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A System Safety Engineering Framework for Non-Invasive Sensor Integration in Commercial Construction Safety Helmets

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ABSTRACT

The integration of sensing and communication technologies into commercial safety helmets requires consideration of physical compatibility, safety constraints, and functional interfaces before prototype development. This study developed a system safety engineering framework for the non-invasive integration of sensors into commercial construction safety helmets. Design Science Research (DSR) Requirements Engineering, Systems Engineering, and VDI 2221 were combined to structure operating scenarios, requirements, technology selection, physical-integration constraints, architectural development, and verification priorities. Ten commercial helmet models were comparatively assessed using seven weighted compatibility criteria, while twelve technological alternatives were evaluated through an eleven-criterion multicriteria procedure. The resulting architecture comprised eight functional subsystems addressing helmet wearing, chin-strap status, inertial events, local processing, communication, identification, alerts, and energy management. The mean conceptual compatibility score was 3.75/5; C02 obtained 4.25/5 and was prioritized for subsequent model-specific development, whereas the remaining configurations were classified as conditional. Energy calculations indicated that the 72 h design target was compatible with the eco and nominal operating assumptions but not with intensive operation; these values represent design estimates rather than measured battery autonomy. Content validity was assessed by five judges, yielding a mean Aiken's V of 0.9222, with item-level values from 0.8667 to 1.0000; confidence intervals were retained in the interpretation to reflect the uncertainty associated with the panel size. A multidisciplinary technical review further refined requirements concerning suspension clearance, removable fastening, battery protection, wiring, mass distribution, and maintainability. The proposed framework establishes a traceable pre-prototype engineering baseline for model-specific development and subsequent experimental verification without assuming universal physical compatibility or preservation of certified helmet performance.

1. INTRODUCTION

Construction activities expose workers to falling objects, impacts, moving equipment, falls, and other hazards capable of causing head injuries. Safety helmets therefore constitute a fundamental component of personal protective equipment (PPE) in construction environments [1-3]. Their protective function, however, depends not only on the mechanical characteristics of the helmet but also on correct use, appropriate fit, fastening, maintenance, and compatibility with other protective accessories.

Recent developments in Smart PPE have expanded the role of conventional protective equipment through the incorporation of sensors, embedded processing, wireless communication, identification, and alert functions. Smart helmets have consequently been investigated for worker localization, environmental monitoring, fall and impact detection, physiological monitoring, proximity warning, and verification of PPE use [4-13]. These developments demonstrate the potential of sensing and Internet of Things technologies to provide information that is not available from conventional passive PPE.

Nevertheless, the technological feasibility of a sensor or communication module does not by itself establish its suitability for integration into a commercial safety helmet. Helmets differ in shell geometry, suspension systems, ventilation openings, adjustment mechanisms, accessory interfaces, internal clearances, and available external surfaces. Added components may also introduce mass, wiring, rigid contact areas, maintenance requirements, or interference with existing helmet functions. Consequently, a sensing solution that is technically functional as an electronic system cannot automatically be assumed to be physically compatible with different commercial helmet configurations.

This issue is particularly relevant when integration is intended to be non-invasive. Drilling, cutting, permanent deformation, or poorly controlled attachment of components may alter the original helmet configuration. Even when the shell itself remains unmodified, inappropriate placement may interfere with suspension clearance, adjustment, ventilation, accessories, inspection, or user interaction with the PPE. Sensor integration should therefore be preceded by explicit analysis of requirements, interfaces, physical restrictions, and verification needs.

Previous smart-helmet studies have primarily demonstrated implemented sensing functions, communication architectures, wearable monitoring systems, or detection algorithms [7, 10-13]. These approaches provide important evidence concerning the technical feasibility of Smart PPE. However, comparatively less attention has been given to the engineering decisions that should precede prototype construction when a common sensing architecture is considered across heterogeneous commercial helmet models.

Accordingly, the research gap addressed in this study is not the absence of sensing technologies applicable to safety helmets. Rather, it concerns the need for a traceable pre-prototype engineering procedure that links operating scenarios, monitoring needs, requirements, candidate technologies, subsystems, physical integration zones, safety-related constraints, and subsequent verification activities without assuming universal mechanical compatibility.

To address this gap, this study develops a system safety engineering framework for the non-invasive integration of sensors into commercial construction safety helmets. The framework combines Design Science Research (DSR), Requirements Engineering, Systems Engineering, and VDI 2221 to structure requirements derivation, multicriteria technology selection, helmet compatibility analysis, energy estimation, architectural development, and technical review [14-18].

Ten commercially available helmet models with different geometries, ventilation configurations, suspension systems, adjustment mechanisms, and accessory interfaces were considered to examine the applicability of a common reference architecture under heterogeneous integration conditions.

The proposed architecture addresses eight operating conditions: helmet not worn, unfastened chin strap, abnormal helmet position, insufficient fit, acceleration compatible with a possible impact event, sudden movement, communication loss, and critical energy level. These conditions are associated with functional subsystems covering helmet-wearing detection, chin-strap monitoring, inertial sensing, local processing, wireless communication, identification, alert generation, and energy management.

The objective of this study is to develop and technically evaluate a traceable system safety engineering framework for non-invasive sensor integration in commercial construction safety helmets, establishing the requirements, technological alternatives, architectural relationships, physical-integration constraints, and verification priorities required before prototype development.

The contribution is threefold. First, the framework establishes traceability from operating scenarios to monitoring needs, requirements, functions, technologies, subsystems, integration zones, constraints, and verification activities. Second, it provides a structured procedure for comparing the conceptual compatibility of a reference sensing configuration across heterogeneous commercial helmet models while preserving the provenance of documentary, measured, and calculated evidence. Third, it differentiates potential, optional, and restricted integration zones before prototype construction, allowing unresolved safety and compatibility requirements to remain explicitly identified for subsequent verification.

The proposed framework should therefore be interpreted as a pre-prototype engineering baseline rather than as a validated smart-helmet implementation. Its purpose is to structure and justify the decisions required before detailed electronic and mechanical development and subsequent experimental assessment.

The remainder of this paper is organized as follows. Section 2 describes the methodological framework, information sources, requirement definition, multicriteria technology selection, compatibility assessment, architectural development, energy estimation, and technical review. Section 3 presents the compatibility, technology-selection, energy, architecture, content-validity, technical-review, and traceability results. Section 4 discusses their implications and limitations, and Section 5 presents the conclusions and subsequent development requirements.

2. MATERIALS AND METHODS

2.1 Research design and methodological framework

This study was conducted as applied research focused on conceptual technological development, using a non-experimental design and a descriptive-propositional scope. Its purpose was to develop and technically examine a system safety engineering framework for the non-invasive integration of sensors into commercial safety helmets used in construction. The study did not seek to establish causal relationships or evaluate the performance of an implemented device. Instead, it focused on defining a traceable architectural solution to support subsequent detailed design, prototyping, and experimental validation.

The unit of analysis was the conceptual integration architecture, understood as the structured set of operating scenarios, monitoring needs, requirements, functions, candidate technologies, subsystems, interfaces, information flows, operating states, installation zones, and safety-related constraints. The research artifacts therefore consisted of functional, logical, and physical representations rather than newly manufactured helmets or electronic devices.

The study addressed conceptual architecture development and technical evaluation. Hardware implementation, prototype construction, and physical performance testing were reserved for subsequent development stages. Accordingly, the outcomes reported in this study comprise engineering design decisions, compatibility assessments, architectural representations, and multidisciplinary technical review results.

DSR provided the overall methodological structure through problem identification, definition of objectives, solution design, conceptual demonstration, technical evaluation, and communication of results [16]. Requirements Engineering was used to transform operational needs into functional and non-functional requirements. Their formulation followed principles of clarity, singularity, and traceability consistent with ISO/IEC/IEEE 29148:2018 [15].

Systems Engineering was applied to decompose the solution into interacting subsystems, establish inputs, processing functions, outputs and interfaces, and maintain

correspondence between operational needs and architectural elements. VDI 2221 complemented this approach through task clarification, functional decomposition, generation of technological alternatives, evaluation of solution principles, and conceptual configuration [14, 17, 18].

The procedure comprised seven phases:

(1) identification of the engineering problem and operating scenarios;
(2) derivation of monitoring needs and system requirements;
(3) generation and multicriteria comparison of technological alternatives;
(4) documentary and physical characterization of the helmets;
(5) quantitative compatibility assessment;
(6) development of the functional, logical, and physical architectures; and
(7) content validity assessment, multidisciplinary technical review, refinement, and change control.

The separation of helmet characterization from quantitative compatibility assessment ensured that physical and documentary attributes were established before assigning criterion-level scores. Likewise, architectural development was completed before content validity and multidisciplinary technical review so that the specialists evaluated a defined and traceable engineering artifact.

Figure 1 summarizes the methodological sequence and the general traceability chain used to maintain consistency among design decisions.

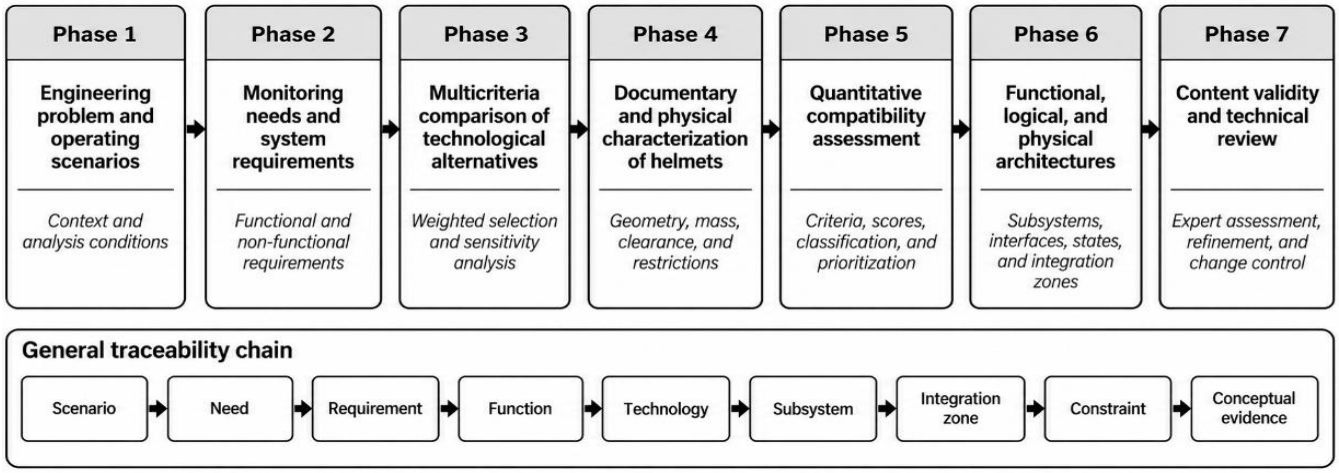

Figure 1. Methodological procedure and traceability chain used to develop and evaluate the conceptual architecture
Note: The procedure integrates Design Science Research (DSR), Requirements Engineering, Systems Engineering, and VDI 2221 and remains at the conceptual design level.

2.2 Information sources and selection of commercial helmets

The information sources comprised peer-reviewed publications, literature reviews, technical standards, manufacturer manuals, commercial catalogs, and technical datasheets for helmets and electronic components. Manufacturer documentation was prioritized for component-specific parameters such as dimensions, operating modes, current consumption, communication characteristics, and operating conditions [19-22]. The subsequent content-validity assessment was based on Aiken's V [23], as detailed in Section 2.7.

The commercial safety helmet models considered in the compatibility analysis are summarized in Table 1.

The information was classified according to its provenance as documentary, directly measured, calculated, or design-assumption data. Documentary values were extracted from technical datasheets, manuals, catalogs, standards, and scientific publications. Directly measured values were obtained from the physical characterization of C01 and C02. Calculated values resulted from mathematical operations performed using explicitly identified inputs, whereas design assumptions were limited to parameters required for the energy and integration analyses.

For reproducibility, the provenance of each helmet parameter used in the compatibility assessment was recorded individually. Manufacturer and model, geometry, ventilation, suspension, declared mass or dimensions when available, accessory interfaces, declared standard or certification, manufacturer source, consultation date, and evidence type were retained in the analysis matrix. A documentary value was not replaced by an estimated physical value when the manufacturer did not report that parameter.

This classification preserved information provenance and prevented documentary specifications, direct measurements, and calculated design estimates from being treated as equivalent evidence. The ten helmet references were used in the documentary comparison, whereas direct dimensional, mass, and clearance measurements were performed only for C01 and C02.

Characterization focused on attributes relevant to conceptual integration: external geometry, declared helmet mass, ventilation configuration, suspension, rear adjustment mechanism, internal clearance, accessory interfaces, chin-strap configuration, potentially usable external surfaces, and restrictions affecting removable fastening.

For C01 and C02, mass, relevant dimensions, and available clearance were measured in three repetitions under the same measurement procedure. The arithmetic mean of the three repetitions was used in the compatibility calculations. Measurements were recorded using consistent units, and the original repetitions were retained to preserve traceability between the physical observations and the values employed in the scoring matrix.

Table 1. Commercial safety helmet models considered in the compatibility analysis

Code	Manufacturer and Model	Geometry	Ventilation	Suspension	Source
C01	MSA V-Gard Cap Style Fas-Trac III	Standard brim	Non-vented	4-point	MSA official product documentation [24]
C02	MSA V-Gard Full Brim Fas-Trac III	Full brim	Non-vented	4-point	MSA official product documentation [25]
C03	MSA V-Gard 500 Non-Vented Fas-Trac III	Short brim	Non-vented	4-point	MSA official product documentation [26]
C04	3M SecureFit X5000 Series	Climbing style	Vented	6-point	3M official product documentation [27]
C05	3M SecureFit X5500 Series	Short brim	Version-dependent	4-point	3M official product documentation [28]
C06	Honeywell Fibre-Metal E1RW Full Brim	Full brim	Non-vented	8-point	Honeywell official product documentation [29]
C07	Delta Plus QUARTZ UP IV	Micro brim	Vented	8-point	Delta Plus official product documentation [30]
C08	JSP EVO3 Micro Peak Wheel Ratchet Vented	Micro brim	Vented	6-point	JSP Safety official product documentation [31]
C09	Portwest PS54 Endurance Plus Hard Hat	Short brim	Non-vented	6-point	Portwest official product documentation [32]
C10	Portwest PS53 Height Endurance Helmet	Work-at-height style	Non-vented	6-point	Portwest official product documentation [33]

No drilling, cutting, sanding, deformation, or material removal was considered as part of the proposed integration strategy. Furthermore, the apparent availability of a surface was not interpreted as authorization for installation. Dimensions, tolerances, clearances, and candidate integration zones must therefore be physically verified on prioritized helmet models before developing final supports, enclosures, or wiring routes.

2.3 Definition of operating scenarios, needs, and requirements

Eight operating scenarios associated with helmet use and functional continuity of the proposed system were defined:

- •helmet not worn;
- •chin strap unfastened;
- •abnormal helmet position;
- •insufficient fit;
- •acceleration compatible with a possible impact event;
- •sudden movement;
- •communication loss; and
- •critical energy level.

For each scenario, the operating condition, monitoring need, potentially observable variable, technological function, associated subsystem, and verification required during subsequent development stages were documented. Monitoring needs were established before selecting individual sensing technologies to avoid assuming a direct relationship between a hazardous condition and a particular sensor.

For the helmet-not-worn scenario, the monitoring need was to represent the absence of proximity between the head and the internal region of the helmet. For the unfastened chin-strap scenario, the requirement was to identify fastening status without modifying the original function of the strap. Abnormal helmet positioning was associated with changes in orientation relative to a reference condition. Acceleration compatible with a possible impact and sudden movement was treated as dynamic events requiring data acquisition. However, acceleration alone was not considered sufficient evidence to confirm an impact, fall, or injury. The architecture was therefore required only to record potentially relevant dynamic information for subsequent evaluation using experimentally established thresholds.

Communication loss was defined as a degraded operating state rather than complete system failure. Local sensing, processing, alerting, and event storage were therefore required to remain conceptually available following interruption of the BLE link. Similarly, a critical energy condition required monitoring of available energy and generation of an alert before loss of operation.

Insufficient fit was treated as a conditional scenario because helmet fit may depend on pressure, force, displacement, distance, and relative stability among the user's head, suspension, and adjustment system. No individual variable was assumed to determine proper or improper fit without experimental evidence. Consequently, the architecture retained the possibility of incorporating an additional sensing principle rather than assigning this function exclusively to the proximity sensor.

Functional requirements included helmet-wearing detection, chin-strap state identification, orientation estimation, recording of dynamic events, communication-link supervision, battery monitoring, equipment identification, alert generation, and temporary event storage.

Non-functional requirements addressed structural preservation, removable integration, low energy consumption, mass distribution, modularity, maintainability, protected wiring, inspectability, compatibility with helmet accessories, and prevention of rigid contact between integrated components and the user's head.

Requirements were formulated using the pattern "The architecture shall…" to define a single capability or constraint that could subsequently be verified. Major safety-related restrictions included maintaining functional clearance, avoiding obstruction of ventilation openings and accessory interfaces, preventing interference with the suspension and adjustment mechanisms, avoiding rigid batteries or enclosures in contact with the head, and not using adhesives as the sole retention mechanism.

The eight scenarios were used as inputs for requirements derivation and were not interpreted as eight experimentally resolved detection functions. Direct functional resolution was established at the architectural level for chin-strap status, communication loss, and critical energy level. The remaining scenarios require calibration, combined sensing, decision thresholds, or physical verification during subsequent development.

2.4 Multicriteria selection of technologies

Candidate technologies were identified from the functions

and requirements derived in the previous phase. The alternatives included time-of-flight (ToF) sensors, capacitive sensors, force-sensitive resistors, Hall sensors, reed switches, accelerometers, inertial measurement units, Bluetooth Low Energy (BLE), LoRa, Near-Field Communication (NFC), Ultra-Wideband (UWB), low-power microcontrollers, and visual and acoustic actuators.

The consolidated decision matrix comprised 12 technological alternatives evaluated using 11 criteria. Related sensing or actuation principles were grouped according to the function evaluated in the matrix so that each row represented one comparable technological alternative.

A weighted-sum model was used to compare technological alternatives:

$$P_i = \sum_{j=1}^{m} w_j \, x_{ij}$$

where, P_i is the score of alternative i, w_j is the weight assigned to criterion j, x_{ij} is the rating of alternative i with respect to criterion j, and m is the total number of criteria.

Each alternative was rated on a five-point scale, where higher values represented greater suitability. Eleven criteria were considered: functional relevance, form-factor suitability, power consumption, reliability, ease of adoption, maintainability, weight and size, environmental resilience, cost, accessibility, and scalability.

The reference weighting scheme was established as follows: functional relevance, 0.20; form-factor suitability, 0.12; power consumption, 0.12; reliability, 0.10; ease of adoption, 0.10; maintainability, 0.08; weight and size, 0.08; environmental resilience, 0.07; cost, 0.06; accessibility, 0.04; and scalability, 0.03.

The weights summed to 1.00. For each alternative, the criterion rating was multiplied by its corresponding weight, and the resulting products were added to obtain a score ranging from 1.00 to 5.00. The complete criterion-level ratings and weighted results are reported in the technology-selection results table.

These weights constituted internal engineering decision rules rather than regulatory or experimentally validated thresholds. Functional relevance received the greatest weight because an alternative first had to satisfy the intended monitoring function before secondary considerations such as cost or scalability could justify its selection.

A sensitivity analysis was performed using two alternative weighting scenarios. The first increased the relative importance of power consumption, whereas the second increased the importance of form-factor suitability. The purpose was to determine whether substantial changes in the most integration-sensitive criteria altered the ranking of candidate technologies.

For each sensitivity scenario, the modified weights were normalized to sum to 1.00 and the scores of all twelve alternatives were recalculated. The resulting scores and category changes are reported explicitly in the Results section rather than only describing the overall ranking as stable. This distinction allows alternatives located close to the 3.40 and 4.20 classification thresholds to be identified when a change in weighting modifies their category.

For the reference model, alternatives obtaining scores of at least 4.20 were classified as Priority, those scoring from 3.40 to 4.19 as Conditional, and those below 3.40 as Not prioritized.

2.5 Compatibility assessment and architectural development

Conceptual compatibility between the reference configuration and each commercial helmet was evaluated using seven criteria: dimensional availability, volumetric occupancy, increase in helmet mass, internal clearance, ventilation, interference with the rear adjustment mechanism, and compatibility with accessories.

Dimensional availability, volumetric occupancy, mass increase, internal clearance, interference with the adjustment mechanism, and accessory compatibility were each assigned a weight of 0.15. Ventilation received a weight of 0.10 because ventilation openings were not present in all evaluated models.

The volumetric-occupancy and relative mass-increase indicators were calculated as follows:

$$O_i = \frac{V_{module}}{V_{available,i}} \times 100$$

$$M_i = \frac{m_{added}}{m_{helmet,i}} \times 100$$

where, O_i is the estimated volumetric occupancy for helmet i, V_{module} is the volume required by the reference module, $V_{available,i}$ is the available integration volume, M_i is the relative mass increase, m_{added} is the mass of the proposed components, and $m_{helmet,i}$ is the original helmet mass.

For the reference configuration, component dimensions and masses were tabulated individually before calculating the integration indicators. The total added mass was 25.9 g, and the summed geometric volume of the documented electronic components was 15,644.5 mm³. The geometric component volume was not treated as equivalent to the installation-envelope volume. Volumetric occupancy was calculated using the design envelope assigned to the candidate integration zone because the physical installation must accommodate component arrangement, enclosure space, wiring, and support requirements. Component geometric volume, module-envelope volume, and available helmet-zone volume were therefore maintained as three distinct quantities throughout the calculations.

For C01 and C02, the available posterior-zone dimensions used to establish $V_{available,i}$ were derived from the triplicate direct measurements described in Section 2.2. The arithmetic means of the corresponding measurements were used only after the three original observations had been retained. The Results section reports the raw measurements, available-volume inputs, module-envelope input, helmet mass, and resulting occupancy and mass-increase calculations so that the derived indicators can be independently recalculated. For C03–C10, documentary information was retained as documentary evidence and was not presented as direct physical verification.

The compatibility score was calculated as:

$$C_i = \sum_{j=1}^{7} w_j \, y_{ij}$$

where, C_i represents the compatibility score of helmet i, w_j is the weight assigned to criterion j, and y_{ij} is the rating assigned to helmet i for criterion j.

Criterion-level ratings were assigned on a five-point scale, with higher scores indicating greater compatibility and lower expected interference. The seven weighted contributions were added to produce a compatibility score ranging from 1.00 to 5.00 for each helmet. The criterion-level matrix, rather than only the final score, is presented in the Results section to ensure reproducibility.

Values of $C_i \geq 4.20$ were classified as Priority, values from $3.40 \leq C_i < 4.20$ as Conditional, and values below 3.40 as Redesign. These classification thresholds were internal engineering decision rules and were not interpreted as regulatory acceptance limits or experimentally validated safety thresholds.

Documentary characteristics were used for the comparative assessment of C01–C10, while direct mass, dimensional, and clearance measurements were incorporated only for C01 and C02. Consequently, the compatibility assessment was interpreted together with the provenance of the evidence supporting each criterion rather than treating all ten helmet models as having an equivalent level of physical verification.

Potential integration areas were also classified according to geometry, ventilation, suspension, adjustment, maintainability, and accessory compatibility. The side accessory slot was designated Z5, the external rear surface Z6, and the rear adjustment mechanism Z7. Z6 was considered a candidate location for the primary enclosure because of its dimensional availability and accessibility. Z5 was considered optional when not required by manufacturer-compatible accessories. Z7 was classified as restricted because components, batteries, wiring, or fastening devices could interfere with the helmet adjustment mechanism. Internal areas near the crown and suspension were also treated as restricted whenever integration could reduce functional clearance or generate rigid contact with the head.

The architecture was developed at three complementary levels. The functional architecture specified what the system was required to accomplish. The logical architecture represented inputs, operating states, processing rules, outputs, and interfaces. The physical architecture associated functions with candidate technologies, components, and potential installation zones.

Eight subsystems were defined: S1, helmet-wearing detection; S2, chin-strap monitoring; S3, inertial sensing; S4, local processing; S5, communication; S6, identification; S7, alerts; and S8, energy management.

Logical operating states comprised startup, verification, normal operation, alert, degraded communication, critical energy, and maintenance. BLE disconnection was treated as a degraded state in which local functions should remain available rather than as an automatic system shutdown.

2.6 Energy budget

The energy budget was estimated from active and standby current values reported in manufacturer datasheets [19-22] and from theoretical duty cycles established for three operating scenarios: eco, nominal, and intensive.

The average current of each component was calculated as:

$$I_{avg,k} = I_{active,k} D_k + I_{standby,k}(1 - D_k) \quad (1)$$

where, $I_{active,k}$ represents the active current of component k, $I_{standby,k}$ is the standby current of component k, and D_k is its duty cycle expressed as a proportion from 0 to 1.

The total design current was calculated as:

$$I_{design} = \sum_{k=1}^{n} I_{avg,k} \quad (2)$$

where, n is the number of electronic components included in the reference configuration.

The theoretical operating time was calculated as:

$$t_{theoretical} = \frac{C_{bat}}{I_{design}} \quad (3)$$

where, C_{bat} represents the nominal battery capacity and I_{design} is the total estimated design current.

The useful operating time was estimated by applying a 20% reduction margin:

$$t_{useful} = 0.80 t_{theoretical} \quad (4)$$

A 500 mAh battery was adopted as the reference capacity to examine the conceptual trade-off among operating time, additional mass, and volume. This value represented a design assumption rather than final component selection. A useful operating-time target of 72 h was established as a conceptual requirement to cover multiple working shifts without daily recharging. The 20% reduction factor was incorporated to account conceptually for conversion losses, consumption variability, battery aging, and non-ideal operating conditions. The eco, nominal, and intensive scenarios differed mainly in the assumed duty cycle of the proximity sensor, BLE communication frequency, and frequency of alert activation.

The resulting operating-time values were treated as design estimates derived from nominal component data and the duty-cycle assumptions defined for each operating scenario.

No battery-discharge test was conducted. Therefore, the calculated values were used only to compare operating scenarios and assess compliance with the conceptual 72 h design target.

2.7 Content validity and technical review

Evaluation was performed through two separate procedures. The first assessed the content validity of the instrument developed to review the architecture. The second consisted of a multidisciplinary technical review of the architecture itself. The two procedures addressed complementary evaluation objects: content validity of the assessment instrument and multidisciplinary technical evaluation of the proposed architecture.

Five judges participated in the content-validity assessment. Selection considered professional training related to engineering, occupational safety, technological systems, or research; experience in evaluating instruments, technical projects, or engineering solutions; and familiarity with design methodologies or occupational safety.

The version evaluated by the five judges was the 12-item content-validity instrument. The twelve items addressed relevance, clarity, coherence, sufficiency, physical compatibility, non-invasive integration, safety, ergonomics, maintainability, traceability, graphical clarity, and overall sufficiency. The exact wording of the twelve evaluated statements is reported together with the individual judge ratings in the Results section, thereby identifying the specific 12-item version on which the Aiken's V calculations were based.

Each item was scored using an ordered four-category numeric scale coded 1, 2, 3, and 4, with increasing values representing increasingly favorable assessments. Code 1 represented the least favorable category and code 4 the most favorable category, while codes 2 and 3 represented the intermediate ordered categories. The same numerical coding was applied to all five judges, and no intermediate numerical values were used.

Content validity was estimated using Aiken's V [23]:

$$V = \frac{\sum s}{n(c-1)} \quad (5)$$

where, s is the difference between the assigned rating and the minimum value of the scale, n is the number of judges, and c is the number of response categories.

Aiken's V was calculated separately for each item from the five raw judge ratings. Ninety-five percent confidence intervals were calculated using the Wilson score method. The predefined value of $V \geq 0.80$ was retained as a point-estimate reference for content validity; however, an item was not classified as unconditionally accepted solely because its point estimate exceeded 0.80. The lower and upper limits of the 95% confidence interval were reported alongside each coefficient and considered when interpreting the precision of the estimate, particularly because the panel comprised five judges.

Accordingly, item-level results are reported descriptively as the observed Aiken's V coefficient together with its 95% confidence interval rather than as a binary Accepted/Rejected decision. The overall coefficient was obtained as the arithmetic mean of the twelve item-level values, while the minimum and maximum coefficients were also reported to show the observed range.

Following this assessment, the architecture was reviewed by four specialists representing complementary domains: occupational safety and health and PPE; embedded electronics and wireless communication; Systems Engineering and Requirements Engineering; and engineering design and ergonomics.

The review guide comprised twenty criteria addressing functional relevance; functional, logical, and physical architecture; compatibility; non-invasive integration; conceptual safety; ergonomics; maintainability; modularity; traceability; graphical clarity; and documentary sufficiency.

Each criterion was rated on a four-point scale. Because of the small number of specialists and the ordinal nature of the ratings, results were summarized using the median and the proportion of favorable responses, considering scores of 3 and 4 as favorable. No inferential statistical analysis was performed.

Qualitative observations were classified as minor, major, or critical. Minor observations concerned improvements in documentation, clarity, or maintainability. Major observations indicated conditions potentially affecting functionality or compatibility. Critical observations represented potential safety-related or structural inconsistencies requiring correction before subsequent design stages.

For every observation, the severity category, affected architectural element, adopted decision, required modification, and incorporation into change control were documented.

2.8 Traceability, information management, and ethical considerations

A traceability matrix was developed to link each operating scenario with its monitoring need, observable variable, requirement, function, technology, subsystem, integration zone, constraint, and subsequent verification activity. This structure allowed each architectural element to be associated with an explicitly documented need and enabled identification of aspects requiring experimental validation.

Pending verification activities included determination of inertial thresholds; assessment of the helmet-wearing sensor under variations in hair, sweat, dust, and geometry; mechanical robustness and alignment of the Hall-sensor configuration; BLE range; actual operating time; and mechanical compatibility of removable supports.

Changes derived from the technical review were incorporated through a change-control process documenting the original criterion, specialist observation, resulting engineering decision, affected architectural element, and implemented modification. This procedure preserved differentiation between the initial proposal and the technically refined architecture.

The analysis records were organized using consistent identifiers for helmets (C01–C10), subsystems (S1–S8), integration zones (including Z5–Z7), requirements, technological alternatives, validity items, and technical-review criteria. These identifiers were maintained across the calculation matrices, tables, figures, and narrative results to preserve traceability.

The study did not involve construction workers, patients, collection of physiological or biometric information, impact testing on human participants, or intentional exposure to occupational hazards. Human participation was limited to content assessment of the evaluation instrument and technical review of the architecture. Responses were coded and analyzed in aggregated form without reporting personal identifiers.

Participation was voluntary, and informed consent was obtained from the five judges and four technical specialists before their evaluations were collected. No sensitive personal information was requested or processed.

The research project was reviewed and approved by the Research Ethics Committee of Universidad de Ciencias y Humanidades (UCH), Lima, Peru, under approval code 017-2026, dated February 21, 2026. The approval is documented in ACTA CEI N.° 017 and corresponds to the project registered by the Committee as "un marco de ingeniería de seguridad de sistemas para la integración de sensores no invasivos en cascos de seguridad para la construcción comercial."

Technical information obtained from standards, scientific literature, and manufacturer documentation was used exclusively for research and engineering analysis purposes.

Finally, the proposed architecture was not interpreted as authorization to modify certified commercial helmets. Any subsequent physical integration would require model-specific dimensional verification, detailed engineering design, prototype testing, assessment of mechanical and ergonomic compatibility, and evaluation against the applicable regulatory and manufacturer requirements.

3. RESULTS

3.1 Conceptual compatibility with commercial safety helmets

The reference electronic configuration had a total added

mass of 25.9 g and a summed geometric component volume of 15,644.5 mm³. For the posterior integration zone Z6, the engineering calculation matrix used a module-envelope volume of 23,100 mm³. The geometric component volume and the module-envelope volume were treated as different quantities because the latter represents the space allocated for integration rather than the simple sum of the individual component volumes.

Direct physical measurements were used only for C01 and C02. For C01, the three measured masses were 299.8, 300.1, and 300.0 g. External length was 279.8, 280.2, and 280.0 mm; external width was 219.9, 220.1, and 220.0 mm; and external height was 139.8, 140.1, and 140.0 mm. Minimum internal clearance was 23.8, 24.1, and 24.0 mm, while maximum internal clearance was 43.8, 44.2, and 44.0 mm. The posterior free-distance measurements were 64.8, 65.1, and 65.0 mm, and posterior free depth was 17.8, 18.1, and 18.0 mm.

For C02, the corresponding masses were 399.8, 400.1, and 400.0 g. External length was 306.8, 307.2, and 307.0 mm; external width was 269.8, 270.1, and 270.0 mm; and external height was 149.8, 150.2, and 150.0 mm. Minimum internal clearance was 25.8, 26.1, and 26.0 mm, and maximum internal clearance was 47.8, 48.2, and 48.0 mm. Posterior free distance was 74.8, 75.2, and 75.0 mm, and posterior free depth was 17.8, 18.2, and 18.0 mm. Arithmetic means were used only after retaining the three original observations.

The available posterior-zone volumes retained in the calculation matrix were 52,650 mm³ for C01 and 67,500 mm³ for C02. Using the module-envelope volume of 23,100 mm³, the volumetric occupancy was calculated as (23,100/52,650) × 100 = 43.87% for C01 and (23,100/67,500) × 100 = 34.22% for C02. Likewise, using the total added mass of 25.9 g and the mean measured helmet masses of 299.97 g for C01 and 399.97 g for C02, the relative mass increase was (25.9/299.97) × 100 = 8.63% and (25.9/399.97) × 100 = 6.48%, respectively. With a 12 mm module depth, the minimum residual clearances were 11.97 mm for C01 and 13.97 mm for C02. These calculations provide direct traceability between the measured inputs, the derived indicators, and the criterion-level assessment reported in Table 2.

No overall mean volumetric occupancy or overall mean mass increase is reported across C01–C10 because direct physical measurements were not available at the same evidence level for all ten helmets. For C03–C10, manufacturer documentation and documented configuration characteristics were retained for comparative screening and were not represented as triplicate physical measurements.

Table 2 presents the criterion-level conceptual compatibility assessment. The overall mean compatibility score was 3.75/5. C02 obtained the highest score (4.25/5) and was the only model classified as Priority. C01 obtained 3.95/5, while C03–C10 ranged from 3.50/5 to 3.80/5 and were classified as Conditional. None of the evaluated models was classified as Redesign.

Table 2. Criterion-level conceptual compatibility assessment of commercial safety helmets

Code	Commercial Model	DA	VO	MI	IC	VE	RA	AC	Score	Classification
C01	MSA V-Gard Cap Style Fas-Trac III	5	4	3	5	5	3	3	3.95	Conditional
C02	MSA V-Gard Full Brim Fas-Trac III	5	5	4	5	5	3	3	4.25	Priority
C03	MSA V-Gard 500 Non-Vented Fas-Trac III	3	4	4	5	5	3	3	3.80	Conditional
C04	3M SecureFit X5000 Series	3	4	4	5	2	3	3	3.50	Conditional
C05	3M SecureFit X5500 Series	3	4	4	5	2	3	3	3.50	Conditional
C06	Honeywell Fibre-Metal E1RW Full Brim	3	4	4	5	5	3	3	3.80	Conditional
C07	Delta Plus QUARTZ UP IV	3	4	4	5	3	3	3	3.60	Conditional
C08	JSP EVO3 Micro Peak Wheel Ratchet	3	4	4	5	2	3	3	3.50	Conditional
C09	Portwest PS54 Endurance Plus Hard Hat	3	4	4	5	5	3	3	3.80	Conditional
C10	Portwest PS53 Height Endurance Helmet	3	4	4	5	5	3	3	3.80	Conditional
	Overall mean	-	-	-	-	-	-	-	3.75	Conditional

Note: DA = dimensional availability; VO = volumetric occupancy; MI = relative mass increase; IC = internal clearance; VE = ventilation preservation; RA = rear-adjustment compatibility; AC = accessory compatibility. C01 and C02 incorporate triplicate direct measurements. For C03–C10, the criterion-level values represent comparative documentary screening and should not be interpreted as directly measured volumetric-occupancy or mass-increase percentages. The weighted score used DA = 0.15, VO = 0.15, MI = 0.15, IC = 0.15, VE = 0.10, RA = 0.15, and AC = 0.15.

These classifications represent comparative engineering decision rules and should not be interpreted as evidence of regulatory conformity, preservation of certified protective performance, or authorization to modify a commercial helmet.

Compatibility was not determined exclusively by apparent physical space. External geometry, ventilation, suspension, adjustment mechanisms, accessory interfaces, internal clearance, and the provenance of the available evidence affected the resulting prioritization. Accordingly, a documentary specification was not treated as equivalent to a directly verified physical measurement.

Among the analyzed integration areas, the external rear surface, designated Z6, was retained as a potential location for the main module because it offered external accessibility and separation from internal head-contact areas. Its use remained conditional on dimensional verification, mass-distribution assessment, and avoidance of interference with the rear adjustment mechanism.

The side accessory interface, designated Z5, was retained as an optional integration zone because these slots may be required for visors, earmuffs, face shields, or other manufacturer-compatible accessories. In contrast, the rear adjustment mechanism, designated Z7, was classified as a restricted zone and was required to remain free of batteries, modules, wiring, and fastening elements.

3.2 Multicriteria selection of technologies

The multicriteria analysis differentiated technologies according to their functional relevance and integration constraints. The complete decision matrix evaluated 12 technological alternatives using 11 weighted criteria, as presented in Table 3.

The VL53L4CD time-of-flight sensor obtained a score of 4.11 for helmet-placement detection, compared with 3.94 for the capacitive sensor and 3.45 for the force-sensitive resistor. These three alternatives were classified as Conditional. The VL53L4CD was retained as the reference option because it can

provide proximity information without requiring continuous pressure against the head. However, its actual response under variations in hair, sweat, dust, internal geometry, and surface reflectivity remains to be experimentally verified.

The DRV5032 Hall sensor obtained a score of 4.93 for chin-strap state monitoring. The LIS2DW12 accelerometer obtained 4.87 for inertial sensing, the MDBT42Q module obtained 4.87 for local processing and BLE communication, the NT3H2111/NT3H2211 NFC device obtained 4.90 for identification, and the buzzer/LED configuration obtained 4.61 for local alerts. These alternatives were classified as Priority and retained in the reference configuration.

LoRa and UWB obtained scores of 2.84 and 2.27, respectively, and were classified as Not prioritized. Therefore, they were excluded from the minimum reference configuration.

The sensitivity analysis produced the following scores under the reference, energy-oriented, and form-factor-oriented scenarios, respectively: VL53L4CD, 4.11/4.12/4.12; capacitive sensor, 3.94/3.96/3.98; force-sensitive resistor, 3.45/3.61/3.39; DRV5032 Hall sensor, 4.93/4.94/4.95; reed switch, 4.15/4.24/4.12; LIS2DW12, 4.87/4.89/4.91; six-axis IMU, 3.85/3.80/3.75; MDBT42Q BLE, 4.87/4.89/4.91; LoRa, 2.84/2.78/2.84; NFC NT3H2111/NT3H2211, 4.90/4.90/4.92; UWB, 2.27/2.18/2.23; and buzzer/LED, 4.61/4.55/4.68.

The five alternatives classified as Priority in the reference scenario remained Priority under both alternative weighting schemes. However, the classifications were not completely invariant: the reed switch increased from 4.15 to 4.24 under the energy-oriented scenario and therefore moved from Conditional to Priority, whereas the force-sensitive resistor decreased from 3.45 to 3.39 under the form-factor-oriented scenario and moved from Conditional to Not prioritized. The sensitivity analysis therefore indicates stability of the principal reference selections while also identifying two alternatives located close to the predefined classification thresholds.

The Hall-sensor configuration was conceptually associated with a magnet incorporated into the chin-strap fastening arrangement. Its distance, alignment, and support tolerances require physical verification. The LIS2DW12 was retained for tri-axial acceleration and static orientation measurement; because the selected device does not include a gyroscope, it was not considered a six-axis inertial measurement unit.

The MDBT42Q integrated local processing and BLE communication within the reference architecture. NFC identification was maintained as an independent function so that identification did not depend on the availability of the BLE connection.

3.3 Estimated energy budget

Table 4 presents the estimated energy budget for the eco, nominal, and intensive operating scenarios using the 500 mAh reference battery and the 20% conservative reduction factor defined in the methodology. The eco scenario produced an estimated design current of 3.15 mA, corresponding to a theoretical operating time of 158.8 h and an estimated useful operating time of 127.1 h. The nominal scenario required an estimated 5.00 mA and resulted in 100.0 h of theoretical operation and 80.0 h of useful operation. The intensive scenario increased estimated current consumption to 8.34 mA, reducing theoretical operating time to 60.0 h and useful operating time to 48.0 h.

The eco and nominal scenarios exceeded the conceptual target of 72 h, whereas the intensive scenario did not meet it. The reduction in estimated operating time under intensive operation resulted from the higher assumed ToF duty cycle, more frequent BLE communication, and greater use of alert functions.

All values presented in Table 4 are calculation-based design estimates derived from nominal component information and the duty-cycle assumptions defined for the three operating scenarios. They do not represent experimentally measured battery autonomy.

Table 3. Multicriteria assessment of candidate technologies

Function	Technology	FR	FF	PC	RL	EA	MT	WS	ER	CO	AC	SC	Score	Decision
Presence	VL53L4CD ToF	5	4	4	4	4	4	4	3	3	5	4	4.11	Conditional
Presence	Capacitive sensor	4	4	4	3	4	4	5	2	5	5	4	3.94	Conditional
Presence/fit	Force-sensitive resistor	3	3	5	3	3	3	4	2	5	5	3	3.45	Conditional
Chin strap	DRV5032 Hall sensor	5	5	5	5	5	5	5	4	5	5	5	4.93	Priority
Chin strap	Reed switch	4	4	5	4	4	4	4	3	5	5	4	4.15	Conditional
Inertial sensing	LIS2DW12	5	5	5	5	5	5	5	4	4	5	5	4.87	Priority
Inertial sensing	Six-axis IMU	5	3	3	5	3	4	3	4	3	4	5	3.85	Conditional
Processing/ communication	MDBT42Q BLE	5	5	5	5	5	5	5	4	4	5	5	4.87	Priority
Communication	LoRa	3	3	2	4	2	3	2	4	2	3	4	2.84	Not prioritized
Identification	NFC NT3H2111/NT3H2211	5	5	5	5	5	5	5	4	5	5	4	4.90	Priority
Positioning	UWB	3	2	1	4	2	2	1	3	1	2	4	2.27	Not prioritized
Alert	Buzzer/LED	5	5	4	4	5	5	5	3	5	5	4	4.61	Priority

Note: Functional relevance (FR); form-factor suitability (FF); power consumption (PC); reliability (RL); ease of adoption (EA); maintainability (MT); weight and size (WS); environmental resilience (ER); cost (CO); accessibility (AC); scalability (SC); time-of-flight (ToF); inertial measurement unit (IMU); Bluetooth Low Energy (BLE); Long Range (LoRa); Near-Field Communication (NFC); Ultra-Wideband (UWB); light-emitting diode (LED).

Table 4. Estimated energy budget by operating scenario

Scenario	Estimated Current (mA)	Theoretical Operating Time (h)	Useful Operating Time (h)	72 h Target
Eco	3.15	158.8	127.1	Meets
Nominal	5.00	100.0	80.0	Meets
Intensive	8.34	60.0	48.0	Does not meet

3.4 Resulting conceptual architecture

The resulting architecture comprised eight subsystems: S1, helmet-wearing detection; S2, chin-strap monitoring; S3, inertial sensing; S4, local processing; S5, communication; S6, identification; S7, alerts; and S8, energy management.

At the functional level, S1, S2, and S3 generated inputs related to proximity, chin-strap state, and acceleration or orientation. These signals were transferred to S4 for local processing and application of the corresponding decision rules. Processed information could subsequently be communicated through S5, associated with local alerts through S7, and incorporated into event recording.

Subsystem S6 provided NFC-based identification independently of BLE communication, while S8 supplied and monitored the energy required by the remaining architectural elements.

The logical architecture comprised seven principal operating states: start-up, checking, normal operation, alert, degraded communication, critical energy, and maintenance. BLE disconnection resulted in a degraded communication state rather than complete loss of local functionality. The critical-energy state incorporated an advance warning and the conceptual possibility of transitioning to a reduced-power state or controlled shutdown.

At the physical level, the main module was assigned to the external rear zone Z6 and conceptually grouped the processing unit, BLE communication, accelerometer, battery, energy-management elements, and alert components. The ToF sensor was assigned to an internal frontal location using a flexible removable support without rigid contact with the head. The Hall sensor and its corresponding magnetic element were associated with the chin-strap fastening region, while the NFC tag was assigned to a side or rear location without obstruction to near-field communication.

Figure 2 integrates the functional, logical, and physical views and differentiates the optional accessory interface (Z5), potential main-module zone (Z6), and restricted adjustment-mechanism zone (Z7).

The architecture incorporated removable fastening concepts such as clips, sleeves, or dedicated supports with secondary retention. Adhesive bonding was not considered acceptable as the sole fastening mechanism. Rigid elements, including the main enclosure and battery, were excluded from zones that could create direct rigid contact with the head or interfere with the functional clearance of the suspension.

The representation in Figure 2 constitutes a conceptual allocation of functions and components. It does not correspond to a manufactured prototype, demonstrate physical compatibility, or imply experimental validation of the proposed locations.

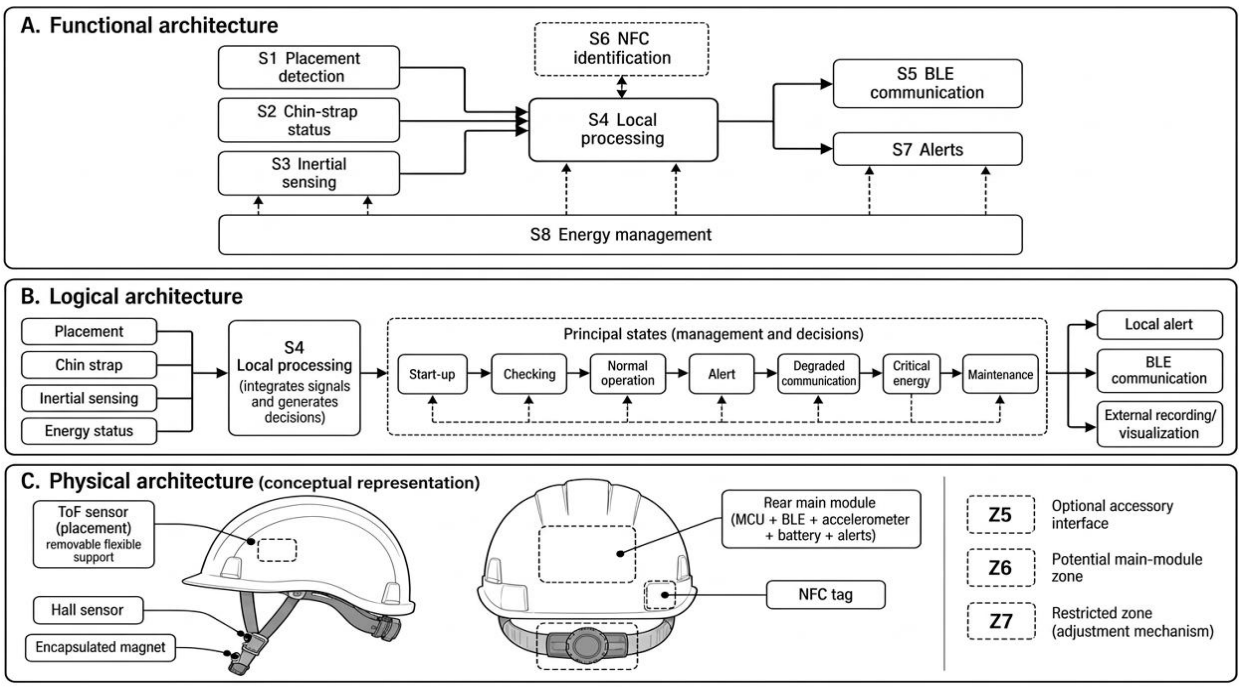

Figure 2. Integrated representation of the functional, logical, and physical architectures of the proposed helmet monitoring system

3.5 Content validity of the evaluation instrument

Five judges assessed the twelve-item version of the architecture evaluation instrument. The mean Aiken's V was 0.9222, with item-level point estimates ranging from 0.8667 to 1.0000. Table 5 provides the exact wording evaluated for each item, the five individual judge ratings, the resulting Aiken's V coefficient, and its 95% confidence interval.

Although all item-level point estimates exceeded the predefined reference value of 0.80, the lower limits of their 95% confidence intervals ranged from 0.6212 to 0.7961 and therefore did not uniformly exceed 0.80. Consequently, the results are reported as point estimates together with their uncertainty rather than through an unconditional binary Accepted/Rejected decision.

The highest point estimates corresponded to physical compatibility (I05) and safety (I07), both with V = 1.0000. Coherence (I03), sufficiency (I04), graphical clarity (I11), and overall sufficiency (I12) presented the lowest point estimates, V = 0.8667. These results indicate favorable item-level point estimates while also making explicit the precision limitation associated with the five-judge panel.

The criterion-level results of the multidisciplinary technical review are summarized in Table 6.

Table 5. Raw judge ratings and item-level content-validity results

Item	Dimension	Evaluated Statement	J01	J02	J03	J04	J05	Aiken's V	95% Confidence Interval (CI)
I01	Relevance	The criterion evaluates a relevant characteristic of the architecture.	4	4	4	3	4	0.9333	0.7018–0.9881
I02	Clarity	The statement is precise and understandable.	4	3	4	4	4	0.9333	0.7018–0.9881
I03	Coherence	The criterion corresponds to the dimension being evaluated.	4	4	3	4	3	0.8667	0.6212–0.9626
I04	Sufficiency	The set covers the essential aspects.	3	4	4	3	4	0.8667	0.6212–0.9626
I05	Physical compatibility	It allows interference with the helmet to be assessed.	4	4	4	4	4	1.0000	0.7961–1.0000
I06	Non-invasive integration	It assesses reversibility and the absence of permanent modification.	4	4	4	4	3	0.9333	0.7018–0.9881
I07	Safety	It identifies risks related to the battery, edges, wiring, and rigid contact.	4	4	4	4	4	1.0000	0.7961–1.0000
I08	Ergonomics	It assesses mass, balance, localized pressure, and movement.	4	4	3	4	4	0.9333	0.7018–0.9881
I09	Maintainability	It assesses inspection, cleaning, disassembly, and replacement.	4	4	4	3	4	0.9333	0.7018–0.9881
I10	Traceability	It links scenario, requirement, technology, zone, and verification.	4	4	4	3	4	0.9333	0.7018–0.9881
I11	Graphical clarity	It differentiates modules and feasible and restricted zones.	4	3	4	4	3	0.8667	0.6212–0.9626
I12	Overall sufficiency	The instrument guides refinement of the architecture.	3	4	4	4	3	0.8667	0.6212–0.9626
		Overall mean	-	-	-	-	-	0.9222	Observed V range: 0.8667–1.0000

Table 6. Criterion-level multidisciplinary technical review of the conceptual architecture

Code	Technical Criterion	E01	E02	E03	E04	Median	Favorable Ratings	Observation Severity
ET01	Functional relevance	4	4	4	4	4.0	100%	Minor
ET02	Requirements clarity	4	3	4	4	4.0	100%	Minor
ET03	Traceability	4	4	4	4	4.0	100%	None
ET04	Shell compatibility	3	4	3	4	3.5	100%	Major
ET05	Suspension compatibility	3	3	4	4	3.5	100%	Critical
ET06	Adjustment-system compatibility	4	3	4	3	3.5	100%	Major
ET07	Ventilation preservation	4	4	3	4	4.0	100%	Major
ET08	Accessory compatibility	3	4	4	3	3.5	100%	Major
ET09	Removable fastening	4	4	4	4	4.0	100%	Critical
ET10	Protected wiring	4	3	4	4	4.0	100%	Major
ET11	Battery protection	4	4	3	4	4.0	100%	Critical
ET12	Mass distribution	3	4	3	4	3.5	100%	Major
ET13	Ergonomics	3	3	4	4	3.5	100%	Major
ET14	Maintainability	4	4	4	3	4.0	100%	Minor
ET15	Environmental protection	3	4	4	3	3.5	100%	Major
ET16	Energy consumption	4	4	3	4	4.0	100%	Major
ET17	Communication-loss management	4	4	4	4	4.0	100%	Minor
ET18	Alert configuration	3	4	3	4	3.5	100%	Major
ET19	NFC identification	4	4	4	3	4.0	100%	None
ET20	Verification plan	4	4	4	4	4.0	100%	Minor

The observations provided during this process concerned wording precision, clarity of evaluation criteria, differentiation of restricted integration areas, fastening requirements, battery placement, wiring, enclosure configuration, and maintainability. These observations were incorporated into the refinement of the evaluation instrument and the documentation used for the subsequent technical review.

These results support the use of the instrument for the structured technical review within the scope of this study. They do not constitute evidence of experimental performance, regulatory conformity, or physical validation of the proposed architecture.

3.6 Technical review of the architecture

Four specialists evaluated the architecture using twenty technical criteria. Criterion-level median scores ranged from 3.5 to 4.0 on the four-point evaluation scale, and all criteria received 100% favorable ratings.

Qualitative observations were recorded for eighteen of the twenty criteria. Three observations were classified as critical, ten as major, and five as minor; two criteria generated no observations. The critical observations concerned preservation of suspension compatibility and functional clearance, the use of removable fastening with secondary mechanical retention, and battery protection to prevent rigid contact between batteries or modules and the user's head.

Major observations addressed shell compatibility, adjustment-system compatibility, ventilation preservation, accessory compatibility, protected wiring, added-mass distribution, conceptual ergonomics, environmental protection,

energy consumption, and alert configuration. Minor observations concerned functional relevance, requirements clarity, maintainability, communication-loss management, and the verification plan.

As a result of the technical review, the architecture incorporated explicit restrictions for critical internal areas, secondary mechanical retention, enclosures with rounded geometries, protected wiring routes, separation from the rear adjustment mechanism, and independent accessibility to components requiring inspection or maintenance.

The specialist review strengthened the technical and documentary coherence of the architecture and established a refined baseline for subsequent detailed engineering. However, favorable specialist ratings were not interpreted as certification, conformity assessment, or validation of a physically implemented system.

3.7 Traceability and scenario coverage

The final traceability analysis linked the eight operating scenarios to their corresponding subsystems, candidate technologies, level of architectural resolution, and required verification activities, as summarized in Table 7.

Direct functional correspondence was established at the architectural level for chin-strap status, communication loss, and critical energy. Helmet-wearing detection and abnormal positioning remained conditional because their interpretation requires subsequent definition and experimental verification of operating thresholds.

Acceleration-based sensing provided a mechanism for recording possible impact-related events and sudden movements, but the architecture did not interpret these signals as confirmation of an impact, fall, or injury.

Insufficient fit represented the scenario with the greatest unresolved sensing requirement. Although proximity can provide information concerning relative distance between the head and helmet, it cannot independently determine the tension or stability of the adjustment system. The architecture therefore retained the possibility of incorporating an additional force-, pressure-, or displacement-based sensing principle at a subsequent design stage.

Overall, the architecture represents all eight scenarios at the requirements and traceability levels, but not at an equivalent level of functional resolution. Three scenarios have direct architectural correspondence, two remain conditional, two are limited to event recording, and insufficient fit requires an additional sensing principle. The resulting framework therefore establishes the design baseline and verification priorities for subsequent detailed engineering and model-specific prototype assessment without claiming complete experimental coverage.

Table 7. Summary traceability of the operating scenarios

Scenario	Subsystem / Technology	Architectural Resolution	Required Verification
Helmet not worn	S1 / ToF	Conditional	Hair, sweat, dust, and geometry
Chin strap unfastened	S2/ Hall sensor	Direct	Distance, alignment, and tolerances
Abnormal position	S3/ Accelerometer	Conditional	Orientation thresholds and false alarms
Insufficient fit	S1/ Additional sensor	Conditional	Select and evaluate sensing principle
Possible impact event	S3 / Accelerometer	Recording only	Range, sampling, saturation, and thresholds
Sudden movement	S3 / Accelerometer	Recording only	Classification and false alarms
Communication loss	S5 / BLE	Direct	Timeout, range, and local storage
Critical energy	S8 / Energy management	Direct	Threshold and actual operating time

Note: Time-of-flight (ToF); Bluetooth Low Energy (BLE).

4. DISCUSSION

4.1 Physical compatibility and non-invasive integration

The findings indicate that non-invasive sensor integration into commercial safety helmets cannot be approached as a component-placement problem independent of the original PPE configuration. Compatibility depended on the combined effects of geometry, internal clearance, ventilation, suspension, adjustment mechanisms, accessory interfaces, and the provenance of the available evidence. This extends previous Smart PPE and smart-helmet research [4, 12, 13] by addressing an earlier engineering question: how candidate sensing functions can be incorporated without assuming that available physical space is equivalent to a suitable installation area.

The distinction is particularly relevant for certified commercial PPE. A geometrically accessible surface may simultaneously support adjustment, ventilation, accessory attachment, inspection, or maintenance. The zoning approach adopted in this study therefore differentiates potential, optional, and restricted regions before detailed mechanical design. Z6 represents a potential external location rather than a validated mounting position; Z5 remains dependent on accessory requirements; and Z7 is restricted because interference with the rear adjustment mechanism could affect normal helmet use. This interpretation deliberately avoids treating conceptual compatibility as evidence that the protective performance of a commercial helmet would remain unchanged after physical integration.

The compatibility assessment also demonstrates why model-specific evidence remains necessary. The Priority classification obtained for C02 identifies it as the most suitable candidate within the comparative decision rules used in this study, but it does not constitute regulatory approval or proof of physical integration feasibility. Conversely, Conditional classifications do not imply that the remaining helmets are unsuitable; they indicate that additional dimensional, mechanical, or configuration-specific verification would be required before proceeding to detailed design. In this sense, the compatibility matrix functions as a screening and prioritization mechanism rather than as a conformity assessment.

A further implication concerns evidence provenance. Direct physical measurements were available for C01 and C02, whereas the broader comparison of C03–C10 relied principally on manufacturer documentation. Maintaining this distinction prevents calculated indicators from being

interpreted as experimental observations and identifies where model-specific physical verification remains necessary. At the pre-prototype stage, this distinction is important because numerical outputs should not imply a level of physical verification greater than that actually available.

4.2 Technology selection and functional complementarity

The technology-selection results support a function-oriented rather than sensor-oriented architecture. No single sensing principle adequately represents all eight operating scenarios. Proximity sensing, magnetic state detection, inertial sensing, local processing, wireless communication, identification, alerting, and energy management therefore perform complementary roles within the proposed architecture. This differs from approaches centered primarily on an individual sensing technology or detection algorithm [7, 10-13], because the present framework begins with operating scenarios and requirements before assigning technologies.

This distinction is particularly important for interpreting inertial information. Acceleration compatible with a possible impact event and sudden movement were intentionally limited to event recording because acceleration alone cannot establish that an impact, fall, or injury has occurred. Similarly, proximity information can contribute to helmet-wearing detection but cannot independently determine adequate fit. By retaining these scenarios as conditional or unresolved where appropriate, the architecture avoids converting a measurable signal into a safety conclusion without experimental thresholds and validation data.

The multicriteria procedure provides a transparent rationale for selecting the reference technologies, but the sensitivity analysis also shows that the resulting categories are not completely invariant to changes in criterion weighting. The principal reference selections remained broadly stable, while alternatives located close to the classification thresholds showed category changes under the alternative scenarios. In particular, the reed-switch alternative crossed into the Priority range under the energy-oriented weighting scheme, whereas the force-sensitive resistor fell below the Conditional threshold under the form-factor-oriented scenario. These changes reinforce the interpretation of the multicriteria results as engineering decision support rather than as fixed performance rankings.

Component availability, environmental exposure, enclosure design, sampling requirements, communication strategy, and subsequent prototype testing may therefore modify the preferred configuration during detailed development.

4.3 Energy management and operational continuity

The energy analysis shows that autonomy is not an intrinsic property of the architecture but a consequence of sensing duty cycles, processing activity, communication frequency, and alert use. The conceptual 72 h target was compatible with the eco and nominal assumptions but not with the intensive operating scenario. This difference is relevant because increasing sensing or communication activity to obtain more frequent information directly increases the energy burden and may require a larger battery, more frequent charging, or revised firmware strategies.

These values should remain clearly separated from experimentally measured battery performance. The calculations were based on nominal component information, assumed duty cycles, a 500 mAh reference battery, and a conservative reduction factor; no discharge test was performed. Their purpose is therefore to identify an architectural trade-off and establish a verification requirement for subsequent development rather than to predict field autonomy.

The treatment of communication loss as a degraded state rather than total system failure is consistent with the same principle of operational continuity. Local sensing, processing, alerting, and temporary event storage should not conceptually depend on uninterrupted BLE connectivity. This separation between local safety-related functions and external communication reduces architectural dependence on a single wireless link, although actual behavior under communication failure remains to be verified experimentally.

4.4 Content validity and technical review

The content-validity analysis provided favorable point estimates for the twelve evaluation items, but the confidence intervals require a more cautious interpretation than a binary acceptance rule. Although all Aiken's V point estimates exceeded the predefined reference value of 0.80, the lower limits of the 95% confidence intervals did not uniformly exceed that value. The revised interpretation therefore considers the coefficients together with their uncertainty rather than treating $V \geq 0.80$ alone as unconditional evidence of item acceptance.

This distinction is methodologically relevant because the panel comprised five judges. With a small expert panel, a favorable point estimate may coexist with a comparatively wide confidence interval. The results therefore support the use of the instrument within the scope of this study while making the precision of that evidence explicit; they should not be interpreted as population-level validation or as evidence of physical performance of the proposed system.

The subsequent multidisciplinary review served a different purpose. Rather than validating sensor performance, it identified design conditions requiring refinement before prototype development. The observations concerning suspension clearance, removable fastening, battery protection, wiring, mass distribution, environmental protection, maintainability, and adjustment-system interference reinforce the central premise of the framework: integration decisions that may affect PPE functionality should be identified before hardware is permanently incorporated into a commercial helmet.

Accordingly, content validity and technical review provide complementary but distinct forms of expert evidence. The former addresses the evaluation instrument, whereas the latter supports refinement of the engineering architecture. Neither substitutes for mechanical, electrical, ergonomic, environmental, or protective-performance testing.

4.5 Methodological contribution and system safety implications

The principal methodological contribution of this study lies in organizing pre-prototype decisions into a traceable engineering sequence. DSR provides the development structure; Requirements Engineering translates operating needs into explicit requirements; Systems Engineering maintains relationships among functions, subsystems, interfaces, and operating states; and VDI 2221 supports systematic comparison and configuration of technological

alternatives [14-18]. Their combined use shifts the development process from component-first integration toward requirements- and safety-driven integration.

This sequence is relevant because many integration uncertainties cannot be resolved simply by selecting smaller or lower-power electronic components. Physical compatibility, suspension clearance, accessory use, removable fastening, battery location, maintainability, and model-specific geometry involve interactions between the proposed electronics and the existing protective equipment. Making these constraints explicit before prototype construction reduces the risk of treating a technologically functional sensing system as automatically compatible with the PPE on which it is installed.

Traceability also clarifies the maturity of the eight operating scenarios. Some functions have direct architectural correspondence, whereas others remain conditional, are limited to event recording, or require an additional sensing principle. The uneven level of resolution is therefore informative: it identifies where experimental evidence is still required rather than presenting unresolved sensing functions as completed capabilities. The architecture consequently serves as a structured baseline for subsequent verification.

4.6 Limitations and future work

The principal limitation is the conceptual and pre-prototype scope of the study. No complete physical prototype, firmware implementation, or integrated electronic system was evaluated. Consequently, the study does not provide experimental estimates of detection accuracy, sensitivity, specificity, latency, false-alarm rate, wireless range, mechanical stability, or actual battery autonomy. Mechanical, electrical, environmental, ergonomic, electromagnetic-compatibility, and protective-performance testing were also outside the present scope.

A second limitation concerns the different levels of evidence available for helmet compatibility. Direct repeated measurements were obtained for C01 and C02, whereas the comparison of C03–C10 relied principally on manufacturer documentation and calculated indicators. The comparative results are therefore appropriate for architectural screening and prioritization, but they should not be interpreted as equivalent physical verification across all ten models.

The multicriteria weights, compatibility thresholds, and classification rules are likewise internal engineering decision rules developed for this framework rather than standardized regulatory limits. The sensitivity analysis further showed that alternatives positioned near classification boundaries may change category when criterion weights are modified. Commercial variants, helmet sizes, manufacturing tolerances, accessory configurations, and environmental conditions may also modify actual integration requirements.

Finally, the content-validity and technical-review panels were intentionally small and specialized. Their assessments provided structured expert evidence for instrument evaluation and architectural refinement but do not support population-level inference. The confidence intervals reported for Aiken's V make this limitation explicit.

Subsequent development should progress sequentially from model-specific physical verification to removable-support and electronic prototype development, followed by experimental characterization of sensing thresholds, false alarms, BLE performance, actual energy consumption, mechanical stability, ergonomics, environmental resistance, and applicable protective-equipment requirements. Evaluation under representative occupational conditions should occur only after these controlled verification stages.

5. CONCLUSIONS

This study developed a system safety engineering framework for the non-invasive integration of sensors into commercial construction safety helmets. By combining DSR, Requirements Engineering, Systems Engineering, and VDI 2221, the framework establishes a traceable sequence from operating scenarios and monitoring needs to requirements, technological alternatives, subsystems, integration zones, constraints, and subsequent verification activities.

The main contribution is the formalization of pre-prototype engineering decisions rather than the development or validation of a finished smart helmet. The compatibility assessment showed that integration cannot be determined from available space alone, because geometry, internal clearance, suspension, ventilation, adjustment mechanisms, accessory interfaces, mass distribution, and evidence provenance must also be considered. Within the comparative screening procedure, C02 was prioritized for subsequent model-specific development, while the remaining configurations require additional verification before detailed integration. These classifications are engineering decision rules and do not constitute evidence of regulatory conformity or preservation of certified protective performance.

The resulting architecture provides a modular and traceable basis for helmet-wearing detection, chin-strap monitoring, inertial sensing, local processing, communication, identification, alerts, and energy management. The eight operating scenarios were represented at the requirements and traceability levels, but not with an equivalent degree of functional resolution: some have direct architectural correspondence, whereas others remain conditional, are limited to event recording, or require an additional sensing principle. This distinction makes unresolved verification needs explicit rather than treating them as completed system capabilities.

The expert-based evaluation supported refinement of the assessment instrument and the proposed architecture, but it does not replace experimental verification. In particular, Aiken's V results must be interpreted together with their confidence intervals, and the multidisciplinary review should be understood as structured engineering evidence rather than as certification or validation of physical performance.

Overall, the framework establishes a pre-prototype engineering baseline for model-specific development. The next stage should include physical verification of the prioritized helmet configuration, development of removable supports and electronic prototypes, and experimental assessment of sensing performance, false alarms, BLE communication, actual energy consumption, mechanical stability, ergonomics, environmental resistance, and applicable protective-equipment requirements before evaluation under representative occupational conditions.

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