/m^3, hardness ≈ 10^7-10^8 Pa **PP**: density ≈ 900-950 kg/m^3 Good impact resistance	Lightweight, ergonomic shaping possible, good wear resistance, recyclable, low cost	**Plywood**: needs surface finish to resist scratches **PP**: lower natural aesthetics	**Plywood**: 1.8-4 **PP**: 1.5–3
Roofing	1. Bamboo or plywood (treated) 2. Polycarbonate (PC) sheets 3. Polyethylene/ polypropylene (opaque option)	**Bamboo/Plywood**: $E^{1/2}/\rho$ ≈ 60-100, density ≈ 600-800 kg/m^3 **PC**: density ≈ 1200 kg/m^3, High impact resistance, UV stable	Lightweight, good stiffness, natural look (bamboo/plywood), translucency (PC), affordable	**Bamboo/plywood**: needs UV & water treatment **PC**: higher cost than opaque polymers	**Bamboo**: 2-6 **Plywood**: 1.8-4 **PC**: 4-9

* Properties are approximate averages from CES EduPack 2013 (Granta Design Ltd., 2013); actual values depend on specific grades. Costs are (2024-2025) estimates and may vary.

Table 4. Normalized scoring and ranking of shortlisted materials for pod components (0–10 scale, relative within category; higher = better)

Component	Material	M1	M2	M3	M4	M5	M6	Overall Score (avg.)	Overall Rank
Frame	5000 series Al alloys (e.g., 5052/5083)	10.0	10.0	-	-	–	6.0	8.7	1
	Stainless steel (for comparison)	4.8	5.0	-	-	–	10.0	6.6	2
Panels	Cork	3.5	-	–	6.4	–	1.4	3.8	3*
	Rigid PU foam	10.0	-	–	10.0	–	3.7	7.9	1
	Softwoods (pine) / Bamboo	8.7	–	–	2.3	–	10.0	7.0	2
Seating	Plywood (birch/pine)	–	10.0	2.7	-	–	6.4	6.4	3**
	Polypropylene (PP)	–	5.8	10.0	-	–	8.2	8.0	1
	HDPE	–	4.8	8.0	-	–	10.0	7.6	2
Roofing	Bamboo / Treated plywood	10.0	10.0	-	–	10.0	5.0	8.8	1
	Polycarbonate (PC) sheets	2.6	5.4	-	–	4.0	3.1	3.8	3
	Polyethylene / PP (opaque)	2.5	4.7	-	–	1.5	10.0	4.7	2

* Cork ranks 3rd in weighted score because its low modulus penalises M1. However, cork is specified as a thin acoustic inner layer in the sandwich panel system, not a standalone structural panel. Its selection for that functional role is justified on M4 (thermal/acoustic), not M1.

** Plywood ranks 3rd among seating materials once M3 (hardness, H = 20 MPa) is correctly weighted alongside polypropylene (H = 75 MPa) and HDPE (H = 60 MPa). The primary recommendation remains a plywood or PP surface depending on the procurement context, and the text now reflects the correct ranking.

Table 5. Key properties of shortlisted materials

Component	Material	Density (kg/m³)	Young's Modulus (GPa)	Tensile Strength (MPa)	Thermal Conductivity k (W/m·K)	Hardness	Cost Range (USD/kg)	Key Advantages
Frame	5000-series Al alloys (5052/5083)	2,700	70–72	190–300	130–150	–	3.5–6.5	Lightweight, corrosion resistant, recyclable
Panels	Cork	120–240	0.02–0.04	–	0.04–0.07	–	9–14	Excellent thermal & acoustic insulation
	Rigid PU foam	30–80	0.01–0.03	–	0.02–0.05	–	3–6	Superior thermal insulation, lightweight
	Treated softwood / Bamboo	400–600	8–12	40–80	0.12–0.18	–	0.8–2.5	Natural aesthetics, good stiffness, sustainable
Seating	Plywood (birch/pine)	500–650	8–12	<50	0.12–0.15	10–30	1.8–4	Ergonomic, good wear resistance, low cost

	Polypropylene (PP)	900–950	1.3–1.8	30–40	0.10–0.22	–	1.5–3	Moisture resistant, recyclable, mouldable
	HDPE	940–970	0.8–1.2	20–30	0.40–0.50	–	1.2–2.5	Durable, impact resistant, easy to clean
Roofing	Treated bamboo / Plywood	600–800	8–15	50–100	0.12–0.18	–	2–6 / 2–4	High stiffness-to-weight, sustainable
	Polycarbonate (PC)	1,200	2.3–2.4	60–70	0.19–0.21	–	4–9	High impact resistance, translucent, UV stable

Table 6. Sensitivity of weighted scores and top-ranked material to weighting changes

Component	Weighting scenario	Material A: score	Material B: score	Material C: score	Top
Frame (A=Al, B=Steel)	M6 − 30%	9.07	6.09	–	A
	Baseline (equal)	8.67	6.60	–	A
	M6 +30%	8.27	7.11	–	A
Panels (A=PU foam, B=Softwood, C=Cork)	M6 − 30%	8.53	6.55	4.12	A
	Baseline (equal)	7.90	7.00	3.77	A
	M6 +30%	7.27	7.45	3.41	B*
Seating (A=PP, B=HDPE, C=Plywood)	M6 − 30%	7.97	7.24	6.36	A
	Baseline (equal)	8.00	7.60	6.37	A
	M6 +30%	8.03	7.96	6.37	A
Roofing (A=Bamboo/Ply, B=PE/PP, C=PC)	M1/M2 − 20%, M6 +20%	8.42	5.07	3.72	A
	Baseline (equal)	8.75	4.67	3.77	A
	M1/M2 +20%, M6 − 20%	9.05	4.32	3.83	A

* Asterisk denotes the one case where the top-ranked material changes under the tested weighting range (panels, M6 +30%: rigid PU foam is overtaken by softwood/bamboo).

Justification of Constraints and Limits

The density limits for each component were set as follows. For the structural frame, a maximum of 3,000 kg/m³ was used to exclude heavy metals (steels at ~7,800 kg/m³) while retaining aluminium alloys (~2,680 kg/m³), which offer a superior M1–M2 position. For seating and desks, a maximum of 2,000 kg/m³ targets lightweight, portable furniture materials. For roofing, a maximum of 1,500 kg/m³ excludes dense metals and masonry while accommodating polymers, such as polycarbonate (~1,200 kg/m³), that serve a functional role as translucent roofing. The cost ranges were set as upper limits for economic feasibility in educational projects with budget constraints. One deliberate exception applies to cork for enclosure panels: its cost (~9–14 USD/kg) exceeds the 5 USD/kg panel limit, but cork is used only as a thin inner acoustic layer (~10–15 mm), so the per-panel cost impact is modest and its unique acoustic performance (NRC ~0.5–0.6) justifies its inclusion. All other cost exceptions are noted explicitly in Table 5. The selection of modulus thresholds stems from deflection limits under typical outdoor loads, such as self-weight, wind, and user interaction, targeting stiffness-to-weight optimization for bending-limited panels. The upper tensile strength limit of 50 MPa for seating surfaces ensures that shortlisted materials provide ergonomic compliance and avoid overly rigid contact zones, consistent with EN 1729 and ISO 9241-5. This approach is consistent with Ashby's methodology where fixed parameters reflect functional requirements (Ashby, 2010).

RESULTS

For an on-campus study pod material selection work, which emphasizes structural metals, polymers, woods, composites, and foams for lightweight panels, alongside thermal, acoustic, and cost properties, the Level 2 database in CES EduPack 2013 was selected. This database covers around 3,000 materials (including metals, polymers, elastomers, ceramics, hybrids, and woods) with more than 70 attributes focused on engineering performances, such as E, σ_f, ρ, k, α, H, and cost (Ashby, 2010). Therefore, this database was used for core screening process.

Quantitative Illustration of Index Performance

A quantitative comparison between shortlisted materials is given by two concrete examples as illustrated in the following sub-sections.

Structural Frame Comparison (M2)

To quantify the mass advantage of 5000-series aluminium over stainless steel for the frame, a direct comparison was performed under identical design conditions. The governing load case is a simply supported beam with span L = 4.0 m (the maximum frame dimension), carrying a distributed line load w = 750 N/m derived from the occupancy load of 1.5 kN/m² over a 0.5 m tributary width plus self-weight. The serviceability limit is deflection $\delta \leq L/360$ = 11.1 mm, and the safety factor against yield is 1.5. For a hollow square tube of outer dimension D and wall thickness t, the moment of inertia and section modulus are:

$$I = \frac{D^4 - (D - 2t)^4}{12}, Z = \frac{1}{D/2}$$

Thus, the deflection requirement for both 5000-series aluminium alloy and stainless steel tube give a minimum I of 3.17×10^{-6} m^4 and 1.13×10^{-6} m^4. Similarly, the strength requirement gives minimum Z of 9.0×10^{-6} m^3 and 7.5×10^{-6} m^3. For each material, the lightest hollow square tube that satisfies both requirements was found by varying the D/t ratio. The aluminium frame achieves a 41.9% mass reduction relative to the stainless steel frame while meeting identical yield and deflection criteria. This directly illustrates the advantage of maximizing the stiffness-to-weight (M1) and strength-to-weight (M2) indices for portable structures.

Enclosure Panel Thermal Example (M4)

For thermal insulation, panel thickness t = 50 mm, ΔT = 25 °C, heat flux $q = k{\cdot}\Delta T/t$. Cork ($k \approx 0.05$ W/m·K) yields $q \approx 25$ W/m², rigid PU foam ($k \approx 0.03$ W/m·K) $q \approx 15$ W/m², and pine softwood ($k \approx 0.15$ W/m·K) $q \approx 75$ W/m². Thus, cork and PU foam reduce heat transfer by 3–5 times compared to untreated wood, demonstrating clear superiority on M4 for thermal comfort in outdoor pods.

Structural Frame

Figure 3(a) displays the plot of performance indices M1 ($E^{1/3}/\rho$) *vs.* M2 ($\sigma_f^{1/2}/\rho$) for material kingdoms enclosed inside bubbles. The bubbles are annotated inside the figure to show the borders of each bubble with respect to the plot axes. The slope value between M1 and M2 was selected to be 3 corresponding to the performance index M1. The line appears in the chart positioning the lightest stiff panel material in the upper left corner. Limit constraints of 3000 kg/m^3 maximum density, Young's moduli in the 60-210 GPa range, 1.8 MPa minimum tensile strength, 0.06 minimum elongation and the cost between 2 and 8 USD/kg were applied to shortlist all passed candidates. The candidate structural materials are stainless steel, aluminium alloys, and zinc alloys, which fall within the metals and alloys bubble, as shown in Figure 3(b). Comparing the densities of all candidate materials, the qualified materials narrowed down to include aluminium alloys.

Aluminium alloys have the lowest densities as compared to other shortlisted materials. However, aluminium alloys list contains tens of choices that must be minimized to meet the given criteria.

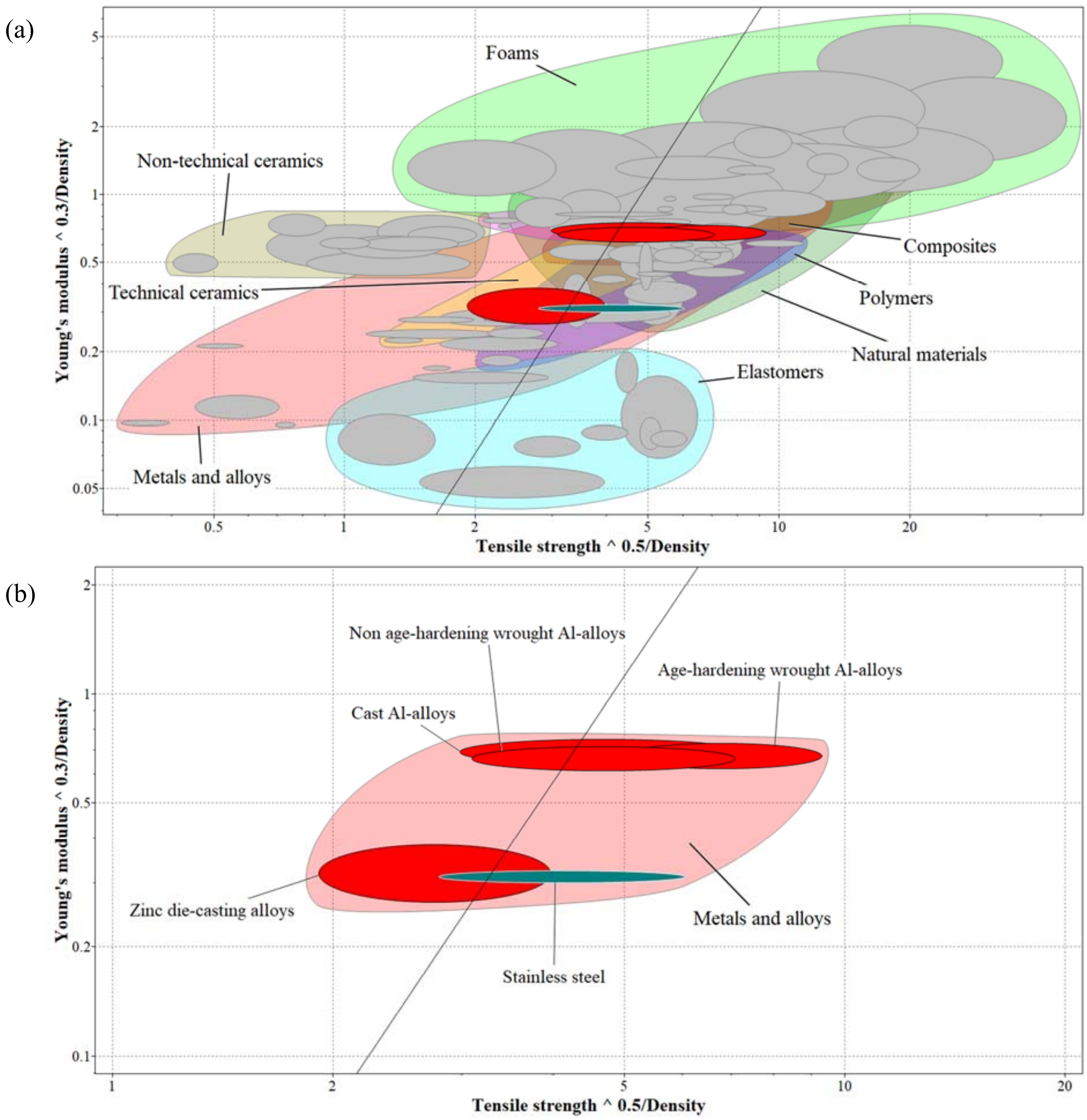


Figure 3. Ashby material selection charts for the structural frame. (a) Performance indices M1 (stiffness-to-weight) versus M2 (strength-to-weight) with guideline slope of 3; (b) shortlisted candidates after applying density, modulus, strength, and cost constraints (metals and alloys family)

Wrought aluminium alloys are widely used lightweight materials. They are strain hardened instead of being hardened by precipitation heat treatment, which makes them robust, weldable, and suitable for fabricated structures (Ashby, 2010; Kaufman & Rooy, 2004). The 1000 series are known as the commercially pure aluminium alloys that offer superior ductility and excellent electrical and thermal conductivities. However, because of their low strengths, they are inappropriate for structural uses. On the other hand, the 3000 series (Al–Mn alloys) provides moderate strength and good formability, but remains less suitable for primary structural components. The 5000 series achieves higher strength while retaining adequate formability (Davis, 2001). The 5000 series is particularly used for structural applications requiring sheets and tubes. Its alloys contain approximately 0.5–5.5% magnesium, provide a favourable balance of moderate strength (up to about 300 MPa), good corrosion resistance, and excellent weldability (Davis, 2001). Because their strengths do not depend on heat treatment, welding does not significantly degrade their mechanical properties, which is a key advantage for structural assemblies. These alloys are commonly supplied as sheets, tubings, and extrusions, making them well suited for load bearing and frame-like components (Kaufman & Rooy, 2004). Due to their low density, structural reliability, corrosion resistance, and manufacturability in sheet and tubular forms, 5000 series aluminium alloys are an appropriate and practical choice for the structural components of a study pod, where lightweight construction is essential (Callister & Rethwisch, 2007; Kaufman & Rooy, 2004).

Enclosure Panels

The bubble diagram that effectively visualizes the trade-offs between structural performance M1 and thermal insulation M4 index is shown in Figure 4(a). The bubble diagram of candidate materials within the specified constraints of 1-5 USD/kg, good thermal insulators and minimum compressive strength of 0.5 MPa (for material handling) is illustrated in Figure 4(b). This is highly relevant for enclosure panels in a study pod, where acoustic/thermal isolation, structural integrity, ease of fabrication, and cost without excessive weight are balanced.

It can be concluded from Figure 4 that foams dominate the low k region (0.02-0.05 W/m°C) with moderate stiffness-to-weight (0.1-1 $GPa^{1/3}/(Mg/m^3)$), prioritizing insulation, but often needing reinforcement or thicker sections for rigidity. Natural materials sit farther right ($k \approx 0.2$-0.5 W/m°C) with superior $E^{1/3}/\rho$ up to 4, enabling lighter, and stiffer panels. Polymers offer a balanced middle ground, while elastomers at the bottom provide excellent insulation, but negligible stiffness, making them unsuitable for primary panels. Candidates include cork, which combines low k with reasonable stiffness and natural acoustic damping, being ideal for quiet, insulated pods. Flexible polymer foams are excellent insulators, but work best as cores. Softwoods, like pine and bamboo, deliver high structural efficiency and meet the compressive strength requirement easily, though their higher k may require added insulation layers. Paper/cardboard is moderately balanced, but less durable long-term.

Overall, no single material dominates both axes in this price range, so the best approach depends on priorities: foams or cork for maximum thermal insulation performance, or woods, like pine/bamboo, for lightweight structure, potentially combined in composites. Although glasses were not shortlisted due to the screening constraints, they can be effectively utilized for front and/or rear pod facades to provide natural light and visual connection with the environment. The strength constraint reinforces the practicality of these affordable, insulating materials for study pod enclosures.

Seating and Desks

The performance index M3, considered for maximizing the wear resistance of seating materials, is presented in Figure 5(a) by plotting the H *vs.* ρ relationship. The harder the material is, the lower is the wear rate (Mostafa, 2019). The slope was selected to be 1 to provide materials with balanced hardness-to-density properties. The candidate materials are those falling above the line. The limiting constraints, such as maximum density of 2000 kg/m^3, maximum price of 8 USD/kg and maximum tensile strength of 50 MPa, were applied to shortlist all candidates as given in Figure 5(b). These limits effectively target soft, lightweight, and affordable materials suitable for study pod seating and desks, where high strength is undesirable to ensure comfort and safety under impact. Hardness provides essential resistance to scratches, dents, and everyday wear from books, laptops, and user contact.

The plot reveals a broad upward trend, with hardness generally increasing alongside density, yet considerable variation allows for low-density selections. Natural materials, primarily woods, cluster on the left at densities of approximately 450–800 kg/m^3 and moderate hardness levels of around 10^7–10^8 Pa, establishing a lightweight and aesthetically pleasing baseline. Polymers occupy the central region at 900–1400 kg/m^3 with comparable or slightly superior hardness, offering mouldable and moisture-resistant alternatives. Non-technical ceramics, and composites appear farther right, but approach or exceed the density limit, rendering them less appropriate for portable, lightweight furniture.

Among the candidates, plywood stands out for its optimal balance of very low density of about 500–600 kg/m^3 and provides sufficient hardness, combined with ease of shaping into ergonomic forms and strong screw retention for assembly. Softwoods like pine and hardwoods like oak deliver greater hardness with low densities, enhancing surface durability. Paper and cardboard achieve the lowest densities, but offer minimal hardness, making them better suited to prototypes or secondary elements. Common polymers, including polypropylene, polyethylene, polystyrene, ABS, phenolics, and cellulose acetate, match woods in hardness while providing advantages in injection molding for consistent ergonomic shapes, water resistance, and recyclability (Gardner et al., 2015). The applied constraints successfully exclude heavier, higher-performance materials, focusing the selection on practical, comfortable, and cost-effective options that support prolonged student use without compromising safety or portability.

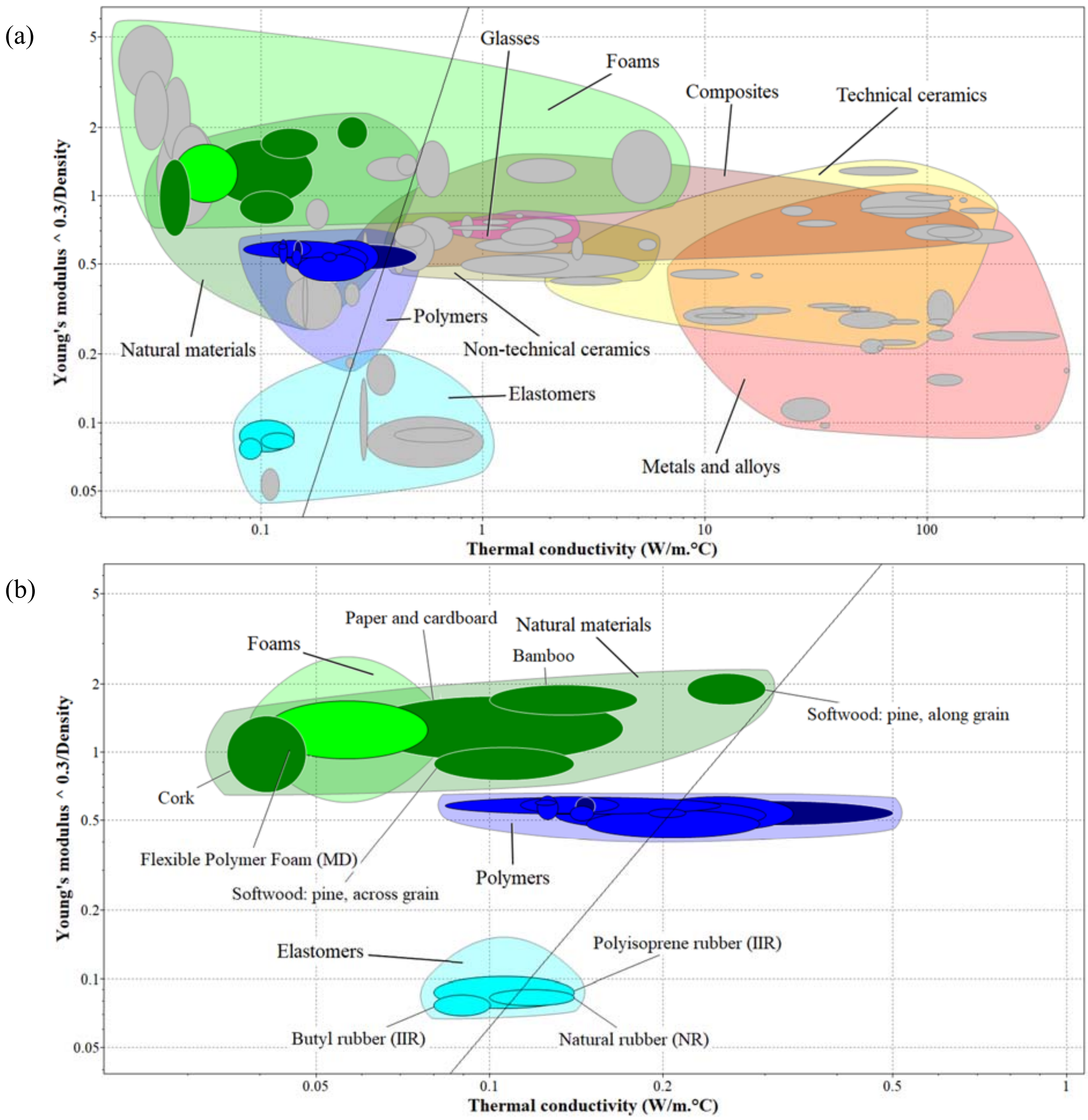


Figure 4. Ashby charts for enclosure panel materials. (a) Stiffness-to-weight (M1) versus thermal conductivity (*k*); (b) Shortlisted candidates after applying cost (1-5 USD/kg), thermal insulation, and minimum compressive strength constraints

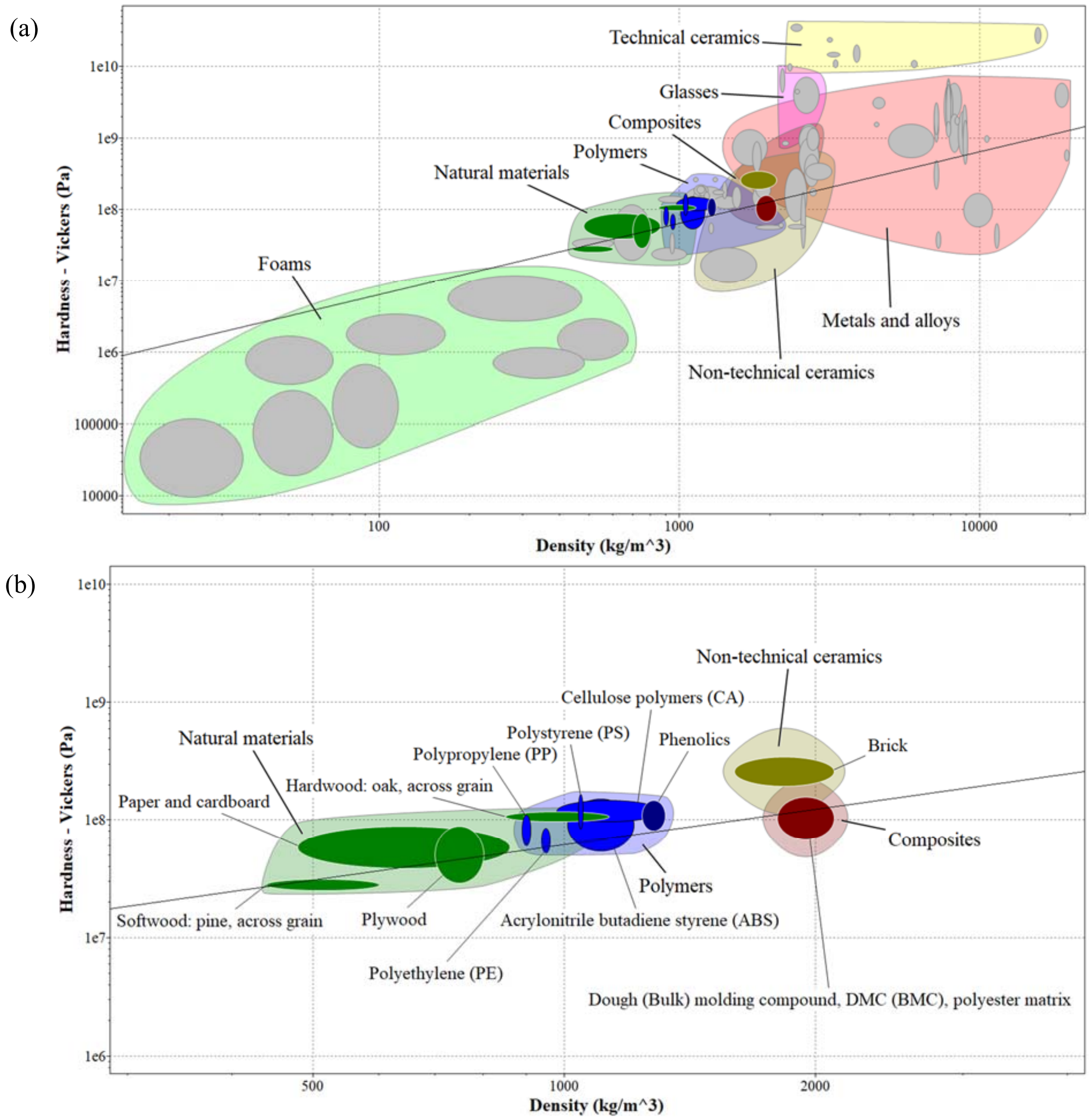


Figure 5. Wear resistance screening for seating and desk materials. (a) Hardness versus density with guideline slope of 1; (b) Shortlisted candidates after applying density (<2000 kg/m³), cost (<8 USD/kg), and strength constraints

Roofing

Roofing materials are often a significant and sometimes expensive part of any construction or renovation project, though costs vary widely depending on the material costs (influenced by oil/metal prices), complex labour, and increasing demand. The cost of roofing materials are further influenced by material quality, roof complexity, and market conditions (Perera & Fernando, 2002). Selecting appropriate, function-oriented roofing materials is therefore a challenging task that can be effectively addressed through systematic material selection. The cost per unit volume *vs.* stiffness-to-weight index is were plotted in Figure 6(a) to correlate mechanical efficiency with cost of the roofing materials. The price×ρ axis represents the cost per unit volume in USD/m³, where lower values indicate cheaper material for a given roof volume. The $E^{1/2}/\rho$ is used here for spanning beam or purlin elements. This exponent differs from the $E^{1/3}/\rho$ index used for M1, which applies to flat plates loaded in bending. Roofing members in this pod span between frame supports and behave primarily as beams rather than plates; for a stiffness-limited beam of minimum mass, the correct index is $E^{1/2}/\rho$ (Ashby, 2010). This index is critical for lightweight roofing that resists deflection under wind or self-weight. Two constraint limits were used to narrow the list of candidates, shown in Figure 6(b). These constraints are a maximum price of 15 USD/kg and a maximum density of 1500 kg/m^3.

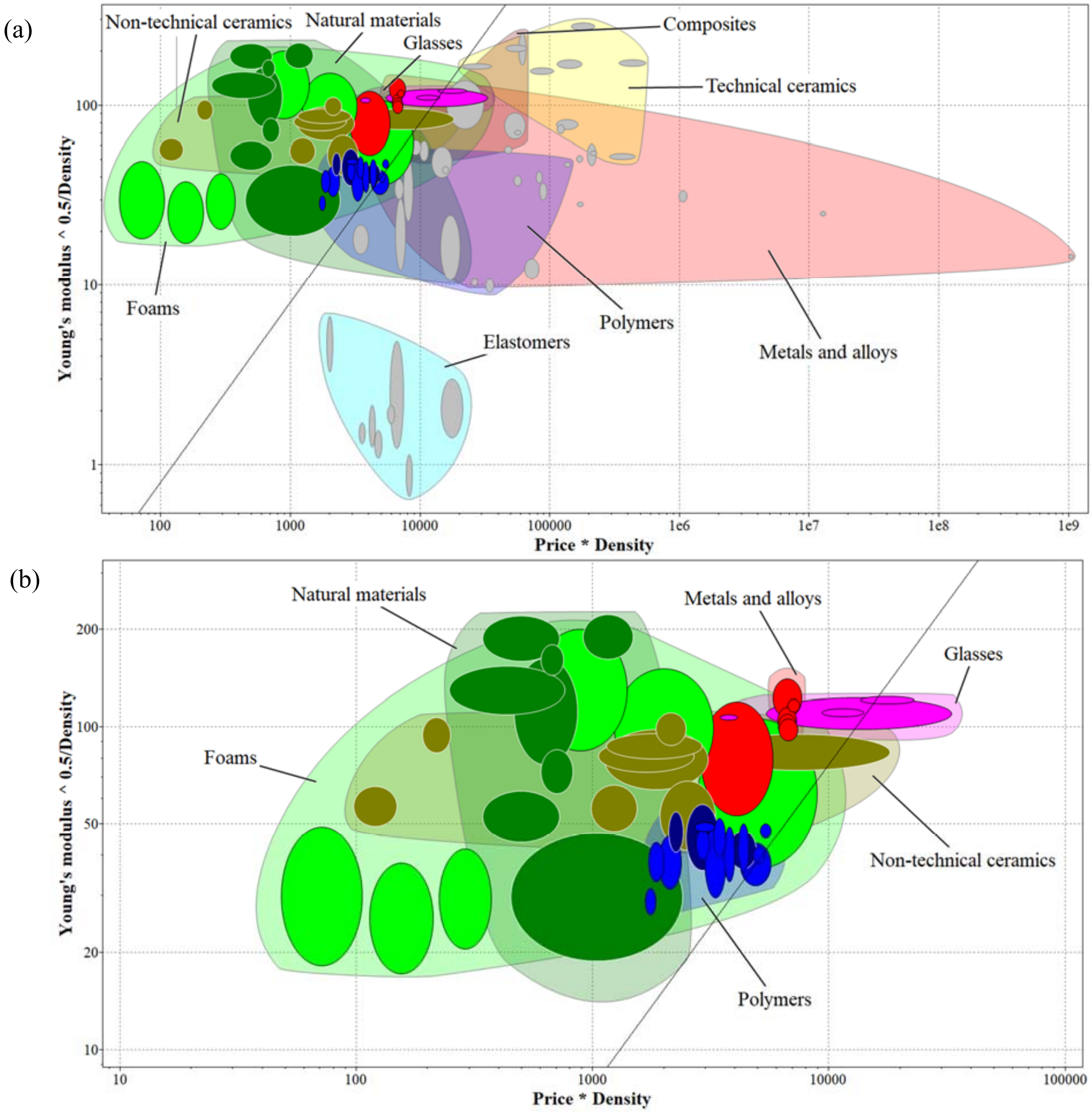


Figure 6. Roofing material selection. (a) Cost per unit volume versus stiffness-to-weight index with guideline slope of 1; (b) Shortlisted candidates after applying maximum cost (15 USD/kg) and density (1500 kg/m³) constraints

The plots reveal distinct family clusters along a rising guideline. Foams dominate the bottom-left with extremely low cost per volume (~10–100 USD/m³) and low specific stiffness index of about 10–50, ideal for ultra-cheap, lightweight insulation, but requiring thick sections or supports to avoid excessive bending. Natural materials, such as woods like bamboo, plywood, soft/hardwoods, cork, and paper/cardboard, occupy the central-left region with moderate cost per volume of about 100-1000 USD/m³ and higher specific stiffness, offering an excellent balance of low weight, reasonable rigidity, natural aesthetics, and sustainability. Polymers cluster lower-centre with similar or slightly lower volumetric costs and variable stiffness index of about 20-100, providing mouldable, and UV-resistant options. Metals and alloys, glasses, and non-technical ceramics shift rightward with much higher cost per volume due to greater densities, despite high stiffness in some cases.

Among the candidates, natural materials emerge as frontrunners for study pod roofing. Bamboo, plywood, and softwoods combine strong specific stiffness for spanning without heavy framing, low volumetric cost, and good weather resistance when treated, making them suitable for eco-friendly, portable designs. Cork and rigid polymer foams are best in low cost and weight for insulated roofs, but may need protective overlayers. Transparent polymers, like polycarbonate (PC), acrylic, or polyethylene terephthalate (PET), offer moderate stiffness at acceptable volumetric cost, enabling skylight-style roofing for natural overhead light in a study environment. Metals, such as Al and Mg alloys, glasses, and masonry (brick, concrete, slate), are less favourable due to high volumetric expense and weight, though thin Al sheets could work if budget allows.

For roofing verification, the following representative conditions were assumed (based on moderate climate typical of Amman): span L = 2.0 m between supports, uniform distributed load = self-weight + wind uplift pressure (0.8 kPa); snow load not considered, consistent with the design basis. Deflection limit: $\delta \leq L/360 = 5.56$ mm. Using the performance index approach, treated bamboo/plywood (E = 11.5 GPa, ρ = 700 kg/m³) requires a thickness of ≈35 mm to keep maximum deflection under 5.56 mm. In comparison, polycarbonate (E = 2.35 GPa, ρ = 1,200 kg/m³) would require ≈68 mm for equivalent performance — more than double the thickness — substantially increasing weight and cost. This confirms the superiority of bamboo/plywood on the combined stiffness-to-weight and cost indices for the roofing component.

Overall, the results highlight woods (bamboo, plywood, pine) and select polymers (PC for translucency, polyethylene/polypropylene for opacity) as optimal for affordable, lightweight, stiff roofing aligned with modern study pod designs that prioritize portability, cost, and user comfot.

DISCUSSION

This study contributes by bridging the gap between large-scale architectural projects and indoor furniture design. The results show that the dual nature of this work — simultaneously functioning as a concrete design case study and a generalizable application framework — is intentional rather than a limitation. The case-study format grounds the framework in realistic constraints and enables direct validation of the derived indices, while the systematic derivation of application-specific indices (M1–M6) ensures transferability beyond the specific pod application. By quantifying trade-offs, like thermal expansion mismatch and surface hardness alongside traditional weight and cost factors, this framework offers practical guidance for developing sustainable, student-centered learning pods.

Structural Frame

The selection of 5000 series aluminium alloys for the structural frame aligns well with the emphasis on lightweight, corrosion-resistant materials that facilitate modular assembly, as evidenced by their low density (around 2.7 g/cm³) and moderate strength (up to 300 MPa) (Callister & Rethwisch, 2007). This choice outperforms stainless steel and zinc alloys in density while meeting stiffness-to-weight (M1) and strength-to-weight (M2) indices, reducing overall pod weight for easier on-campus relocation. Compared to literature, such as Ashby (Ashby, 2010) and Kaufman (Kaufman & Rooy, 2004), these alloys offer superior weldability without heat treatment degradation, ideal for outdoor exposure. However, trade-offs include higher initial costs than basic steels, although this high cost can be minimized by long-term durability and recyclability, supporting circular economy principles (Leary, 2011). Limitations involve potential anodizing needs for enhanced corrosion resistance in humid climates, which could add fabrication steps. Overall, this selection enhances pod structural integrity while promoting sustainability, potentially reducing maintenance costs in high-traffic educational settings.

To validate the selection of 5000-series aluminium, a structural check was performed on the pod's primary overhead frame. The frame was modelled as a simply supported beam with a span length (L) of 2.0 meters, representing a typical sub-span between intermediate supports within the 1.78–4.0 m overall frame range. A hollow square profile was selected for the beam. The outer dimensions are 50mm by 50mm. The wall thickness is 3 mm. The area moment of inertia (I) for this specific cross section is calculated as 2.08×10^{-7} m⁴. The selected material is aluminium 5083. Its modulus of elasticity (E) is 71 GPa. The applied load combines three components over a tributary width of 109 mm: self-weight of the aluminium section (≈ 49 N/m), occupancy load (1.5 kN/m² × 0.109 m = 164 N/m), and wind pressure (0.8 kPa × 0.109 m = 87 N/m), giving a total distributed line load q = 300 N/m. This value is consistent with the unified design basis (wind = 0.8 kPa; snow not considered). The maximum deflection (δ) was calculated using the standard simply supported beam formula:

$$\delta = \frac{5qL^4}{384EI}$$

By substituting the defined parameters, the maximum deflection is calculated to be 0.00423 m. This is within the L/360 = 5.56 mm serviceability limit, confirming that the selected aluminium section is adequate under the design loads.

The same comparison methodology was applied to the 2.0 m representative sub-span validated above. With the unified load q = 300 N/m and deflection limit $\delta \leq L/360$ = 5.56 mm, the minimum-mass tubes are: 1.04 kg/m for Al 5083 and 1.80 kg/m for SS 304. The mass reduction is 42.2%, consistent with the 4.0 m frame member result. This confirms the robustness of the performance index ranking across different span lengths within the pod frame.

While the selection of 5000-series aluminium is justified by its superior stiffness-to-weight ratio and corrosion resistance, it is important to note the scope of this analysis. This study focuses on material screening and global performance. A final structural implementation would require a detailed design phase to address specific joint configurations, welding specifications, and localized stress concentrations. The calculations provided here serve as a foundational validation of the material's viability, but they do not replace a full-scale structural engineering assessment.

Enclosure Panels

Foams, natural materials like cork, and softwoods emerged as optimal for enclosure panels due to their balance of low thermal conductivity (M4, 0.05-0.5 W/m·°C) and moderate stiffness-to-weight (M1), ensuring thermal comfort and structural support. The acoustic damping properties of cork further address noise reduction capability, as noted in Şatiroğlu et al. (2023), making it suitable for quiet study environments. Two distinct acoustic mechanisms are relevant here and should not be conflated. Sound absorption describes how much sound energy inside the room is absorbed rather than reflected, reducing reverberation and echo; this is quantified by the noise reduction coefficient (NRC). Sound insulation describes how much external sound is blocked from entering the pod, or internal sound from leaking out, and is quantified by the sound transmission class or weighted sound reduction index (Rw). These two properties depend on different material characteristics and do not necessarily track together. For sound absorption, cork (NRC ≈ 0.4–0.6) and rigid polyurethane foam offer comparable performance with high internal damping. Sound insulation, by contrast, is governed mainly by mass and airtightness rather than porosity: the aluminium frame and the layered sandwich panel, combined areal density of softwood skin, foam core, and cork layer, provide the principal insulation against external campus noise, with an estimated Rw in the range of 25–30 dB for the proposed assembly, comparable to a standard timber-stud partition. The porous cork and foam layers contribute only marginally to insulation and instead serve their primary role of absorbing reflected sound within the pod interior. Softwoods and bamboo exhibit moderate absorption performance, which can be enhanced through increased thickness or surface treatment, while their insulation performance depends mainly on panel thickness and any air gaps in the assembly. This ties to restorative quiet spaces (Song et al., 2024).

Polymers provide moldability and UV stability, but natural options, like bamboo or pine, offer better environmental integration and lower embodied energy, aligning with Well Building Standards (Mohamed & Ali, 2023). Trade-offs include foams' need for reinforcement to achieve compressive strength (>0.5 MPa), and woods' higher thermal conductivity requiring insulation layers. Glasses, though not shortlisted, are recommended for facades to enable natural light, enhancing mental health benefits (Khoudi, 2022). Limitations stem from weather exposure, suggesting protective coatings. This multilayered approach optimizes privacy and energy efficiency, filling gaps in small-scale infrastructure literature by prioritizing affordable, eco-friendly composites.

A proposed multilayer sandwich configuration for enclosure panels is illustrated in Figure 7. The structure consists of three layers: (1) outer layer: treated softwood or bamboo (~5–10 mm) provides weather resistance, natural aesthetics, structural rigidity, and UV/durability protection; (2) core layer: rigid polyurethane foam (~40–50 mm) delivers excellent thermal insulation (low *k*) and lightweight contribution; and (3) inner layer: cork sheet (~10–15 mm) offers superior acoustic absorption (NRC ≈ 0.5–0.6), tactile warmth, and additional thermal damping for a restorative indoor feel. This sandwich configuration leverages the strengths of each material while mitigating individual weaknesses. For example, cork's higher cost offset by thin layer, foam's need for reinforcement provided by wood outer skin.

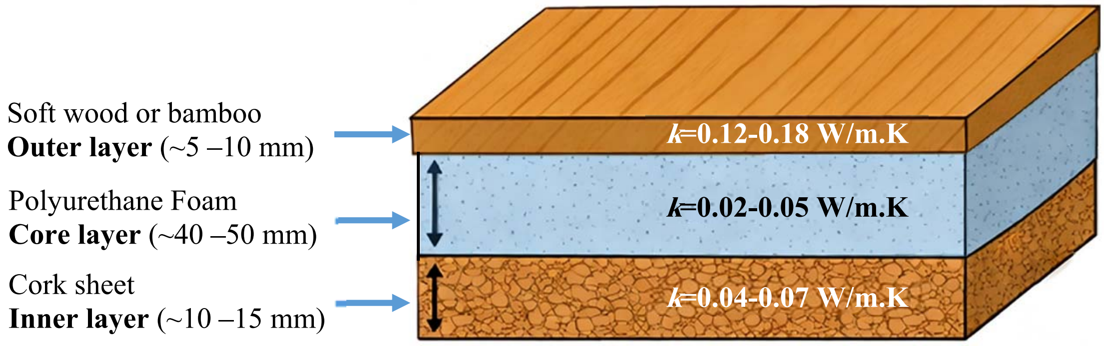


Figure 7. Proposed multilayer configuration for enclosure panels (total thickness 55–75 mm): (1) outer weather-resistant treated softwood or bamboo layer, (2) rigid polyurethane foam core for thermal insulation, (3) inner cork layer for acoustic absorption and tactile comfort. Approximate thicknesses and key thermal conductivities (*k*-values) are indicated

To justify the engineering viability of the sandwich panel, the total thermal resistance (R_{total}) of the assembly was calculated. The total resistance is the sum of the individual layers:

$$R_{total} = \frac{t_{outer}}{k_{outer}} + \frac{t_{core}}{k_{core}} + \frac{t_{inner}}{k_{inner}} = \frac{0.0075}{0.15} + \frac{0.045}{0.03} + \frac{0.0125}{0.05} = 1.80\ m^2.K/W$$

Using the thermal conductivities and thicknesses proposed in Figure 7, R_{total} equals 1.80 m^2.K/W. This *R*-value confirms excellent thermal buffering. It ensures that that the internal space remains insulated from external temperature extremes.

The *R*-value above describes heat transfer through the panel field only, away from edges and joints. For a complete picture of enclosure performance, three additional effects must be considered: overall thermal transmittance, thermal bridging, and moisture behaviour at joints. The overall U-value of the panel field is the inverse of the total resistance, $U = 1/R_{total} = 1/1.80 \approx 0.56$ W/m²·K, which is well below the 1.5 W/m²·K target stated before. However, this clear-field value does not account for the aluminium frame members that interrupt the panel at regular intervals. Aluminium has a thermal conductivity roughly 1,200 times higher than the PU foam core, so each frame member acts as a thermal bridge, locally raising heat flow well above the clear-field rate. Using a simplified linear thermal bridging approach, with frame members spaced at 1.0–1.5 m intervals and a typical linear thermal transmittance of 0.05–0.15 W/m·K for an uninsulated aluminium-to-panel junction, the bridging contribution raises the area-weighted U-value of the assembly to approximately 0.7–0.9 W/m²·K. This remains within the 1.5 W/m²·K target, but is meaningfully higher than the clear-field estimate, and it should be treated as the design-relevant figure rather than the panel-only *R*-value. A thermal break, such as a low-conductivity polymer strip between the aluminium frame and the panel skin, is recommended to reduce this bridging effect in a future detailed design stage. At panel-to-panel and panel-to-frame joints, the structural polyurethane adhesive bonds the layers, but does not by itself prevent moisture ingress along the joint line. Moisture entering an unsealed joint can wet the foam core, increasing its effective thermal conductivity and risking long-term degradation of the bond. To address this, the joint detailing includes a weather-resistant sealant bead along all panel-to-frame interfaces and a polymer edge trim that caps the exposed foam core, consistent with the moisture protection noted earlier. These measures, together with the treated softwood or bamboo outer skin, are intended to keep the foam core dry under normal outdoor exposure; however, the present analysis remains a conceptual estimate, and the values above should be confirmed through detailed thermal bridge modeling (e.g., guarded hot box testing or finite element thermal simulation) at the prototype stage.

Practical implementation requires durable bonding. A structural polyurethane adhesive is proposed for the sandwich assembly. This adhesive handles the different thermal expansion rates of the wood, foam, and cork (Rutkowski et al., 2024). To prevent moisture damage, the wood exterior can be treated with a weather-resistant sealant. The edges can also be protected with a polymer trim.

Seating and Desks

Plywood, softwoods, and polymers, like polypropylene, were shortlisted for seating and desks based on high wear resistance index (M3), ensuring durability under repeated use with densities below 2000 kg/m³ and costs under 8 USD/kg. The low density (500-600 kg/m³) and sufficient hardness (10^7–10^8 Pa) of plywood make it ergonomic and lightweight, while polymers add moisture resistance and recyclability, as discussed in Gardner et al. (2015). The screening process set an upper limit of about 50 MPa for tensile or bending strength in seating surfaces and desktops to balance structural performance and user comfort. Very strong materials, such as metals or advanced composites above 100 MPa, tend to be hard and non-compliant, creating rigid contact surfaces that can cause discomfort during prolonged sitting or leaning and increase pressure points or minor impact risks. In contrast, materials at or below 50 MPa provide sufficient strength for typical loads of about 1–2 kN while offering moderate flexibility and surface compliance. This allows better pressure distribution and reduces perceived hardness, which are important for ergonomic comfort in student furniture, as reflected in standards, such as ISO 9241-5 and EN 1729.

The selection aligns with key educational furniture standards, including EN 1729 (furniture for educational institutions — strength, durability and stability) and ANSI/BIFMA X5.5 (general-purpose office chairs and desks), which emphasize functional strength combined with user safety and comfort rather than maximum material strength. These standards typically require seating surfaces to withstand 1–2 kN static loads with limited deflection and no sharp edges or overly rigid contact zones.

Limitations include hygiene concerns in shared spaces, recommending antimicrobial treatments. However, hygiene considerations favor non-porous or easily cleanable surfaces: polypropylene and HDPE offer excellent moisture and stain resistance and can be disinfected with standard campus cleaning agents. Fire performance is addressed by selecting inherently low-flammability polymers and surface-treated plywood, sufficient for open, low-occupancy outdoor pods without upholstered components. By focusing on low-maintenance materials, this selection supports prolonged student productivity (Song et al., 2024) and integrates sustainability through recycled plastics, aligning with urban furniture trends (Grabiec et al., 2022).

Roofing

Natural materials, like bamboo, plywood, and softwoods, alongside polymers, such as polycarbonate, were identified as ideal roofing options for their low cost per volume and high stiffness-to-weight ratios, enabling lightweight, deflection-resistant designs under environmental loads. The sustainability and rigidity of bamboo reflect eco-friendly recommendations as reported by Mohamed and Ali (2023), while transparent polymers allow natural light, improving occupant comfort (Papaioannou et al., 2023). Foams provide insulation, but require overlays for weatherproofing. Trade-offs include the exclusion of metals due to their high density and cost, though thin aluminium could be viable for such applications. Limitations involve market fluctuations in material prices (Perera & Fernando, 2002) and the need for treatments against UV degradation.

UV degradation is a key concern for outdoor roofing. Treated bamboo and plywood require UV-resistant coatings or stains. With maintenance, their service life is about 8–12 years. Polycarbonate sheets offer inherent UV stability due to protective co-extruded layers. However, they come at a higher cost. Polyethylene and polypropylene require UV stabilizers to prevent brittleness. Without protection, degradation can occur after 5–7 years of exposure. These treatments were considered in the final ranking.

This selection promotes affordable, modular roofing that minimizes energy demand (Sorrell, 2015), addressing climate-appropriate designs (Şatiroğlu et al., 2023) and advancing portable educational infrastructure.

Lifecycle, Circularity, and Overall Implications

This sub-section presents a qualitative lifecycle and embodied carbon comparison, drawing on published third-party data rather than an original LCA conducted for this study. Wood- and bamboo-based panels are reported in the literature with embodied carbon equivalent to roughly 0.4–1.0 kg CO_2-eq/kg, and bamboo is renewable with a 3–5 year growth cycle (MOSO, 2018). Primary aluminium production carries a substantially higher footprint, reported globally at approximately 14.8 kg CO_2-eq/kg, though this varies considerably by region and electricity source, from below 4 kg in hydropower-based regions to over 20 kg in coal-based regions (European Aluminium, 2023; International Aluminium Institute, 2023). Secondary (recycled) aluminium requires only about 5% of the energy of primary production and emits roughly 0.5 kg CO_2-eq/kg (International Aluminium Institute, 2023). Cork and rigid PU foam have moderate production impacts, but may reduce operational heating and cooling energy over the structure's service life, through superior insulation; this operational offset has not been quantified here. From a circularity perspective, the literature reports aluminium end-of-life recovery rates above 90% in established recycling markets, bamboo and plywood as compostable or recyclable into particleboard, and PP/HDPE as mechanically recyclable. Modular construction further enables disassembly without damage, supporting multiple reuse cycles. These figures are drawn from third-party industry and academic sources; they have not been verified for the specific materials, suppliers, or regional context of this study, and a dedicated LCA is required before they can be cited as project-specific performance claims.

While prior studies link well-designed private study spaces to improved focus and stress recovery (Khoudi, 2022; Song et al., 2024), the present work does not directly measure user outcomes. The selected materials are intended to create environments consistent with restorative design principles, but actual mental health or productivity benefits remain hypothetical and require empirical validation.

Validation Considerations and Limitations

The present study uses database-driven screening *via* the Ashby methodology and CES EduPack to identify optimal material candidates for the on-campus study pod. This approach is appropriate for the conceptual design phase, providing a systematic, first-principle basis for recommendations in the absence of prior prototypes for this specific small-scale outdoor application. The results are theoretical and require further validation to confirm performance under real campus conditions. Three practical validation pathways were considered, but they fall outside the current scope: finite element analysis (FEA), comparative benchmarking, and sensitivity analysis.

Future static FEA simulations could apply self-weight, wind load (0.8 kPa), and point loads (≈500–1000 N) to verify deflection (e.g., $\delta \leq L/360$) and stress limits for the selected aluminium frame and panel/roof materials. As comparative benchmarking, the recommended materials align closely with proven lightweight modular structures (e.g., aluminium-framed library pods, polycarbonate-roofed shelters, bamboo/plywood eco-pavilions), supporting their practical feasibility.

A full sensitivity analysis was performed on the weighted scoring procedure described earlier, using the normalized index values underlying Table 4 as the baseline. Two tests were run for every component. Test 1 varied the cost weight (M6) alone by −30%, 0%, and +30%, with the remaining weight redistributed equally across the other applicable indices. Test 2, applied to the two structural components (frame and roofing), varied the structural indices (M1 and M2) by ±20% simultaneously while adjusting M6 in the opposite direction, with the remainder redistributed. The complete results, including all weighted scores at each weighting scenario, are given in Table 6. The top-ranked material for frame, seating, and roofing components is unchanged across all tested weighting scenarios: 5000-series aluminium remains top for the frame, polypropylene remains top for seating, and treated bamboo/plywood remains top for roofing. For enclosure panels, the ranking is robust across most of the tested range, but at the upper end of the cost-weight test (M6 weight +30%), the top-ranked material changes from rigid PU foam to softwood/bamboo, with the two scores crossing at approximately +27% cost weight (PU foam = 7.27 vs. softwood/bamboo = 7.45 at +30%, compared to 7.9 *vs*. 7.0 at baseline). This indicates that the panel selection is sensitive to how strongly cost is weighted relative to thermal performance, and procurement teams placing very high priority on cost should treat softwood/bamboo as an equally valid first choice alongside rigid PU foam.

Beyond the specific material recommendations for study pods, the methodology developed here offers a transferable framework for other small-scale, modular, outdoor campus elements (e.g., seating clusters, shaded workstations, pop-up lecture pods). Future researchers can adapt this index set and constraint logic to different climates, occupancy levels, or functional requirements, thereby accelerating sustainable material selection in higher-education infrastructure projects.

Table 2 summarizes the key recommendations from the results section, includes the most important performance properties relevant to each component, and provides practical information for implementation. Table 4 presents the normalized scoring and ranking for the four main pod components. A scale of 0 to 10 is used, where 10 indicates the best performer in each index. Scores are derived from the performance indices M1–M6 using the normalization equations stated earlier. Two notes: (1) Cork ranks third among panel materials, because its low modulus penalizes M1; however, cork is used only as a thin acoustic inner layer in the sandwich panel, not as a standalone structural panel, so its M1 score is not the primary driver. (2) Polypropylene ranks first among seating materials when M3 (hardness) is correctly weighted. The complete intermediate calculations are given in Table 6.

To ensure an objective ranking, a weighted sum model was applied to the performance indices. First, each index M_i was normalized on a scale of 0 to 10 to allow direct comparison between materials with different units. The best-performing material in each index receives a score of 10; all others are scaled proportionally. For indices where a higher value is better (M1, M2, M3), the normalized score S_i was calculated as:

$$S_i = 10 \times (V_{actual}/V_{max})$$

where V_{actual} is the material property and V_{max} is the highest value in the group. For indices where a lower value is better (e.g., thermal conductivity and cost), an inverse relationship was applied. The total performance score (P) for each material was then determined using the following equation:

$$P = \sum (w_i \times S_i)$$

Here, w_i represents the weight assigned to each index. All applicable indices carry equal weights within each component group, rescaled to sum to 1.0. The normalization equations are: $S_i = (v_i/v_{max}) \times 10$ for maximize-indices, and $S_i = (v_{min}/v_i) \times 10$ for minimize-indices. To illustrate, consider 5000-series aluminium for the frame. Three indices apply: M1, M2, and M6, each weighted at 0.333. Raw M1 = 1.534×10^{-3} (vs steel 0.740×10^{-3}), so aluminium scores 10.0 and stainless steel scores (0.740/1.534)×10 = 4.8. Raw M2 = 5.797×10^{-3} (*vs*. steel 2.887×10^{-3}); aluminium scores 10.0, steel scores 5.0. For M6 (cost, lower is better): steel at 3.0 USD/kg scores 10.0; aluminium at 5.0 USD/kg scores (3.0/5.0)×10 = 6.0. Aluminium final score = (10.0 + 10.0 + 6.0) × 0.333 = 8.7. Steel = (4.8 + 5.0 + 10.0) × 0.333 = 6.6. This consistent mathematical approach was applied to all components in Table 4. The key numerical properties of the shortlisted materials are summarized in Table 5. These values were used to derive the performance indices and normalized scores presented in Table 4.

Although material prices are fluctuating due to many factors, for example aluminium influenced by energy costs, polymers by petrochemical prices, and woods by supply-chain factors, a sensitivity check varying the cost weighting (M6) by ±30% in the normalized scoring (Table 4) showed no change in the top-ranked materials for frame, seating, and roofing components. For enclosure panels, the top rank changes from rigid PU foam to softwood/bamboo at the +30% end of this range, with the two scores nearly tied (7.27 *vs*. 7.45); both remain strong, defensible choices. Outside this single panel case, the moderate price fluctuations tested here would not alter the primary recommendations, supporting their validity for current campus budgeting despite the 2013 baseline. The full set of weighting scenarios and scores is given in Table 6.

To further enhance the practical applicability and safety profile of the proposed pod design, considerations for fire resistance, lifecycle environmental impact, and material sustainability are highlighted. The structural frame (5000-series aluminium alloys) is classified as non-combustible under standard fire testing (Euroclass A1 per EN 13501-1), consistent with the established behaviour of aluminium alloys under fire exposure (PROMAT, 2024). Treated woods, bamboo, and plywood are reported in published fire-retardant treatment studies to reach Euroclass B or C under EN 13501-1, or Class A–C flame-spread ratings under ASTM E-84/IBC criteria, when intumescent or impregnated fire-retardant coatings are applied (Trada, 2019). The specific class achieved depends on the coating system, application thickness, and substrate, so the exact rating for the proposed pod assembly would need to be confirmed by an accredited test once a prototype panel is built. Polymers, such as PC and HDPE, can incorporate flame-retardant additives to improve their reaction-to-fire performance, though their baseline flammability without additives is higher than treated wood and this should be verified against the specific polymer grade selected. As an open, low-occupancy outdoor structure without enclosed high-risk spaces or upholstered furnishings, the fire load is lower than for an enclosed indoor room. However, this study has not conducted or sourced a formal fire risk assessment against a specific building code, and the statement above should be read as an engineering judgement rather than a certified compliance claim.

Published life-cycle data supports the qualitative sustainability comparison made here, though the present study did not conduct an original LCA. Wood- and bamboo-based panels report cradle-to-gate embodied carbon figures equivalent to roughly 0.4–1.0 kg CO_2-eq/kg when converted from published volumetric figures (Environmental Product Declarations report plywood at roughly 540 kg CO_2-eq/m^3), and they are renewable with growth cycles of 3–5 years for bamboo. Primary aluminium production carries a substantially higher embodied carbon footprint, reported globally at approximately 14.8 kg CO_2-eq/kg (International Aluminium Institute, 2023), though this varies by region and electricity source (from below 4 kg in hydropower-based regions to over 20 kg in coal-based regions). However, secondary (recycled) aluminium production requires only about 5% of the energy of primary production and emits roughly 0.5 kg CO_2-eq/kg (International Aluminium Institute, 2023), and end-of-life recovery rates for aluminium building products are widely reported above 90%. Cork and rigid PU foam have moderate production impacts relative to bamboo and plywood, yet their low thermal conductivity can reduce operational heating and cooling energy demand, which over the structure's service life may offset upfront production impacts; this trade-off has not been quantified here and would require a full operational-phase LCA. From a circularity perspective, bamboo and plywood are compostable or can be recycled into particleboard, PP and HDPE are mechanically recyclable, and aluminium scrap collection and recycling infrastructure is well established in most regions. These qualitative claims are consistent with published industry and academic sources cited above, but the present study did not perform an original quantitative LCA; the specific percentages and CO_2-eq figures cited are drawn from third-party industry and literature sources rather than measured for this specific pod design. A full quantitative lifecycle assessment is recommended as a future step to evaluate embodied energy, global warming potential, and end-of-life performance under campus conditions.

While prior studies have linked well-designed private study spaces to improved focus, stress recovery, and perceived productivity (Khoudi, 2022; Song et al., 2024), the present work does not directly measure user outcomes. The selected materials are intended to support the creation of environments consistent with restorative design principles—enclosed yet nature-connected, quiet, and thermally comfortable—but actual mental health or academic performance benefits remain hypothetical and require empirical validation through future user studies or field trials.

Figure 8 presents hypothetical rendered visualizations of the proposed on-campus study pod design, incorporating the materials selected as summarized in Table 2. Figure 8 (a) and 8 (b) preserve the original geometric proportion layout (Dabbour, 2012) with large and glazed façades for natural light and campus integration, and a modular structure. Realistic textures and finishes were also applied based on the recommended materials. The interior layouts from different angles are also presented in Figure 8 (c) and 8 (d).

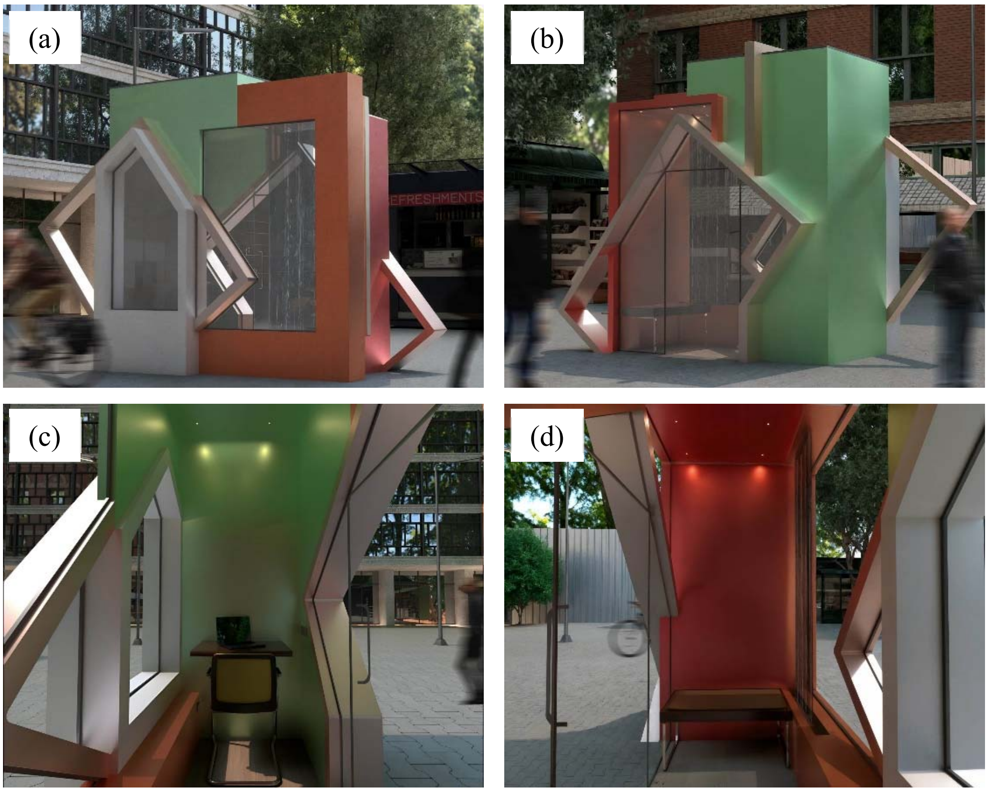


Figure 8. Suggested design of the on-campus study pod incorporating the recommended materials. (a) Front exterior view; (b) rear exterior view; (c) and (d) interior layouts from different angles

It is important to mention that this study has several limitations that should be considered when interpreting the findings. The analysis relies on theoretical screening using 2013 CES EduPack property data and approximate cost estimates; current market prices, material grades, and regional availability may differ. The recommendations assume moderate climatic conditions and typical campus usage patterns. Thus, extreme weather, heavy vandalism, or very high occupancy could necessitate adjustments. The thermal transmittance, thermal bridging, and sound insulation (*Rw*) figures presented earlier are conceptual estimates based on simplified linear thermal bridging and standard partition analogies; they should be confirmed through guarded hot box testing, infrared thermography, or acoustic chamber testing once a prototype is built. Environmental impact assessment is qualitative rather than quantitative, lacking a full LCA of embodied energy, carbon emissions, and disposal scenarios. Finally, the work focuses on material optimization at the conceptual stage and does not include prototype fabrication, user testing, or long-term performance monitoring, limiting direct evidence of real-world efficacy. These constraints highlight the need for future experimental validation and site-specific refinement.

CONCLUSIONS

This study successfully applied the Ashby material selection methodology, supported by CES EduPack, to identify optimal materials for a compact, modular on-campus study pod. By deriving and applying six tailored performance indices (M1–M6), the work provides a systematic approach to designing pods that prioritize environmental comfort. While psychological outcomes were not directly evaluated, the resulting material assembly addresses the physical requirements necessary for a quiet and thermally stable study space.

Key recommendations include 5000-series aluminium alloys for the structural frame (offering approximately 42% lower mass than stainless steel while meeting stiffness and strength requirements), a three-layer sandwich enclosure panel (treated softwood or bamboo outer skin, rigid polyurethane foam core, and cork inner layer) for superior thermal insulation and acoustic absorption, plywood and polypropylene for ergonomic and wear-resistant seating, and treated bamboo/plywood (with polycarbonate as a translucent alternative) for lightweight, stiff roofing. Quantitative illustrations and sensitivity analyses confirm the robustness of these selections under realistic campus loads and moderate price fluctuations.

The proposed materials promote lightweight construction, recyclability, low embodied energy where possible, and compliance with basic fire-safety needs for open outdoor pods, thereby supporting the creation of restorative, nature-connected study environments. While the present work focuses on the conceptual design stage and does not include experimental validation, the developed index set and constraint logic offer a transferable methodology for other modular campus elements. Future research should incorporate finite element structural simulations, small-scale prototype fabrication, user comfort trials, and full lifecycle assessment to confirm real-world performance and further generalize the approach to sustainable higher-education infrastructure.

Acknowledgements

The authors would like to express their gratitude to the Deanship of Scientific Research and Innovation at Al-Zaytoonah University of Jordan for providing the financial support to implement this project through grant No. 54/06/2024-2025.

Conflict of Interests

The authors of this work declare no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

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