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Development of a Safety-Support Prototype for Artisanal Hookah Divers

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Abstract

Artisanal hookah divers in small-scale fisheries face significant occupational safety risks because they rely on surface-supplied compressors and long breathing-air hoses, while existing commercial dive computers are not designed for this operational context. This study aimed to develop a safety-support prototype tailored to the needs of artisanal hookah divers using a human-centred design approach. User needs were identified through preliminary field observations and supported by literature, safety standards, and technology benchmarking. These needs were translated into system requirements and prioritised using an evidence-weighted engineering design process to guide prototype development. The resulting prototype integrates a diver-mounted monitoring module, a surface monitoring and control unit, and a compressor-side flow-proxy module connected through a wired communication pathway. The analysis identified reliable wired communication between the diver and the surface unit as the highest engineering priority, and the prototype successfully implemented a functional manual surface-to-diver warning mechanism. This study contributes a context-specific prototype that reallocates safety-support functions between the diver and the surface operator, providing a practical design framework for improving occupational safety in artisanal hookah diving. Technical validation and field evaluation remain subjects for future research.

Keywords: Artisanal Hookah Diving, Occupational Safety, Prototype Development, Human-Centred Design, Engineering Design, Small-Scale Fisheries.

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1. Introduction

Small-scale fisheries (SSF) contribute approximately 40% of global fishery production and provide livelihoods for more than 60 million people worldwide, with around 90% of fishers operating in the small-scale sector [1]–[3]. In Indonesia, artisanal fisheries constitute the dominant fishing activity, making occupational safety an important issue for both workers and coastal communities [4].

Among artisanal fishing activities, hookah diving is one of the most hazardous occupations because divers depend on a surface compressor and a long breathing-air hose throughout the dive [5]. Any interruption of the compressor, hose blockage, leakage, or contamination of the breathing-air supply may immediately threaten diver safety. Previous studies have reported a high prevalence of decompression sickness (DCS) and other diving-related injuries among traditional fishery divers, while accident investigations have shown that equipment failure and inadequate surface supervision frequently contribute to fatal incidents [6]–[10]. Preliminary field observations conducted at Kenjeran Beach, Surabaya, also identified operational challenges including prolonged dives, direct mouth-held hose use, compressor failures, and hose disconnection incidents, indicating the need for practical safety-support solutions adapted to local working conditions.

Recent commercial dive computers provide depth monitoring, dive-time recording, alarms, and data logging. However, these systems are primarily designed for self-contained underwater breathing apparatus (SCUBA) diving and rely on cylinder-pressure monitoring rather than surface-supplied compressors [11]–[14]. Consequently, they cannot monitor compressor-related failures, hose-delivery conditions, or support communication between divers and surface attendants, limiting their applicability in artisanal hookah-diving operations. Moreover, most existing systems assume trained recreational or professional divers and do not adequately consider the operational constraints of low-resource small-scale fisheries.

To address this gap, this study develops a safety-support prototype specifically for artisanal hookah divers using a human-centred design approach. User needs were identified through field observations and supported by literature, safety standards, and technology benchmarking. These requirements guided the development of a prototype integrating diver monitoring, surface monitoring and warning, and compressor-side flow-proxy functions.

The main contribution of this study is the development of a context-specific safety-support prototype that reallocates monitoring and warning functions between the diver and the surface operator while providing a transparent, evidence-based design process for low-resource diving environments. Rather than replacing commercial dive computers, the proposed system demonstrates how safety-support functions can be adapted to the operational characteristics of artisanal hookah diving and provides a foundation for future technical validation and field evaluation.

2. Methods

This study employed a design-development approach within descriptive engineering research to develop a safety-support prototype for artisanal hookah divers. A human-centred design approach was adopted to ensure that the prototype addressed the operational needs and safety challenges of artisanal hookah diving. The study focused on translating user needs into engineering requirements and implementing them as a functional prototype rather than experimentally evaluating system performance. Engineering prioritisation and design-risk consolidation were conducted after prototype implementation and are therefore presented as post-implementation analytical appraisal rather than as proof that these methods originally selected every as-built component or arrangement. The iterative user evaluation stage described in ISO 9241-210 was not completed and is acknowledged as a limitation of this study.

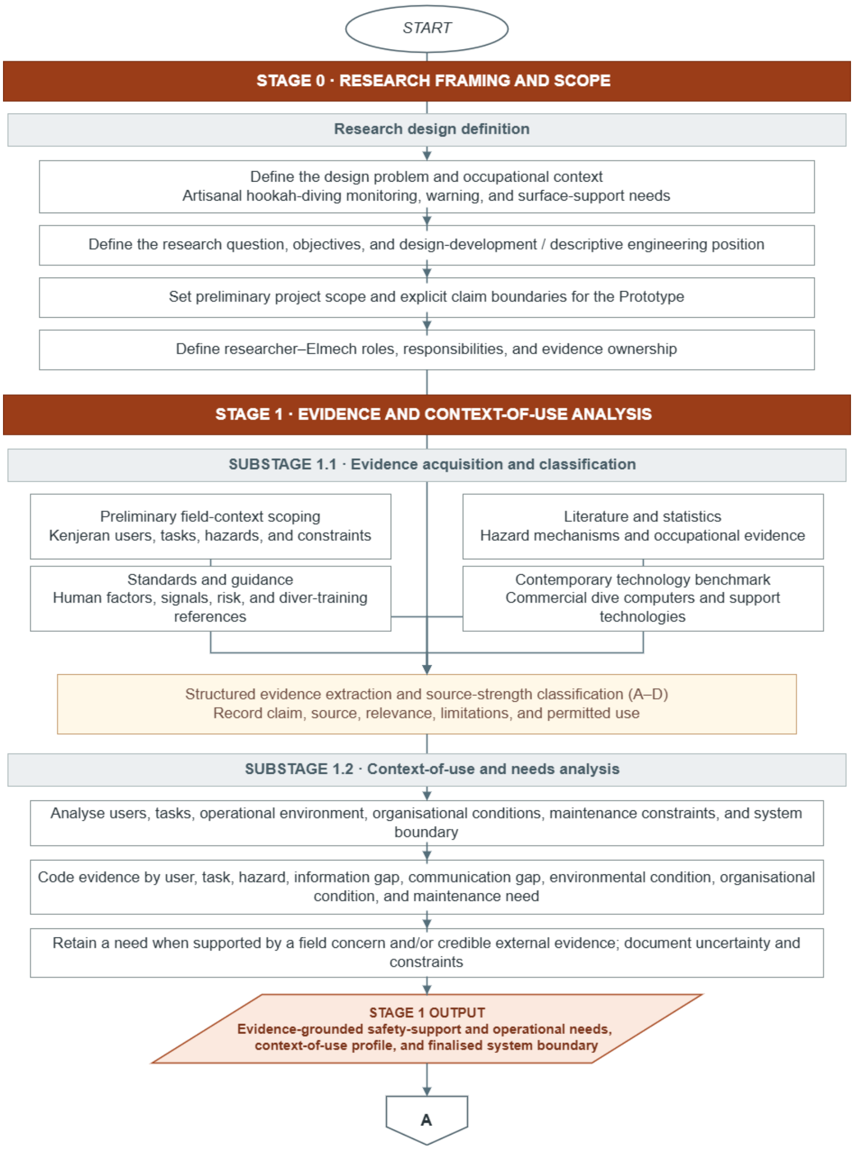

Figure 1. Design-development and analytical-appraisal workflow: research framing, evidence acquisition, and context-of-use analysis (Stages 0–1)

As illustrated in Figure 1 until Figure 3, the research comprised Stage 0 followed by five development and appraisal stages. Stage 0 established the research framing, occupational context, project scope, explicit claim boundaries, and allocation of responsibilities between the researcher and Elmech. Stage 1 comprised evidence acquisition, source-strength classification, and context-of-use analysis to identify evidence-grounded safety-support and operational needs.

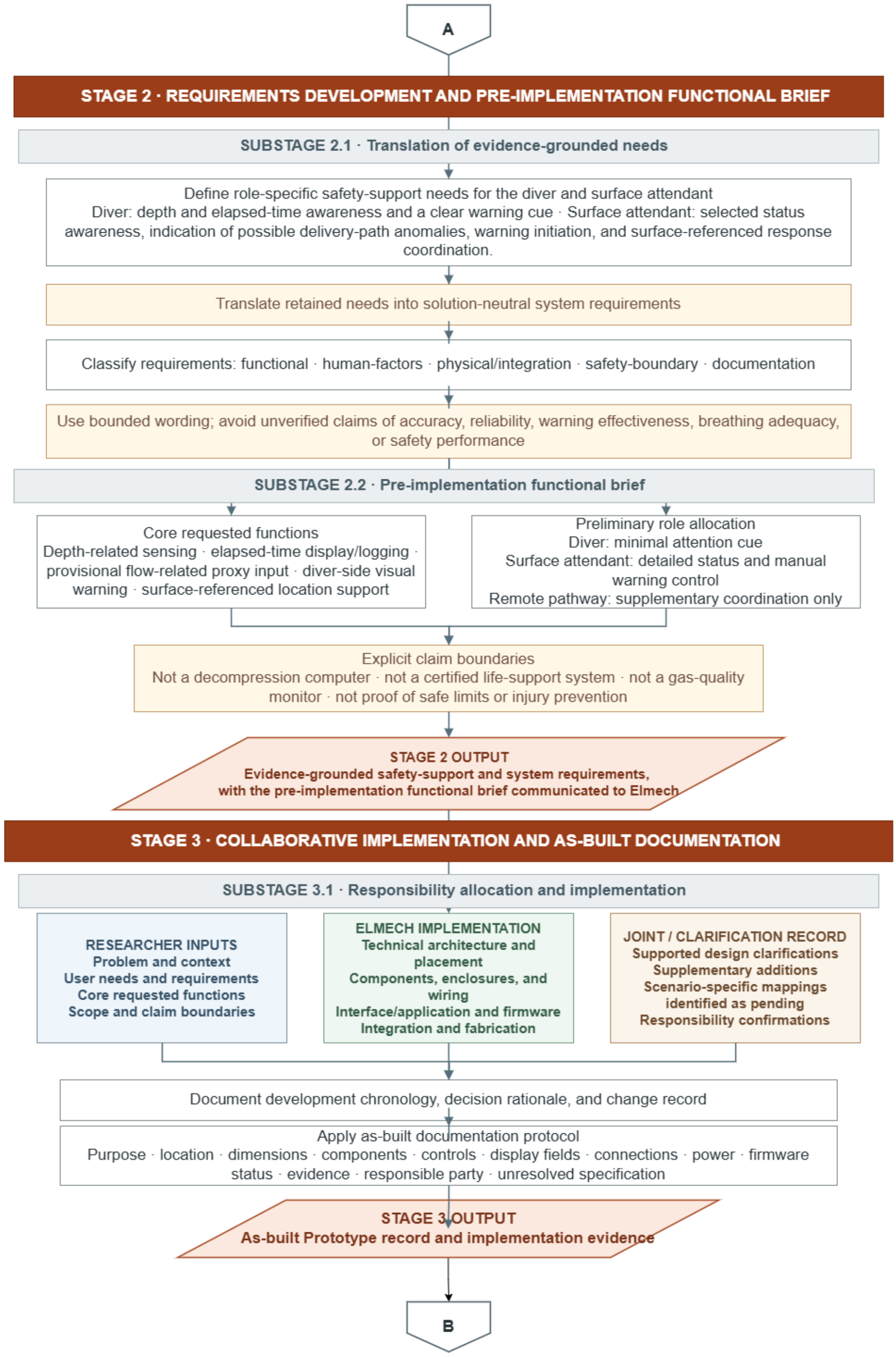

Figure 2. Requirements development and pre-implementation functional brief, followed by collaborative implementation and as-built documentation (Stages 2–3)

Stage 2 translated the retained needs into solution-neutral system requirements and a pre-implementation functional brief communicated to Elmech.

Stage 3 comprised collaborative prototype implementation and systematic documentation of the as-built configuration, development chronology, design clarifications, decision records, and responsibility ownership. Following implementation, Stage 4 applied an evidence-weighted engineering House of Quality, selective technology-transfer analysis, qualitative design-oriented Failure Mode and Effects Analysis, and weighted decision matrices to consolidate analytical priorities, design risks, documented alternatives, and future evidence requirements. Stage 5 assessed requirements-to-implementation traceability, implementation status, provisional flow-proxy treatment, preliminary cost evidence, residual limitations, and requirements for future verification and validation. Detailed scoring procedures and mathematical formulations are provided in the Supplementary Materials.

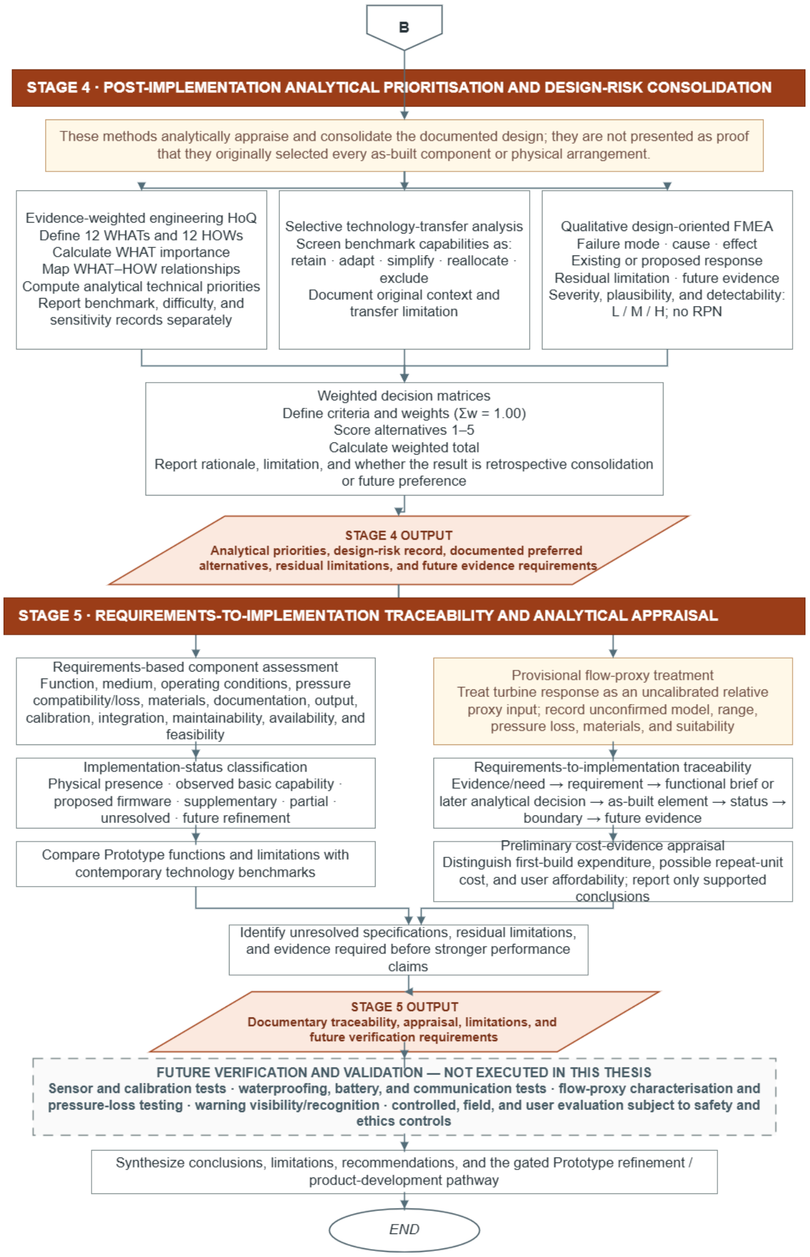

Figure 3. Post-implementation analytical prioritisation, requirements-to-implementation traceability, and future verification boundary (Stages 4–5).

This study employed a design-development approach within descriptive engineering research to develop a safety-support prototype for artisanal hookah divers using a human-centred design approach. Rather than experimentally evaluating system performance, the study focused on translating occupational safety needs into system requirements, communicating a pre-implementation functional brief, documenting collaborative implementation, and analytically appraising the resulting as-built configuration. As shown in Figure 1, the research comprised Stage 0 followed by five development and appraisal stages: (1) research framing; evidence and context-of-use analysis; (2) requirements development and pre-implementation functional briefing; (3) collaborative implementation and as-built documentation; (4)post-implementation analytical prioritisation and (5) design-risk consolidation; and requirements-to-implementation traceability and appraisal. The iterative user-evaluation stage of ISO 9241-210 was not completed and is acknowledged as a limitation.

System requirements were developed from preliminary field observations at Kenjeran Beach, peer-reviewed literature, relevant standards and technical guidance, and benchmarking of commercial dive computers. These sources were synthesised to identify user needs, which were translated into solution-neutral engineering requirements and a pre-implementation functional brief. Elmech proposals, design records, component information, interface and application materials, firmware records, and clarification documents were subsequently used to document the implementation process and as-built configuration.

Following implementation, an evidence-weighted House of Quality (HoQ) was used to relate the documented requirements to engineering characteristics and calculate conditional analytical priorities. Selective technology-transfer analysis screened benchmarked capabilities according to whether they should be retained, adapted, simplified, reallocated, or excluded. Qualitative Failure Mode and Effects Analysis (FMEA) consolidated design risks, existing responses, residual limitations, and future evidence requirements, while weighted decision matrices retrospectively compared documented alternatives and identified preferred options for future refinement. These analyses were used for post-implementation appraisal and are not presented as proof that they originally selected every as-built component or arrangement. Detailed scoring procedures and calculations are provided in the Supplementary Materials.

The prototype was collaboratively implemented with Elmech between February and July 2026. Following implementation, the prototype was evaluated through requirements-to-implementation traceability to assess the correspondence between intended requirements and implemented functions, together with a preliminary cost appraisal based on documented development expenditures. Since laboratory validation, human-subject testing, and operational field trials were beyond the scope of this study, the reported results describe the prototype development and implementation rather than its validated operational performance.

3.Results and Discussion

3.1 User Requirements and Engineering Prioritisation

Table 1. Work-system requirements, as-built responses, and interpretation boundaries

ID	Work-system need / requirement	As-built response and status	Boundary / next action
W1	Access current depth status for awareness	Pressure/depth-related output present; performance unverified	No safe-depth, no-decompression, or decompression claim
W2	Display and log elapsed submersion time	Surface duration field and logging specified	No automatic time cue; confirm start/stop/reset behaviour
W3	Recognise an abnormal relative flow-proxy condition	Turbine pulse input present; provisional proxy only	No calibrated L/min, fault diagnosis, or breathing-adequacy claim
W4	Provide a simple diver visual attention cue	One red indicator; blinking installed	Visibility, recognition, and scenario coding unverified
W5	Distinguish the condition at the surface	Display and beeper present	Readability and recognition unverified
W6	Allow the surface operator to activate the diver cue	Installed and functional over the wired path	Surface-to-diver only; no diver-triggered SOS
W7	Access a surface-referenced coordinate	Boat GPS and last surfaced-diver fix concept	No submerged-diver tracking
W8	Maintain local transfer without internet	Approximately 50 m wired power/data path	Continuity, voltage drop, latency, and routing unverified
W9	Integrate the proxy assembly with the documented hose	Small-port turbine/adapter arrangement	Bore, retention, pressure suitability, and leakage unresolved
W10	Provide power for the intended controlled period	12 V, approx. 7.2 Ah battery documented	Two-hour design target; measured runtime pending
W11	Resist water ingress in controlled immersion	Diver enclosure exists	No IP or deployment claim; testing pending
W12	Remain secured, inspectable, and serviceable	Forearm unit and separable assemblies documented	Mass, retention, and service procedure require reporting

The design process identified four primary safety-support requirements for artisanal hookah divers: (1) improving awareness of diving depth and elapsed dive time, (2) providing early indication of breathing-air delivery abnormalities, (3) enabling effective communication between the diver and the surface attendant, and

(4) supporting emergency response through surface-referenced location information. These requirements were derived from field observations, literature, technical standards, and technology benchmarking, and subsequently translated into engineering requirements for prototype development **Table 1**.

Following prototype implementation and documentation of the as-built configuration, the evidence-weighted House of Quality (HoQ) was applied as a post-implementation analytical appraisal, as shown in **Figure 4**. This analysis identified wired power/data-link continuity as the highest conditional engineering priority (18.82%), followed by surface monitoring and warning presentation (10.72%) and diver enclosure integrity (10.31%). These priorities indicate that reliable communication between the diver and the surface operator is more critical than adding increasingly sophisticated sensing functions. Unlike conventional dive computers, which primarily support individual diver awareness, the proposed system recognises that safety in artisanal hookah diving depends on continuous interaction between divers and the surface support team [4], [15], [18].

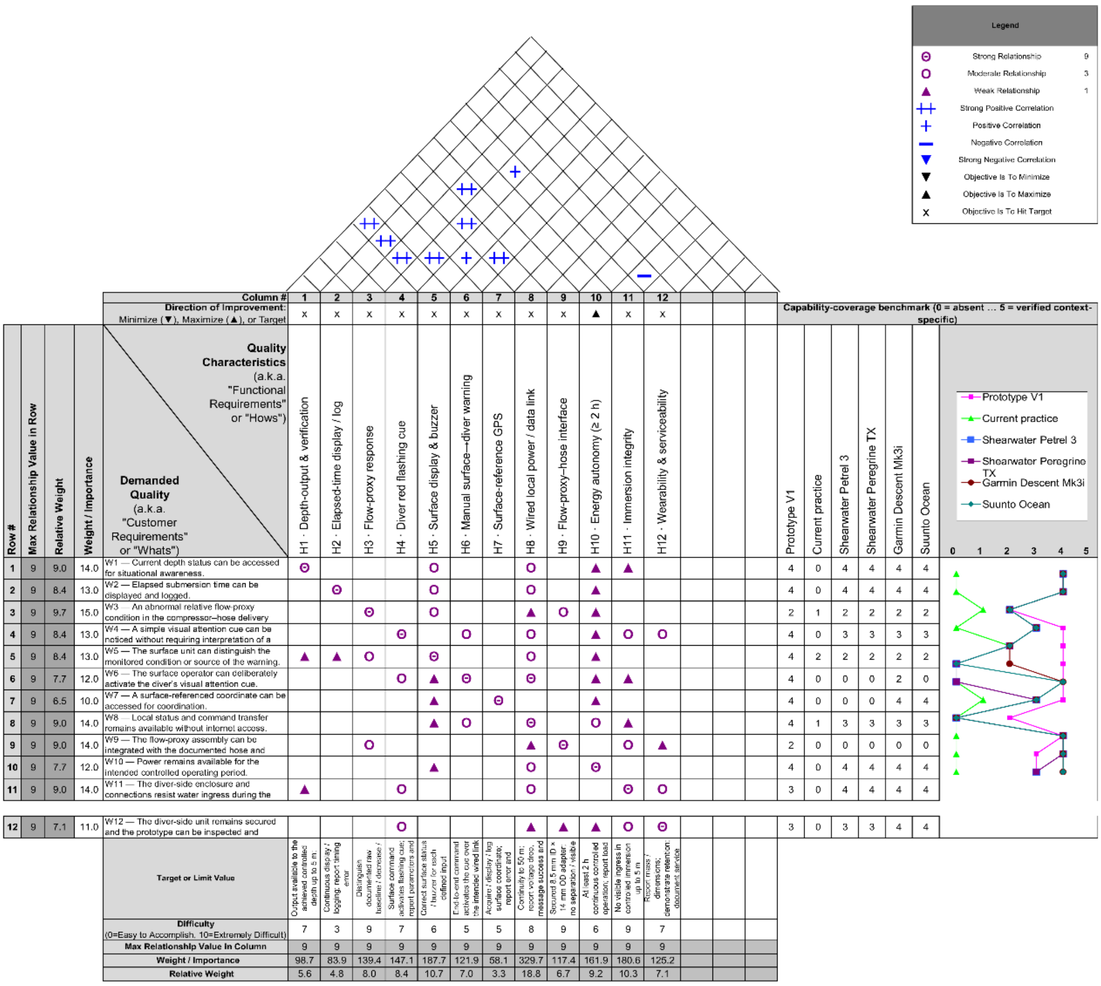

Figure 4. Evidence-weighted engineering House of Quality for the Prototype

This finding is consistent with previous studies reporting that many diving accidents in hookah fisheries are associated with failures in compressor operation, breathing-air delivery, and inadequate surface supervision rather than the absence of depth-monitoring technology [5], [8], [9]. From an occupational safety engineering perspective, these results demonstrate that improving communication reliability and shared situational awareness can reduce operational risk more effectively than focusing solely on individual sensing devices. Such a systems-based approach is widely recognised as an effective strategy for managing hazards in complex work environments [22], [23].

Table 2. Normalized technical priorities of the twelve engineering characteristics

Rank	Engineering characteristic (HOW)	Priority (%)
1	H8 · Wired local power/data-link continuity	18.82
2	H5 · Surface display and beeper status presentation	10.72
3	H11 · Diver-side enclosure and connection immersion integrity	10.31
4	H10 · Controlled-operation energy autonomy (≥ 2 h)	9.24
5	H4 · Diver-side red flashing cue activation and perceptibility	8.40
6	H3 · Relative flow-proxy response	7.96
7	H12 · Wearability, retention, and serviceability	7.15
8	H6 · Manual surface-to-diver warning transmission	6.96
9	H9 · Flow-proxy-hose mechanical interface compatibility	6.70
10	H1 · Depth-output functionality and verification	5.64
11	H2 · Elapsed-time display and logging	4.79
12	H7 · Surface-reference GPS	3.31

Source: HoQ calculation record (Authors, 2026); values are conditional engineering priorities within the constructed matrix, not verified performance

3.2 Prototype Development and Functional Implementation

Based on the retained safety-support needs and the pre-implementation functional brief, a safety-support prototype was developed consisting of a diver-mounted monitoring module, a surface monitoring and control unit, and a compressor-side flow-proxy module connected through a wired communication pathway Figure 3. The subsequent HoQ, FMEA, technology-transfer, and decision-matrix analyses were used to appraise the documented as-built configuration, consolidate analytical priorities and risks, and identify future refinement requirements rather than to claim that they originally determined every implemented component.The prototype provides depth monitoring, dive-time recording, manual surface-to-diver warning, and surface-referenced location information specifically adapted to the operational characteristics of artisanal hookah diving.

Requirements-to-implementation analysis demonstrated that the manual surface-to-diver warning pathway was successfully implemented, whereas airflow monitoring and automatic warning logic remain partially implemented and require further technical verification. The compressor-side turbine was therefore classified as a provisional flow proxy rather than a calibrated airflow sensor because its performance has not yet been validated under compressed-air operating conditions. This conservative interpretation avoids unsupported engineering claims while maintaining traceability between design objectives and implemented functions.

The results illustrate an important principle in safety-critical engineering: prototype functionality should be clearly distinguished from verified operational performance. Transparent reporting of implementation boundaries improves engineering credibility and facilitates subsequent verification and validation activities, which are essential before deployment of safety-related technologies [24], [25]. Data pathway **Figure 5**.

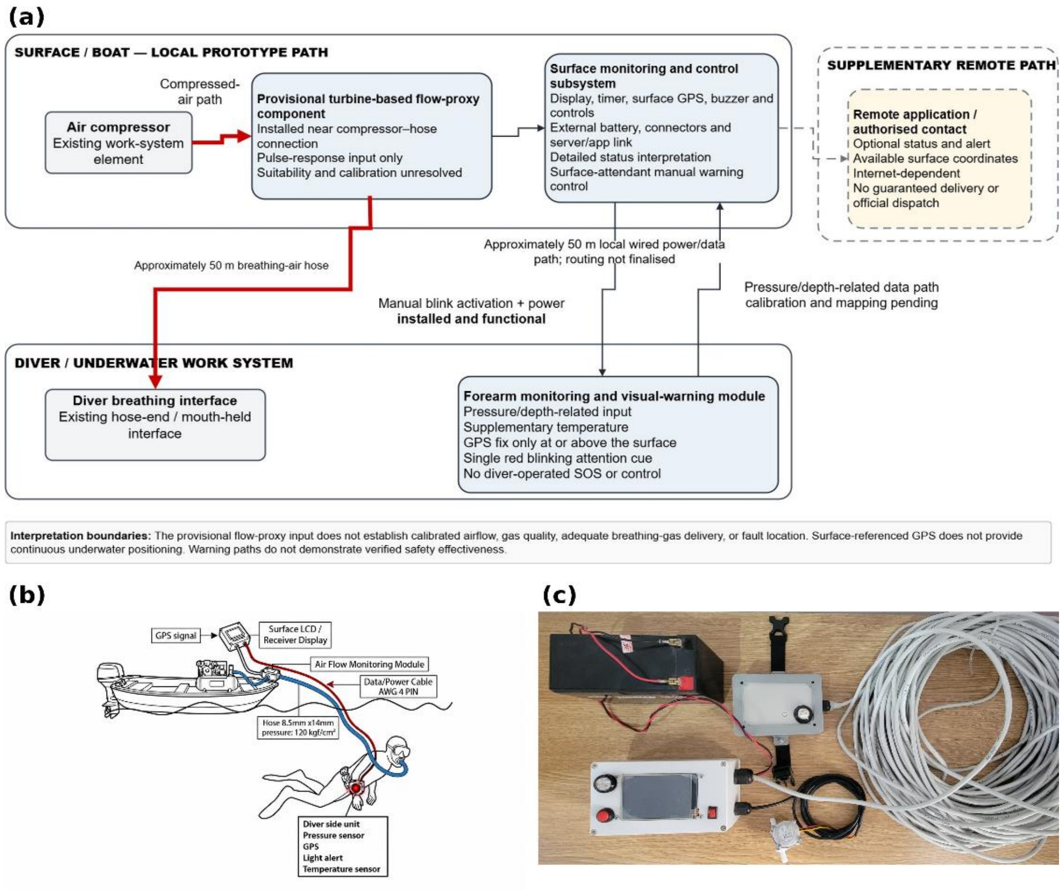

Figure 5. As-built Prototype: (a) system architecture and information allocation across the surface, diver, and supplementary remote paths; (b) deployment arrangement across boat, compressor hose, and diver, with documented hose (8.5 mm bore120 kgf/cm² rated) and four-conductor cable specifications; (c) photograph of the principal as-built assemblies (battery, diver module, surface display unit, provisional flow-proxy turbine, and approximately 50 m cable).

3.3 Contribution to Occupational Safety Engineering

The proposed prototype differs fundamentally from existing commercial dive computers. Commercial systems are designed primarily for recreational and professional SCUBA diving and focus on supporting individual divers, whereas the proposed architecture distributes monitoring and warning functions across the diver, the surface attendant, and the compressor system. This configuration more accurately represents the operational characteristics of artisanal hookah diving, where breathing-air delivery and emergency response depend on continuous surface supervision [4], [5], [18].

From an occupational safety engineering perspective, the prototype contributes in three important ways. First, it demonstrates the application of a human-centred engineering approach for translating operational safety needs into engineering requirements suitable for low-resource fisheries. Second, it proposes a work-system architecture that integrates diver monitoring, surface supervision, and manual warning communication into a single safety-support framework. Third, it introduces a transparent requirements-to-implementation process that explicitly distinguishes implemented functions from those requiring further verification, thereby supporting responsible development of safety-critical technologies [22], [24].

Beyond artisanal hookah diving, this engineering approach may also be applicable to other resource-constrained occupational environments where communication reliability, shared situational awareness, and coordinated human decision-making are more important than highly automated sensing systems [23], [25].

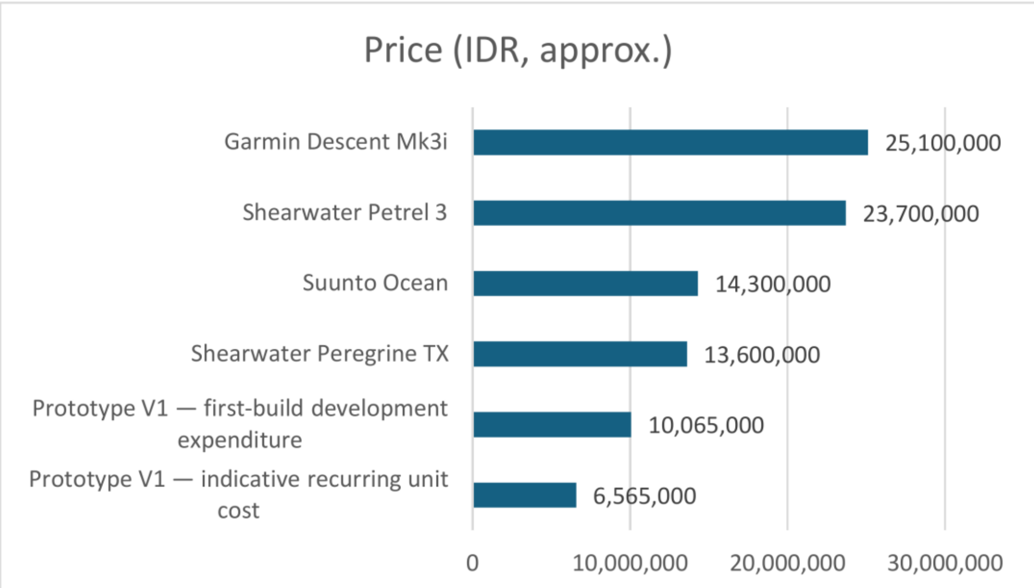

Figure 6. Prototype expenditure versus mid-2026 retail prices of benchmarked dive computers (IDR)

3.4 Cost Considerations and Future Development

The documented prototype development expenditure was approximately IDR 10.1 million, with an estimated recurring production cost of approximately IDR 6.5

million, both of which are lower than the retail prices of benchmarked commercial dive computers **Figure 6**. Although this comparison should not be interpreted as evidence of affordability or economic feasibility, it indicates that a context-specific safety-support system may be developed at a lower initial cost while addressing operational requirements that conventional dive computers do not consider.

This study presents an early-stage engineering prototype rather than a validated safety device. Sensor accuracy, communication reliability, waterproof integrity, battery endurance, ergonomic suitability, and operational effectiveness remain to be experimentally verified before deployment. Future research should therefore focus on laboratory characterisation, human-factors evaluation, controlled field validation, and compliance assessment to establish the prototype's technical reliability and practical effectiveness [24], [25].

4. Conclusion

This study developed a human-centred safety-support prototype tailored to the operational characteristics of artisanal hookah diving. By systematically translating user needs and occupational safety challenges into engineering requirements, the study demonstrates a structured approach for designing safety-support technologies for low-resource diving environments. Rather than adapting existing commercial dive computers, the proposed system introduces a work-system architecture that integrates diver monitoring, surface supervision, and communication to address hazards specific to surface-supplied compressor diving.

The principal scientific contribution of this research lies in demonstrating how human-centred design, evidence-based engineering prioritisation, and requirements-to-implementation traceability can be integrated into the development of an occupational safety-support system. This approach extends the application of engineering design methods beyond conventional recreational diving technologies by addressing the operational realities of artisanal fisheries. From a practical perspective, the prototype provides a foundation for developing affordable and context-appropriate safety-support systems that may improve situational awareness, communication, and emergency coordination in small-scale fishing operations.

The proposed prototype represents an early-stage engineering development and has not yet undergone comprehensive technical or operational validation. Future research should therefore focus on sensor validation, human-factors evaluation, controlled field testing, and compliance assessment to verify system performance and support practical implementation. The design framework presented in this study may also serve as a reference for developing occupational safety technologies in other resource-constrained work environments.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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