

A Multi-Criteria Decision Model for Preliminary Selection of UAV Outer-Shell Material Architectures

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ABSTRACT

In this study a standards-guided multi-criteria decision analysis (MCDA) model is developed for preliminary screening of UAV outer-shell material architectures. It categorizes printable skins, short- and continuous-fiber reinforcement, composite laminates, local metallic features and cellular crash absorbers and tests them against 12 mechanicals, impact, vibration, environmental, thermal/fire, RF, manufacturing, repair and lifecycle criteria. Scores are treated as auditable engineering screening values rather than experimental measurements; their provenance is classified using E1-E4 evidence-traceability levels. Reference and mission-specific weights are evaluated using deterministic sensitivity analysis and a reproducible Monte Carlo procedure. Numerical recalculation confirms the reference ranking: PETG-CF lattice 3.758/5, CFF carbon-nylon 3.550/5, and PETG/ABS honeycomb hybrid 3.500/5. Under alternative missions, CFF carbon-nylon leads the stiffness/load-path case, PETG/ABS honeycomb leads the RF-sensitive enclosure case, and Al 6061-T6 leads the thermal/fire-constrained case. PETG-CF lattice is first in 95.03% of 20,000 base-case Monte Carlo trials and 81.64% in a conservative evidence-class uncertainty stress test. The results are preliminary screening outcomes, not qualification claims. The PETG-CF lattice is an architecture class rather than a fixed geometry; full coupon-, panel-, shell-, RF-, fire-, environmental-, modal-, FEA-, and lifecycle validation is required before design release.

Keywords: UAV structures; materials selection; MCDA; PETG-CF; lattice structures; RF compatibility.



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1. INTRODUCTION

The outer shell of a small- to medium-sized unmanned aircraft system (UAS/UAV) is not merely an aerodynamic cover. It can contribute to local stiffness and load transfer, protect the battery and electronics payload, dissipate impact energy, resist moisture and ultraviolet exposure, and interact with radio-frequency (RF) systems when conductive composites or metals are placed close to antennas [1]-[5], [24]-[26].

Selecting a shell architecture solely by minimum density or maximum strength is therefore inadequate. A stiff all-composite shell can be structurally efficient while increasing tooling, inspection, repair, lifecycle, or RF-integration burdens; conversely, a printable thermoplastic can be inexpensive and repairable but limited by heat-deflection temperature, flammability, dimensional stability, or environmental aging [2], [4], [5], [10], [11].

The design problem addressed here is the lack of an auditable preliminary-selection method that translates heterogeneous evidence into mission-specific material-architecture decisions. At concept stage, complete coupon-, panel-, and shell-level datasets rarely exist, yet design teams still need to decide which material systems and validation tests deserve further resources.

This paper formulates UAV shell selection as a function-partitioned materials-engineering problem. The shell is decomposed into load paths, external skins, crash absorbers, antenna windows, heat-spreading or threaded interfaces, and replaceable repair modules. Candidate systems are evaluated by a transparent weighted-sum MCDA model under a reference mission and four alternative mission emphases.

The contribution is fourfold: (i) a material-architecture and functional-zone formulation rather than a universal single-material ranking; (ii) an explicit scoring, weighting, sensitivity, and uncertainty workflow; (iii) mission-dependent ranking rules; and (iv) a standards-guided validation matrix linking each criterion to measurable laboratory, environmental, RF, fire, modal, finite-element, or lifecycle outputs.

2. Literature Review

Recent work has expanded the use of fused-filament fabrication, chopped-fiber thermoplastics, continuous-fiber reinforced nylon/Onyx systems, topology-optimized frames, and composite laminates in drones and small airframes [1]-[9]. These studies quantify tensile, flexural, impact, or frame-

level responses for specific material-process combinations, but they do not by themselves establish a universal shell architecture.

PETG-CF and similar composite filaments are also relevant to frame and shell applications due to the different tensile response, stiffness, impact behavior and failure mode that can be achieved with infill and internal architecture [2]. High specific stiffness and strength can be achieved using continuous-fibre thermoplastics, but this is dependent on the direction of the fibre, the routing of the fibre, consolidation, moisture conditioning and local stress concentration [4]. CFRP laminates offer high structural efficiency characteristics, but also add considerations of tooling, inspection, repair, life expectancy and integration with RF systems [10], [11], [24]-[26]. There is more to the influence of internal architecture than to material identity. A variety of approaches have been used to create material redistribution near load paths, including the use of honeycomb and lattice regions as sacrificial crush zones [3] and topology optimization and generative design [6]-[9]. The outdoor UAV structures can be subject to ultraviolet radiation, water, salt, thermal cycles and chemicals depending on the mission. The data obtained from unaged tests is not enough to determine the environmental durability, because FFF polymers can change their properties after conditioning [5]. RF compatibility is a design parameter in and of itself. Carbon-fiber conductive structures can attenuate, shield, detune or otherwise influence the behavior of an antenna, depending on frequency, orientation of the lamination, geometry, placement and separation. Experimental UAV and composite studies have illustrated the ability for carbon-based airframe materials to create significant RF effects, in addition to findings that the conductive structure can be controlled to be part of an antenna system [24]-[26]. This helps ensure that antenna windows and RF testing are not presumed to be universal transparency and incompatibility requirements for the shell design, but rather stated design requirements. Thermal and fire requirements are mission- and zone-dependent. Regions near batteries, electronic speed controllers, motors, or high-current conductors require thermal screening and, where relevant, flammability verification. Polymer use is therefore evaluated locally rather than rejected categorically; the validation matrix below identifies applicable thermal and fire measurements [18].

Lifecycle interpretation should use a functional unit. High-energy-demand composites may be justified where mass reduction produces a demonstrable mission-hour or service-life benefit; repairable thermoplastics may be preferable when replaceability and lower-process burden dominate [10], [11].

2.3 Research Gap

Table 1. Literature streams and the gap addressed by the model.

Evidence stream	What it contributes	Remaining gap addressed in this paper
Material testing studies [1], [2], [4]-[6]	Tensile, flexural, impact, infill, aging, and frame-level evidence	Usually limited to one material/process family and not translated directly into shell-zone selection.
Topology/generative-design studies [3], [7]-[9]	Mass reduction and load-path optimization	Usually emphasize structural efficiency more than RF, fire, repair, and lifecycle integration.
Composite-laminate / aerospace evidence [10], [11], [24]-[26]	High specific stiffness and established aerospace use; lifecycle and electromagnetic behavior	Small-UAV decisions still require explicit repair, RF, lifecycle, and mission-zone treatment.
Standards and qualification protocols [12]-[18], [22], [23]	Repeatable methods for tensile, flexural, impact, UV, fire, and LCA measurement	Standards measure properties; they do not rank mission-specific shell architectures.
MCDA and materials-selection methods [19]-[21]	Transparent multi-attribute decision structures	Require explicit separation of measured data, engineering judgment, and uncertainty.

The problem is not a shortage of appropriate materials, but the absence of a systematic and uniform process of preliminary selection, which brings together and consolidates data on materials, calculation of structural performance, mission-critical weighting, risk management, and formal validation process.

3. Design Basis and Candidate-System Definition

This classification does not consider a lattice and a laminate as equivalent material forms. The ranking is a score of suitability of an architecture-role pair for the mission, not an overall list of materials. The PETG-CF lattice for this study is a screening level material-architecture class, and not a fully specified production geometry. The source dataset does not prescribe a specific lattice topology, cell size, relative density/infill percentage, wall/shell thickness, print orientation, fiber fraction of the filaments, the layer height or other manufacturing parameters. Hence these values are not introduced as part of this revision. Those parameters must be explicitly reported for any physical validation or claim of repeatability. Because of this, it is important to note that the PETG-CF ranking depends on the assumed architecture-level behavior and is not meant to be a qualification of a specific lattice design.

Table 2. Reference design basis used to bound the MCDA model.

Item	Definition
Platform class	Small- to medium-sized electric UAV shell; multirotor or compact fixed-wing shell regions.
Decision level	Preliminary material-architecture screening before full coupon, panel, and shell qualification.
Primary shell functions	Protection, local support, impact attenuation, vibration control, environmental resistance, RF compatibility, and repairability.
Excluded from ranking	Detailed aerodynamic shape optimization, motor-arm structural sizing, certified airworthiness qualification, and full cost accounting.
Decision output	Mission-bounded candidate ranking plus zone-specific architecture recommendation.
Validation output	Test matrix specifying measurable properties required before design release.

Table 3. Candidate systems grouped by architecture and shell function.

Class	Examples in the model	Primary shell role
Printable thermoplastic skins	PLA, ABS, PETG, ASA	Low-cost shells, weather skins, antenna covers, replaceable panels.
Short-fiber reinforced thermoplastics	PA-CF short-fiber	Semi-structural printed brackets, ribs, and stiffened local panels.
Continuous-fiber reinforced thermoplastics	CFF carbon-nylon	Motor bridges, ribs, inserts, and load-oriented reinforcement paths.
Composite laminates	CFRP laminate	High-stiffness load paths, premium skins, endurance-oriented structures.
Light metal inserts or local panels	Al 6061-T6, Mg AZ31	Threaded interfaces, heat spreaders, protected metal features.
Cellular crash architectures	PETG-CF lattice; PETG/ABS honeycomb	Sacrificial energy absorbers, corner modules, battery/camera protection zones.

4. Methodology

A weighted-sum MCDA model is used. The current weights are direct engineering reference weights and are not presented as Analytic Hierarchy Process (AHP) outputs because no pairwise-comparison matrix or consistency ratio was used. The total score of candidate i is:

$$S_i = \sum_{j=1}^m w_j x_{ij}, \quad \sum_{j=1}^m w_j = 1 \quad (1)$$

For measured benefit-type criteria, where larger values are preferred, a 1-5 normalized score can be computed as:

$$x_{ij} = 1 + 4 \left(\frac{m_{ij} - m_{j,\min}}{m_{j,\max} - m_{j,\min}} \right) \quad (2)$$

For cost-type or adverse criteria, where smaller values are preferred:

$$x_{ij} = 5 - 4 \left(\frac{m_{ij} - m_{j,\min}}{m_{j,\max} - m_{j,\min}} \right) \quad (3)$$

When directly comparable measurements are unavailable across all candidates, the model uses an evidence-coded engineering score. Such a score is not treated as measured data; it is assigned by the explicit rubric below and subjected to score uncertainty.

Table 4. Functional requirement decomposition for UAV shell architecture selection.

Requirement cluster	Engineering meaning	Primary measurable outputs
Mechanical support	Payload, battery, motor-interface, landing, and handling loads	Specific stiffness; specific strength; fatigue screening.
Impact protection	Hard landing, collision, corner strike, battery/camera protection	Peak force; absorbed energy; damage area; residual function.
Vibration/acoustic control	Motor excitation, sensor noise, camera stability	Natural frequencies; damping ratio; transmissibility.
Environmental resistance	UV, moisture, salt, dust, oils, agrochemicals, thermal cycles	Property retention after aging; coating adhesion; dimensional drift.
Thermal/fire safety	Battery proximity, motor/ESC heat, thermal-runaway exposure	HDT/thermal cycling; applicable flammability class; dripping behavior.
EMI/RF performance	GNSS, telemetry, Wi-Fi/control links, antenna placement	Signal attenuation; detuning; link-budget change.
Manufacturing and assembly	Printing, lay-up, machining, inserts, bonding, fastening	Tolerance; repeatability; tooling; unit cost; assembly complexity.
Lifecycle performance	Mass, replacement rate, manufacturing energy, recyclability	Functional-unit burden; replacement rate; end-of-life pathway.

Table 5. Auditable 1-5 scoring rubric.

Score	Interpretation	Operational rule
5	Excellent suitability	Direct experimental evidence or strong material consensus supports top-tier performance for the shell function.
4	High suitability	Performance is consistently strong but depends on process control, mission conditions, or local design measures.
3	Moderate suitability	Usable with design controls such as ribs, coatings, inserts, isolators, or hybridization.
2	Low-to-moderate suitability	The criterion is a design-control issue and requires substantial mitigation.
1	Low suitability	The criterion conflicts with ordinary shell requirements unless major redesign is introduced.

Table 6. Evidence traceability classes.

Class	Evidence type	Traceability condition	Use in scoring
E1	Directly comparable test data	Same or close specimen geometry, process, conditioning, and property unit.	Primary score input; quantitative normalization where appropriate.
E2	Comparable but non-identical data	Same material family/architecture but different printer, lay-up, infill, environment, or geometry.	Score input with explicit uncertainty.
E3	Consensus material behavior	Well-established material trend or standard engineering expectation.	Rubric score with conservative interpretation.
E4	Validation-planning criterion	Criterion is functionally required but insufficiently measured in the source set.	Not evidence of achieved performance; retained as a validation requirement and uncertainty source.

The E1-E4 code is not a performance code, but rather a code for the evidence's provenance. So a high score may still be of low confidence if they only have E2/E3 evidence, or evidence is an E4 entry and not proof of performance. No E1 score is claimed in the present manuscript because there was no common experimental campaign, candidate specific, done across all alternatives. This means that the score matrices in Appendix A are engineering screening matrices. Appendix C provides a criterion-by-candidate provenance matrix to ensure that each score can be easily identified as literature-comparable evidence (E2), engineering-consensus judgment (E3), or a validation-planning placeholder (E4). These classifications should be upgraded to E1 evidence, when project-specific tests are available. The reference weights are illustrative of the engineering prior for the bounded small-UAV case only, and not the result of a formal expert elicitation process. They deliberately highlight impact energy absorption, specific stiffness/strength and leave out environmental, RF, thermal/fire, manufacturing, repair and life cycle issues. For an applied project, these weights would be substituted with weights documented by the stakeholders or experts. Here, scenario analysis is performed to check if the

conclusions are mission dependent or not, but not to conclude a universal optimum.

Table 7. Reference weighting scheme for the bounded small-UAV shell case.

Criterion	Weight	Weight (%)
Specific stiffness	0.13	13
Specific strength	0.12	12
Impact energy absorption	0.14	14
Vibration/acoustic damping	0.08	8
Environmental resistance	0.10	10
Thermal/heat tolerance	0.07	7
EMI/RF compatibility	0.07	7
Flammability safety	0.06	6
Manufacturing feasibility / unit cost	0.08	8
Joining/assembly	0.05	5
Reparability	0.05	5
Lifecycle sustainability	0.05	5

Table 8. Scenario-specific weights used to test mission dependence.

Criterion	Reference	Crash/repair	Stiffness/load-path	RF-sensitive	Thermal/fire
Specific stiffness	0.13	0.09	0.22	0.08	0.08
Specific strength	0.12	0.08	0.20	0.07	0.08
Impact energy absorption	0.14	0.22	0.10	0.10	0.10
Vibration/acoustic damping	0.08	0.08	0.04	0.08	0.05
Environmental resistance	0.10	0.09	0.08	0.10	0.09
Thermal/heat tolerance	0.07	0.06	0.08	0.06	0.16
EMI/RF compatibility	0.07	0.06	0.04	0.22	0.06
Flammability safety	0.06	0.05	0.04	0.06	0.16
Manufacturing feasibility / unit cost	0.08	0.10	0.06	0.08	0.07
Joining/assembly	0.05	0.06	0.05	0.05	0.05
Reparability	0.05	0.08	0.03	0.05	0.04
Lifecycle sustainability	0.05	0.03	0.06	0.05	0.06

Deterministic one-way sensitivity varies each criterion weight by -20% and +20% and renormalizes the full weight vector to add up to one. This results

in 24 perturbation cases. Monte Carlo analysis does not perturb weights or scores. The score perturbation is: For each trial r .

$$x_{ij}^{(r)} = \text{clip}[x_{ij} + \varepsilon_{ij}^{(r)}, 1, 5], \quad \varepsilon_{ij}^{(r)} \sim \mathcal{N}(0, \sigma^2) \quad (4)$$

The base case uses $\sigma=0.18$ score points. This value is a modeling assumption rather than an empirically calibrated measurement-error estimate: it is 4.5% of the full 1-5 score range and approximately one-fifth of one ordinal score interval. To address wider uncertainty, additional stress tests use $\sigma=0.10$, 0.30, and 0.50. Weight vectors are sampled from:

$$\mathbf{w}^{(r)} \sim \text{Dirichlet}(\boldsymbol{\alpha}), \quad \alpha_j = \kappa w_j, \quad \kappa = 120 \quad (5)$$

Here $\kappa=120$ is the Dirichlet concentration parameter, so $E[w_j^r] = w_j$.

Here 20,000 trials are analyzed and the random seed is set to 20260914 for repeatability. The 95% Wilson binomial confidence interval is used for first rank probabilities. When the weights of the criteria are not known or are not certain, the use of Monte Carlo robustness analysis is well developed and common in MCDA [27]. The base model is complemented with weight-dispersion stress tests at weight-dispersion factors of 40 and 300, and with an evidence-class stress test where the score uncertainty is increased depending on how strong the traceability is (Appendix C). These uncertainty analyses are performed under a specific set of assumptions, are used to test the internal ranking stability and are not a substitute for laboratory qualification.

Table 9. Validation matrix for converting preliminary selection into an evidence-complete qualification campaign.

Domain	Protocol/standard	Measured outputs	Applicability/reporting rule
Tensile behavior	ASTM D638-22 / ISO 527 for polymers; ASTM D3039/D3039M-17(2025) for applicable oriented laminates	Ultimate strength, modulus, elongation, failure mode	Use the standard appropriate to material class; $n \geq 5$; report orientation, conditioning, print/lay-up parameters, and rate.
Flexural behavior	ASTM D790-25	Flexural modulus, flexural strength, failure mode	Report span, loading rate, specimen geometry, and conditioning.
Low-velocity impact	ASTM D7136/D7136M-25 for applicable	Peak force, absorbed energy, force-time curve,	D7136 is not transferred directly to printed lattice shells; use representative

	laminates; instrumented shell- representative drop test for printed shells/lattices	dent depth, damage area	support and impact conditions.
Compression after impact	ASTM D7137/D7137M-23 where laminate panels apply	Residual compressive strength	Use only for applicable laminate panels and report impact energy/damage state.
Modal response	Impact hammer or shaker modal test	Natural frequencies, damping ratio, transmissibility	Compare with motor excitation bands and camera/sensor requirements.
UV/weathering	ASTM G154-23 or equivalent	Mass/color change, tensile/flexural retention, cracking	Report irradiance, cycle, temperature, and exposure time.
Moisture/salt/chemical exposure	Mission-specific immersion, salt-fog, or chemical exposure followed by retesting	Moisture uptake, dimensional drift, property retention	Required for marine/coastal/agricultural missions; test conditions must match intended environment.
Thermal/fire response	Heat- deflection/thermal cycling; UL 94 where applicable	Dimensional stability, softening, burn rating, dripping	Required near batteries, ESCs, motors, and power electronics; UL 94 is a material flammability test, not a complete battery-fire qualification.
EMI/RF behavior	Antenna gain, RSSI, GNSS reception, S- parameters/link- budget tests with representative enclosure geometry	Signal attenuation, detuning, range impact	Required for conductive composite or metal- continuous shells; geometry and antenna spacing must be reported.
FEA correlation	Coupon-to-panel-to- shell model updating	Correlation of stiffness, mode shape, impact response, stress hot spots	Report boundary conditions, mesh convergence, constitutive models, and validation error.
Lifecycle assessment	ISO 14040/14044- compatible functional unit and inventory	kg CO ₂ -eq per shell or mission- hour; replacement rate; end-of-life path	Report system boundary, database, impact categories, and sensitivity assumptions.

Standards are applied as anchors of measurement only as they apply to the scope of the material/specimen class. Cellular printed architectures are not assumed to be valid by polymer-coupon and laminate standards. The separation ensures that the standards matrix is not perceived as automatic compliance or airworthiness certification.

5. Results

The high consideration of impact performance and manufacturing, repair, and balanced multi-functionality make PETG-CF lattice the first one. Carbon-nylon (CFF) and CFRP continue to be the best solution for specific load paths. The honeycomb hybrid is seen as sacrificial absorber instead of its own primary load path system.

Table 10. Reference small-UAV shell ranking after independent recalculation.

Rank	Material system	Weighted score / 5	Primary interpretation
1	PETG-CF lattice	3.758	Reference shell and crash-zone screening candidate.
2	CFF carbon-nylon	3.550	Load-path and rib screening candidate.
3	PETG/ABS honeycomb hybrid	3.500	Sacrificial absorber and RF-transparent crash-zone candidate.
4	CFRP laminate	3.431	High-stiffness load-path screening candidate.
5	ASA FDM	3.396	Outdoor skin/weather enclosure candidate.
6	PETG FDM	3.391	Repairable outdoor-shell candidate.
7	PA-CF short-fiber	3.347	Stiff printed semi-structural support.
8	Al 6061-T6	3.284	Threaded insert and local heat-spreader candidate.
9	ABS FDM	3.065	Serviceable secondary shell.
10	Mg AZ31	2.809	Specialized low-density metal candidate; explicit ignition/fire controls required.
11	PLA FDM	2.615	Indoor prototype/educational shell.

All the reference weighted scores were reproduced by an independent recalculation from Appendix A score matrices and Table 7 weights. The total weight is 1.000 and PETG-CF lattice (3.758) is the top 3, followed by CFF

carbon-nylon (3.550) and PETG/ABS honeycomb hybrid (3.500).

Reference small-UAV shell ranking

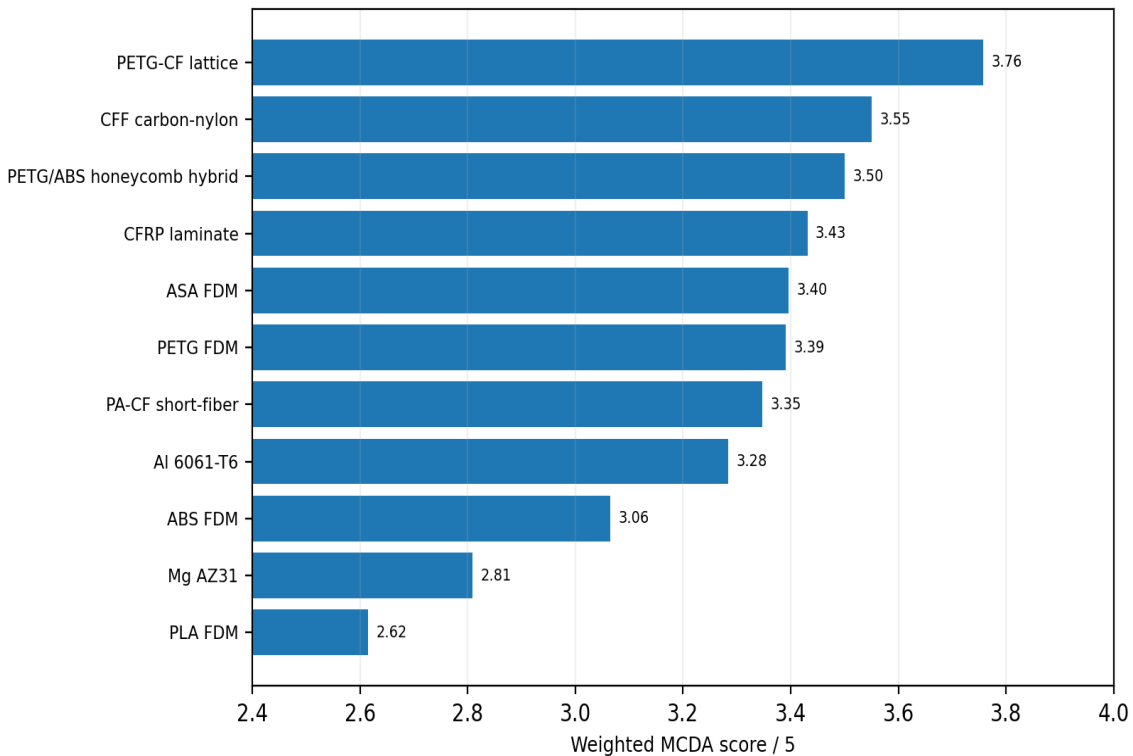


Figure 1. Recalculated reference weighted MCDA ranking.

Table 11. Recalculated scenario-specific top-three rankings.

Scenario	Rank 1	Rank 2	Rank 3
Reference small-UAV shell	PETG-CF lattice (3.758)	CFF carbon-nylon (3.550)	PETG/ABS honeycomb hybrid (3.500)
Crash/repair dominated	PETG-CF lattice (3.921)	PETG/ABS honeycomb hybrid (3.702)	PETG FDM (3.510)
Stiffness/load-path dominated	CFF carbon-nylon (3.899)	CFRP laminate (3.835)	PETG-CF lattice (3.706)
RF-sensitive enclosure	PETG/ABS honeycomb hybrid (3.755)	PETG-CF lattice (3.720)	ASA FDM (3.718)
Thermal/fire constrained	Al 6061-T6 (3.647)	PETG-CF lattice (3.474)	CFF carbon-nylon (3.425)

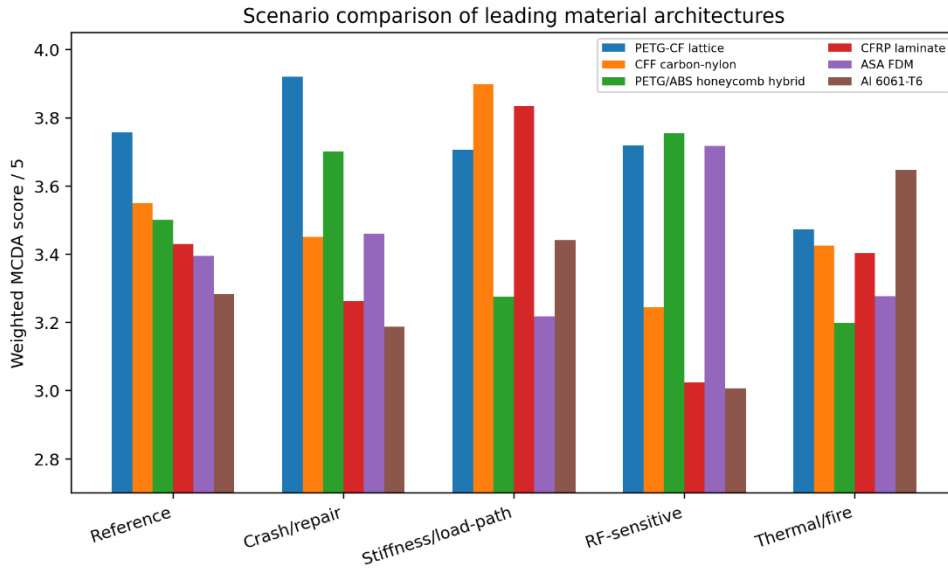


Figure 2. Scenario comparison confirms that the preferred architecture changes with mission emphasis.

All of the reference weighted scores were reproduced by independent recalculation from the score matrices in Appendix A and the weights in Table 7. The total of the weights is 1.000, with the top three being PETG-CF lattice (3.758), CFF carbon-nylon (3.550) and PETG/ABS honeycomb hybrid (3.500). The scenario results are a bounded screening result – not a universal material hierarchy. The materials with the highest ranking for stiffness/load-path behavior are CFF carbon-nylon; for RF-sensitive enclosure case, PETG/ABS honeycomb; for thermal/fire-constrained, Al 6061-T6. The model has undergone these changes as proof of the model's mission-bound nature and not a fixed material leaderboard.

Table 12. Mission-specific material-selection rules derived from the model.

Mission class	Dominant requirement	Recommended architecture	Design rule
Racing/training drones	Crash energy absorption, quick replacement, low mass	PETG-CF lattice shell with replaceable PETG/ABS honeycomb corner zones and CFF reinforcement at motor mounts	Prioritize sacrificial deformation and modular repair.
Aerial photography/survey	Vibration isolation, dimensional	ASA/PETG skin with damping pads; CFF ribs	Separate camera natural frequencies

	stability, camera protection	only where payload loads require stiffness	from motor excitation bands.
Marine/coastal inspection	Moisture, salt, UV, seal integrity, post-aging ductility	ASA/PETG weather shell with protective coating; higher-performance polymers only after aging validation	Retest tensile/flexural retention after UV/salt exposure.
Delivery/cargo UAVs	Payload load paths, battery safety, landing impact	CFF carbon-nylon or CFRP load frame with PETG/ABS honeycomb energy absorbers	Use controlled crush zones to reduce peak transmitted force.
Agricultural drones	Chemical exposure, mud, water, field repair	PETG/ASA replaceable panels with chemical-resistant coating and sealed fasteners	Design panels for washing, replacement, and coating renewal.
Long-endurance UAVs	Mass efficiency, stiffness, aerodynamic cleanliness, lifecycle burden	CFRP laminate or continuous-fiber optimized shell with early lifecycle screening	Use high-footprint composites only where mass saving translates into mission-hour benefit.
RF-sensitive compact UAVs	GPS/telemetry reliability and antenna integrity	RF-transparent PETG/ASA antenna windows integrated into conductive structures	Avoid uninterrupted conductive enclosures around antennas unless RF design is explicitly validated.
Thermal/fire-constrained zones	Battery, ESC, motor, or high-current proximity	Local Al 6061-T6 heat spreaders/shields/inserts with isolated polymer skins	Separate heat spreading from RF-transparent and crash-absorbing functions.

Table 13. One-way sensitivity summary.

Sensitivity output	Result
One-way perturbations tested	24
Reference top candidate	PETG-CF lattice
PETG-CF first-rank cases	24/24
Minimum margin to runner-up	0.170
Most competitive perturbation	Specific stiffness +20%
Closest runner-up in that perturbation	CFF carbon-nylon

Table 14. Monte Carlo first-rank probability; $N=20,000$, $\kappa=120$, $\sigma=0.18$, seed=20260914.

Material system	First-rank probability (%)	95% Wilson CI (%)
PETG-CF lattice	95.025	94.715-95.318
CFF carbon-nylon	4.045	3.781-4.327

CFRP laminate	0.510	0.420-0.619
PETG/ABS honeycomb hybrid	0.290	0.224-0.375
Al 6061-T6	0.060	0.034-0.105
ASA FDM	0.045	0.024-0.086
PETG FDM	0.025	0.011-0.059

Table 15. Wider score-uncertainty stress test.

Score uncertainty σ	PETG-CF first-rank probability (%)	CFF carbon-nylon (%)	PETG/ABS honeycomb (%)	CFRP laminate (%)
0.10	97.32	2.37	0.01	0.27
0.18	95.03	4.04	0.29	0.51
0.30	86.99	7.83	2.46	1.42
0.50	69.15	11.97	7.21	3.29

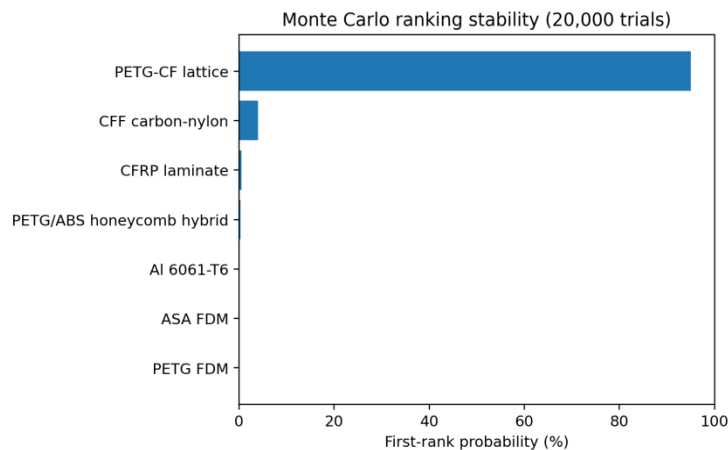


Figure 3. Monte Carlo ranking stability for the base uncertainty case (20,000 trials).

At the base uncertainty setting, PETG-CF lattice is first in 95.025% of simulations (95% CI 94.715-95.318%). The higher the uncertainty of the score, the lower the probability of it being the first rank. For example, with an uncertainty of 0.30 the probability of the score being a first rank is only 86.99%, and with 0.50 only 69.15%. The same applies to weight-dispersion stress testing: When $\kappa=40$ (significantly larger dispersion of Dirichlet weights), PETG-CF is first in 82.42% of the trials, when $\kappa=300$, it is first in 98.54% of the trials. A conservative evidence-aware stress test gives larger score perturbations for the lower-traceability classes (E2: $\sigma=0.22$, E3: $\sigma=0.38$, E4: $\sigma=0.65$; no E1 entries are claimed) and about 81.64% to PETG-CF, compared to 8.77% to CFF carbon-nylon and 4.75% to PETG/ABS honeycomb. These findings indicate a fairly stable but not a conclusive

reference preference when associating epistemic uncertainty with evidence quality. The complete assumptions and output are included in Appendix C.

Table 16. Criterion-level interpretation of leading material families.

Material system	Dominant strengths	Design-control issues
PETG-CF lattice	Impact absorption, manufacturability, modular repair, balanced shell role	Thermal/fire performance near batteries; local stiffness; score depends on lattice geometry that remains to be specified.
CFF carbon-nylon	Specific stiffness and strength along designed fiber paths	Fiber orientation, moisture conditioning, RF behavior, and repair complexity.
CFRP laminate	High structural efficiency and stiffness-to-mass ratio	RF attenuation/shielding, tooling cost, repair/recycling complexity, brittle-damage inspection.
PETG/ABS honeycomb hybrid	Sacrificial crash absorption and RF-transparent architecture potential	Not a primary load path without skins, ribs, or inserts.
ASA FDM	UV/weather resistance and exterior-skin function	Moderate stiffness; ribs/inserts needed at concentrated loads.
PETG FDM	Toughness, printability, RF transparency potential, repairability	Heat/fire and stiffness limits require design controls.
Al 6061-T6	Thermal spreading, threaded interfaces, recyclability	Density, vibration transmission, and RF shielding in continuous enclosures.
Mg AZ31	Low-density metal option	Corrosion protection, handling, and ignition/fire-risk controls are decisive; AZ31 is not treated as intrinsically nonflammable [28].

6. Discussion

The results support interpreting UAV outer-shell design as assignment of different material architectures to different shell roles rather than searching for one universally superior material. This makes polymers, continuous-fiber composites, laminates, metals, and cellular absorbers comparable at the functional level while preserving the distinction between their roles.

PETG-CF lattice leads only within the reference screening assumptions. It is not shown to possess greater primary structural integrity than CFF carbon-nylon or CFRP. Rather, its first-place reference score reflects the combination of impact, manufacturing, repair, and other criteria under the chosen weights. The explicit geometry limitation is important: a different lattice topology, relative density, print orientation, or fiber content could materially change the actual performance and therefore the score.

RF behavior should likewise be treated as a measured enclosure-level property. Carbon-fiber structures are conductive and can produce shielding or antenna detuning, but recent UAV research also shows that the structure can be deliberately integrated as an antenna when geometry and matching are controlled. The design implication is not that carbon fiber must always be excluded near antennas, but that antenna windows, separation, matching, and representative RF testing must be designed and verified.

Thermal and fire behavior is zone-specific. A polymer skin can remain suitable for weather protection, RF windows, or crash absorption while local regions near batteries, ESCs, motors, or high-current conductors receive thermal spacing, shielding, fire-performance verification, or metallic heat spreaders. The same caution applies to light metals: aluminum and magnesium should not be collapsed into one “metal = fire safe” category. Published aerospace-oriented work shows that AZ31 ignition/flame behavior depends strongly on geometry and test conditions and warrants explicit fire-risk control. Accordingly, the Mg AZ31 flammability screening score was conservatively set to 2.5 rather than the previous generic-metal value. Lifecycle conclusions should likewise be reported per functional unit rather than by manufacturing burden alone.

The independent recalculation is important because the MCDA arithmetic is now auditable: the reference weights sum to unity, all reference scores in Table 10 reproduce directly from Appendix A, and the scenario-specific top-three rankings reproduce from Table 8. This verification addresses numerical consistency without converting evidence-coded scores into experimental measurements.

7. Limitations

First, the score matrix combines heterogeneous evidence. It includes literature-supported behavior, comparable but non-identical material data, and engineering screening judgments; it is therefore not a database of measurements made on a common specimen set. E1-E4 coding is used to make this distinction explicit, but candidate-specific testing remains necessary.

Second, the reference and scenario weights are constructed engineering weights rather than values elicited from a formal expert panel. The results should therefore be interpreted as model demonstrations for bounded mission cases, not as stakeholder preference estimates.

Topology, cell size, relative density/infill, wall thickness, build orientation, filament grade, fiber fraction, and processing conditions all need to be determined prior to experimental replication/qualification. Fourth, Monte Carlo uncertainty assumes independent perturbations of the scores and of the weights as Gaussians. These are transparent and reproducible, but are not empirical error models. This choice of modeling is reflected in the wider- σ analysis. Lastly, the standards listed in Table 9 are anchors for measurement and validation. They are not to be interpreted as applying automatically to any architecture of a project, nor as providing certified airworthiness. Project specific coupon-, panel-, shell-, RF-, fire-, environmental-, modal-, FEA- and lifecycle validation for production use.

8. Conclusions

The new model features a transparent weighted-sum MCDA model, a clear 1-5 rubric, evidence traceability, scenario weights, deterministic sensitivity analysis and a reproducible Monte Carlo implementation. It does not make AHPs where no two-by-two consistency analysis is carried out. Based on the results of the independent recalculation, the bounded reference ranking is confirmed, with PETG-CF lattice in the first place (3.758/5). The outcome is conditional: CFF carbon-nylon/CFRP is a better option for stiffness dominated load paths, PETG/ABS honeycomb is a better choice for the enclosure scenario where RF effects are of interest, and Al 6061-T6 is a better option for the thermal/fire-constrained scenario. The updated uncertainty analysis indicates that the "reference ranking" is fairly stable when coupled with a reasonable level of uncertainty in the scores, but becomes less determinate as the level of uncertainty rises, and this result further supports the call for laboratory test data, as opposed to relying on a single first "rank" probability. The hybrid, zone-based shell design includes continuous fiber composite load paths where structural efficiency is needed, sacrificial CF or PETG/ABS crash zones, ASA/PETG weather skins, local metallic heat-spreading features, and explicitly validated RF transparent or RF-integrated zones. These are screening recommendations to be experimented prior to design release.

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Appendix A. Full MCDA Score Matrix

Scores use the 1-5 rubric in Table 5. The matrices are reproduced so the model can be recalculated when new laboratory or field data become available. The values are screening scores and must not be relabeled as measured data unless candidate-specific measurements exist.

Table A1. MCDA scores: mechanical, impact, damping, environmental, and thermal criteria.

Material system	Specific stiffness	Specific strength	Impact absorption	Vibration damping	Environmental resistance	Thermal tolerance
PLA FDM	2.0	2.0	2.0	3.0	1.5	1.5
ABS FDM	2.5	2.5	3.0	3.5	2.5	2.5
PETG FDM	2.5	2.8	3.5	3.5	3.8	2.5
ASA FDM	2.7	2.7	3.2	3.2	4.5	3.0
PA-CF short-fiber	4.0	3.8	3.2	2.8	3.0	3.2
CFF carbon-nylon	5.0	4.8	3.8	2.3	3.1	3.8
CFRP laminate	5.0	5.0	3.4	2.0	4.0	4.0
Al 6061-T6	3.5	3.4	2.8	1.8	3.5	4.5
Mg AZ31	3.2	3.3	2.7	1.8	2.2	4.0
PETG-CF lattice	3.7	3.6	5.0	3.4	3.8	2.8
PETG/ABS honeycomb hybrid	2.8	2.8	4.8	3.8	3.4	2.3

Table A2. MCDA scores: RF, fire, manufacturing, assembly, repair, and lifecycle criteria.

Material system	EMI/RF	Flammability	Manufacturing	Joining/assembly	Reparability	Lifecycle
PLA FDM	5.0	1.5	5.0	3.0	4.0	3.0
ABS FDM	5.0	2.0	4.0	3.5	4.0	3.0
PETG FDM	5.0	2.0	4.5	3.8	4.2	3.5
ASA FDM	5.0	2.2	4.0	3.8	4.0	3.3
PA-CF short-fiber	3.5	2.5	3.5	3.5	3.5	3.0
CFF carbon-nylon	2.5	2.8	3.3	3.0	2.5	3.0

Material system	EMI/RF	Flammability	Manufacturing	Joining/assembly	Reparability	Lifecycle
CFRP laminate	1.8	3.4	2.5	2.5	2.0	2.2
Al 6061-T6	1.5	5.0	3.0	4.0	3.0	4.5
Mg AZ31	2.0	2.5	2.5	3.2	2.5	4.0
PETG-CF lattice	3.7	2.2	4.2	3.8	4.2	3.4
PETG/ABS honeycomb hybrid	5.0	1.8	4.0	3.5	4.0	3.4

Table A3. Evidence anchors and conservative provenance interpretation by candidate family.

Candidate family	Primary evidence anchors	Conservative provenance interpretation
PETG-CF / printed carbon-fiber systems	[1]-[3]	Mechanical/process behavior: E2 where geometries differ; non-measured RF/fire/environmental items: E3-E4 until tested.
Continuous-fiber carbon-nylon	[4]	Load-path mechanical behavior: E2; other shell criteria generally E3-E4 unless project-specific data are added.
CFRP laminate	[10], [11], [24]-[26]	Structural/lifecycle/RF behavior supported by literature, but candidate-specific lay-up remains E2 unless directly matched.
Honeycomb/cellular absorbers	[6] plus architecture literature [7]-[9]	Impact/crush behavior: E2; other criteria E3-E4 unless directly measured.
Printable thermoplastics	[1], [5], [9]	Mechanical/environmental trends mostly E2-E3; candidate-specific fire/RF/aging must be measured.
Metals	Engineering consensus; Mg ignition literature [28]	Architecture-role judgments are primarily E3. Al and Mg are not assigned identical fire behavior; Mg AZ31 requires explicit ignition/fire-risk verification. Mission-specific RF, vibration, corrosion, and thermal integration require direct testing.

Appendix B. One-Way Sensitivity Output

Table B1. Full one-way sensitivity output for $\pm 20\%$ criterion perturbation with renormalization.

Criterion	Change	Top material	Top score	Margin to runner-up	Runner-up
Specific stiffness	-20%	PETG-CF lattice	3.760	0.241	PETG/ABS honeycomb hybrid
Specific stiffness	+20%	PETG-CF lattice	3.757	0.170	CFF carbon-nylon
Specific strength	-20%	PETG-CF lattice	3.762	0.243	CFF carbon-nylon
Specific strength	+20%	PETG-CF lattice	3.754	0.175	CFF carbon-nylon
Impact energy absorption	-20%	PETG-CF lattice	3.722	0.179	CFF carbon-nylon
Impact energy absorption	+20%	PETG-CF lattice	3.792	0.235	CFF carbon-nylon
Vibration/acoustic damping	-20%	PETG-CF lattice	3.764	0.193	CFF carbon-nylon
Vibration/acoustic damping	+20%	PETG-CF lattice	3.752	0.222	CFF carbon-nylon
Environmental resistance	-20%	PETG-CF lattice	3.757	0.198	CFF carbon-nylon
Environmental resistance	+20%	PETG-CF lattice	3.759	0.218	CFF carbon-nylon
Thermal/heat tolerance	-20%	PETG-CF lattice	3.772	0.225	CFF carbon-nylon
Thermal/heat tolerance	+20%	PETG-CF lattice	3.745	0.191	CFF carbon-nylon
EMI/RF compatibility	-20%	PETG-CF lattice	3.759	0.194	CFF carbon-nylon
EMI/RF compatibility	+20%	PETG-CF lattice	3.757	0.222	CFF carbon-nylon
Flammability safety	-20%	PETG-CF lattice	3.777	0.218	CFF carbon-nylon
Flammability safety	+20%	PETG-CF lattice	3.740	0.198	CFF carbon-nylon
Manufacturing feasibility / unit cost	-20%	PETG-CF lattice	3.751	0.197	CFF carbon-nylon

Criterion	Change	Top material	Top score	Margin to runner-up	Runner-up
Manufacturing feasibility / unit cost	+20%	PETG-CF lattice	3.765	0.219	CFF carbon-nylon
Joining/assembly	-20%	PETG-CF lattice	3.758	0.202	CFF carbon-nylon
Joining/assembly	+20%	PETG-CF lattice	3.758	0.214	CFF carbon-nylon
Reparability	-20%	PETG-CF lattice	3.754	0.193	CFF carbon-nylon
Reparability	+20%	PETG-CF lattice	3.762	0.223	CFF carbon-nylon
Lifecycle sustainability	-20%	PETG-CF lattice	3.762	0.206	CFF carbon-nylon
Lifecycle sustainability	+20%	PETG-CF lattice	3.754	0.210	CFF carbon-nylon

Appendix C. Score-Level Evidence Traceability and Robustness Audit

The following matrices make the provenance of every screening score explicit. No E1 entries are claimed because the candidates were not tested in a common project-specific experimental campaign. E2 denotes literature-comparable but non-identical evidence; E3 denotes engineering-consensus judgment; E4 denotes a criterion retained for validation planning where candidate-specific evidence is presently insufficient.

Table C1a. Score-level evidence classes: mechanical, impact, vibration, environmental, and thermal criteria.

Material system	Stiffness	Strength	Impact	Vibration	Environment	Thermal
PLA FDM	E3	E3	E3	E3	E3	E4
ABS FDM	E3	E3	E3	E3	E3	E4
PETG FDM	E3	E3	E3	E3	E3	E4
ASA FDM	E3	E3	E3	E3	E3	E4
PA-CF short-fiber	E2	E2	E2	E3	E3	E3
CFF carbon-nylon	E2	E2	E2	E3	E3	E3
CFRP laminate	E2	E2	E3	E3	E3	E3
Al 6061-T6	E3	E3	E3	E3	E3	E3
Mg AZ31	E3	E3	E3	E3	E3	E3
PETG-CF lattice	E2	E2	E2	E2	E3	E4

Material system	Stiffness	Strength	Impact	Vibration	Environment	Thermal
PETG/ABS honeycomb hybrid	E3	E3	E2	E3	E3	E4

Table C1b. Score-level evidence classes: RF, fire, manufacturing, joining, repair, and lifecycle criteria.

Material system	EMI/RF	Fire	Manufacturing	Joining	Repair	Lifecycle
PLA FDM	E3	E4	E2	E3	E3	E3
ABS FDM	E3	E4	E2	E3	E3	E3
PETG FDM	E3	E4	E2	E3	E3	E3
ASA FDM	E3	E4	E2	E3	E3	E3
PA-CF short-fiber	E3	E4	E2	E3	E3	E3
CFF carbon-nylon	E3	E4	E2	E3	E3	E3
CFRP laminate	E2	E3	E3	E3	E3	E2
Al 6061-T6	E3	E3	E3	E3	E3	E3
Mg AZ31	E3	E3	E3	E3	E3	E3
PETG-CF lattice	E3	E4	E2	E3	E3	E3
PETG/ABS honeycomb hybrid	E3	E4	E3	E3	E3	E3

Table C2. Evidence-class uncertainty scales used only for the conservative robustness stress test.

Evidence class	Score perturbation σ	Interpretation
E1	0.10	Directly comparable project-specific measurement; none claimed here.
E2	0.22	Comparable published evidence with non-identical geometry/process/conditioning.
E3	0.38	Engineering-consensus or well-established trend without matched test data.
E4	0.65	Validation-planning placeholder; candidate-specific evidence insufficient.

The σ values in Table C2 are deliberately conservative modeling assumptions, not measured error standard deviations. Their purpose is to test whether lower-traceability cells are allowed to vary more widely than better-supported cells.

Table C3. Weight-dispersion stress test at fixed score uncertainty $\sigma=0.18$ (20,000 trials; seed=20260914).

Dirichlet κ	PETG-CF first (%)	CFF first (%)	PETG/ABS first (%)	CFRP first (%)
40	82.42	10.29	1.50	3.33
120	95.03	4.05	0.29	0.51
300	98.54	1.35	0.07	0.04

Table C4. Evidence-aware first-rank probabilities (20,000 trials; $\kappa=120$; class-dependent σ ; seed=20260914).

Material system	First-rank probability (%)
PETG-CF lattice	81.64
CFF carbon-nylon	8.77
PETG/ABS honeycomb hybrid	4.75
CFRP laminate	2.03
ASA FDM	1.19
PETG FDM	1.05
Al 6061-T6	0.44
PA-CF short-fiber	0.15
PLA / ABS / Mg AZ31	0.00

Reproduction sequence. (1) Read the 11 x 12 score matrix from Tables A1-A2 in the listed criterion order. (2) Multiply each candidate row by the normalized reference or scenario weight vector and sum to obtain the deterministic weighted score. (3) For one-way sensitivity, change one criterion weight by $\pm 20\%$ and renormalize the complete vector to unity. (4) For each Monte Carlo trial, draw the weight vector from Dirichlet(κw), perturb each score by a zero-mean normal variable, clip scores to [1,5], recompute all candidate totals, and record the first-ranked candidate. (5) Repeat for $N=20,000$ trials with seed 20260914. (6) For the evidence-aware stress test, replace the common σ by the class-specific values in Table C2.

Table-1: Some international and Arab codes specify reinforced concrete with a maximum aggregate size of 20 mm and a compressive strength of more than 25 N/mm²

Code of design [17] 1997	IS 456:2000	8110: Part 1:1985	ACI 318- 2011	Limits
0.42	0.45	0.45	0.4	Water to cement ratio (max limit)
35 for walls and tiles 0.4 for the rest	50	50	50 for walls and tiles 62 for the rest	(mm) Concrete cover (min limit)

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