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Risk-informed decision making for beach nourishment: integrating technical, environmental and operational criteria

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Abstract: Beach nourishment requires repeated decisions during planning, construction, monitoring, and maintenance. These decisions rely on technical, environmental, and operational information collected throughout the project. However, monitoring results do not always lead to clear management responses, and different indicators may provide conflicting assessments. This study proposes a practical risk-informed framework for operational decision making in beach nourishment projects. The framework integrates technical, environmental, and operational criteria without combining them into a single weighted score. Observed conditions are classified into four classes: acceptable, uncertain, correctable deviation, and critical. The four conditions are linked to four responses: continue, verify, modify, or stop and reassess. The framework considers uncertainty in monitoring information and subsequent corrective actions. A non-compensatory logic prevents good performance in one dimension from offsetting a critical condition in another. Economic and management implications are considered as consequences of operational decisions. Illustrative scenarios show how the framework supports decisions during sediment selection, dredging, placement, monitoring, and maintenance. The approach does not replace engineering judgement or provide a formal probabilistic risk assessment. Instead, it organizes available evidence within a transparent and traceable decision process using information already collected by standard nourishment monitoring and quality-control programmes.

Keywords: Beach nourishment, Decision support, Risk-informed management, Environmental monitoring, Operational control, Uncertainty

1. Introduction

Beach nourishment is widely used to manage coastal erosion while maintaining the functions of sandy beaches [1-4]. It can provide coastal protection without the permanent footprint associated with many hard structures [1]. However, nourishment projects require repeated decisions before, during, and after construction. Their performance therefore depends on appropriate engineering design, monitoring, and management practices [5-7].

A typical nourishment project generates information throughout its lifecycle. Borrow-area studies describe sediment characteristics and available resources. Construction monitoring provides data on dredging, transport, placement, and environmental conditions. Post-construction surveys assess beach geometry, sediment redistribution, and subsequent morphological response [8, 9]. These datasets provide the evidence needed to evaluate

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project performance.

Monitoring capabilities have improved substantially during recent decades. Sediment assessment now combines sampling, grain-size analysis, compatibility criteria, and post-placement verification [8, 10]. Global Navigation Satellite System (GNSS), Unmanned Aerial Vehicle (UAV) surveys, and bathymetric techniques provide detailed information on placement and morphological evolution [11-13]. Environmental monitoring can also identify changes associated with dredging and sediment discharge [14]. Such activities may have ecological effects that require assessment [15-16].

The main difficulty often lies between observation and management action. A measured variable must be interpreted against a project objective or requirement. The reliability of the evidence must also be considered. Managers must then determine whether operations should continue or require intervention. This transition is not always explicitly structured in nourishment control procedures.

The problem becomes more important when several indicators provide different assessments. Sediment characteristics may be acceptable while placement performance remains inadequate. Construction targets may be achieved while environmental conditions approach unacceptable levels. Contractual compliance at completion also does not ensure satisfactory subsequent beach behaviour. Operational decisions must therefore consider several dimensions simultaneously [17-19].

Decision-support methods offer established approaches for problems involving multiple and sometimes conflicting criteria [20, 21]. Multi-Criteria Decision Analysis (MCDA) methods are increasingly used within coastal planning and management. Sauve et al. [17] applied Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) to compare coastal defence measures using criteria identified with managers and professionals. Their study showed how multiple perspectives can be incorporated within a structured coastal decision process. Similar approaches have been developed for other coastal adaptation problems. Skidmore and Cohon [19] proposed an MCDA framework for managed retreat under competing economic, social, and policy objectives. More recent studies have used multi-criteria methods to prioritize coastal adaptation strategies using environmental, economic, social, and sustainability criteria [18, 22]. These approaches are particularly useful when several alternatives must be compared and ranked [17-20, 22]. Comparable multicriteria applications in other decision contexts further illustrate the flexibility of structured evaluation methods [23, 24].

Recent decision-support research has extended conventional MCDA through fuzzy representations of uncertain information. Circular picture fuzzy methods can represent uncertainty when alternatives are evaluated under multiple criteria [25].

Related developments combine intuitionistic fuzzy information with specific decision-ranking procedures. The recent Intuitionistic Fuzzy Optimized Pairwise Ratio Analysis (IF-OPARA) framework provides one example for decisions involving uncertain assessments [26]. These methods extend the analytical treatment of uncertainty within alternative-ranking problems.

Beach nourishment operational control presents a different decision problem. The management measure has already been selected, and construction may already be underway. Managers must therefore determine how observed conditions should affect an ongoing operation rather than choose among alternative coastal strategies. Structured decision analysis can also support the assessment of management options under changing conditions [27].

Uncertainty further complicates this process. Measurements can be accurate while the underlying evidence remains insufficient or unrepresentative [28]. Laboratory sediment analysis may be reliable while the sampled material poorly represents the dredged deposit [29]. Environmental observations may also require confirmation before demonstrating persistent non-compliance. Uncertain evidence and confirmed failure should not automatically produce the same response.

Risk-based approaches provide a rigorous basis for decisions when probabilities and consequences can be quantified [30]. However, routine nourishment operations rarely provide such information for every decision. Some responses must be selected from limited observations and within short time periods. A risk-informed approach can therefore be more suitable because it considers adverse conditions and uncertainty without requiring a complete probabilistic model.

Another issue concerns the aggregation of decision criteria. Many MCDA methods combine criteria through weights, preferences, or pairwise comparisons [17-20]. Such approaches are appropriate when trade-offs have a clear decision meaning. However, some operational requirements behave as constraints rather than preferences and may require action regardless of satisfactory performance elsewhere.

This distinction is important during nourishment works. High dredging productivity cannot compensate for a critical environmental condition. Likewise, satisfactory environmental performance cannot compensate for confirmed use of unsuitable sediment. A single aggregated score could obscure the condition responsible for intervention. A non-compensatory structure may therefore be preferable for these operational decisions.

Existing nourishment procedures provide detailed guidance for project monitoring and compliance assessment [7, 31-34]. Coastal monitoring initiatives also demonstrate how observations can inform the assessment of changing coastal conditions [35, 36]. A narrower methodological issue remains during ongoing nourishment operations. Evidence may differ in reliability,

while confirmed deviations may differ in their capacity for correction. The framework therefore addresses how available evidence is translated into an operational condition and corresponding response. This classification is applied consistently throughout the nourishment lifecycle.

This study proposes a risk-informed framework for operational decisions after beach nourishment has already been selected. Its contribution lies in a common procedure for classifying evidence and selecting the corresponding management response. The framework considers evidence from different project dimensions without combining them into a single performance score. It therefore preserves critical requirements while maintaining a consistent operational decision sequence.

It does not rank alternative coastal protection strategies or calculate a composite performance score. Instead, it links observed project conditions with predefined levels of management response.

The framework distinguishes acceptable conditions, uncertainty, correctable deviations, and critical conditions. These situations are associated with four responses: **continue, verify, modify, and stop/reassess**. A non-compensatory rule prevents critical conditions from being offset by satisfactory performance in another dimension. Subsequent monitoring provides feedback after each management action.

The study has three main objectives. First, it identifies indicators that can support operational decisions during beach nourishment. Second, it establishes a transparent link between evidence, uncertainty, and management response. Third, it examines the resulting decision logic using representative operational scenarios. The overall aim is to support consistent decisions using information already generated during routine nourishment monitoring.

2. Methods

2.1 Framework development

The framework was developed to support operational decisions during beach nourishment projects. Its design followed an evidence-informed approach based on published coastal engineering and decision-support studies [17, 22, 27, 31-34]. The analysis focused on information normally available during nourishment control and monitoring. No additional field measurements, expert surveys, or numerical optimization were required.

Framework development followed four steps. First, the main decision stages of a nourishment project were defined. Second, candidate decision indicators were screened according to their operational relevance and routine availability, as described in Section 2.2. Third, uncertainty and condition classes were incorporated into the decision process. Finally, decision rules were defined to connect observed conditions with management responses.

The framework addresses decisions after beach nourishment has been selected as the management intervention. It therefore excludes the strategic comparison of nourishment with seawalls, retreat, or other adaptation measures. Such comparisons are commonly addressed using MCDA and related methods [17-19, 22]. The present framework instead focuses on decisions arising during project implementation and subsequent monitoring.

Five decision stages were considered: planning, dredging, placement, post-construction monitoring, and maintenance. These stages represent the main sequence of nourishment control activities. Information generated during each stage can modify decisions taken later in the project. The resulting structure therefore follows a sequential rather than a single-decision approach.

2.2 Identification and classification of decision criteria

Decision criteria were identified from published nourishment studies, coastal management literature, and documented operational control practices [7-10, 31-34, 37-38]. Only criteria with a clear relationship to a management action were retained. Preference was given to variables commonly available during standard project monitoring. Indicators requiring specialized information not normally collected during nourishment were excluded.

Indicator selection followed an operational screening procedure rather than a systematic literature review. Candidate indicators were first examined for their direct relevance to decisions arising during beach nourishment.

Indicators were retained when their interpretation could reasonably lead to a change in project operation or monitoring. Preference was also given to indicators obtainable through routine project control without requiring additional specialized investigations.

Indicators were excluded when they lacked a clear operational response or depended primarily on information not routinely available during nourishment projects. Similar indicators describing the same operational condition were consolidated to avoid unnecessary duplication.

The selected criteria were grouped into three dimensions: **technical, environmental, and operational**. This classification preserves the engineering meaning of each indicator. It also allows different project requirements to be assessed independently. Economic implications were considered as consequences of operational decisions rather than as a separate weighted dimension.

Technical criteria describe sediment suitability and physical project performance [8-10]. They include sediment representativeness, grain-size compatibility, placed volume, achieved geometry, and subsequent morphological response [12-13]. These variables support decisions concerning material acceptance and construction

compliance. They can also indicate whether later reassessment is required.

Environmental criteria represent conditions that may constrain dredging or placement activities [14]. They include turbidity, suspended sediment concentration, plume behaviour, and project-specific environmental requirements [14, 32]. No universal environmental limits were assigned. Applicable thresholds remain dependent on regulation, permits, and local environmental conditions [32, 33].

Operational criteria describe how the planned works are executed. They include dredging productivity, placement accuracy, positioning, volume control, and operational continuity [31, 32, 34]. These variables help identify whether a deviation originates from project design or execution. They also support the selection of corrective measures during construction.

The initial indicator set was compared with criteria reported in coastal decision-support studies. This comparison was used to check conceptual coverage rather than assign weights. Previous MCDA applications have emphasized technical, environmental, economic, and management criteria when comparing coastal interventions [17, 18, 22]. Recent multi-criteria applications have followed a similar multidimensional structure for coastal adaptation planning [18, 22].

2.3 Treatment of uncertainty

Uncertainty was incorporated because available observations do not always justify an immediate operational change. The framework therefore distinguishes uncertain evidence from confirmed deviation. This distinction prevents limited information from being interpreted automatically as non-compliance. It also provides a specific pathway for additional verification.

Three practical uncertainty sources were considered. **Observation uncertainty** concerns the reliability or representativeness of measured information. **Interpretation uncertainty** concerns the significance assigned to an observed change. **Implementation uncertainty** concerns whether a selected corrective action produces the intended result. Monitoring programmes for coastal infrastructure illustrate the importance of systematic observations [39]. Advances in wave run-up measurement techniques also provide relevant context for assessing observational limitations [40].

Observation uncertainty can arise from sediment sampling, survey accuracy, sensor performance, or limited monitoring duration [11, 29]. A representative problem occurs when laboratory results are reliable but the collected sediment sample is questionable [29]. In this situation, the uncertainty concerns the evidence itself. Additional verification is therefore preferable to immediate classification as sediment failure.

Interpretation uncertainty becomes relevant when the measured change can have several explanations [41]. Post-nourishment morphological changes may reflect short-term adjustment or storm-induced responses, making their interpretation dependent on the prevailing conditions [42]. Temporary turbidity increases provide another [14]. Comparable environmental responses have been reported across nourishment projects under different sediment and monitoring conditions [16]. Available project context is therefore considered before assigning the final condition class.

Implementation uncertainty occurs after a management response has been selected [34, 36]. Corrective actions may be incomplete or may produce unexpected effects. Monitoring must therefore continue after modification or restart [34, 36]. This creates feedback between operational action and subsequent assessment.

No probability distributions were assigned to these uncertainty sources. The framework is risk-informed rather than a formal probabilistic risk assessment [30]. Uncertainty instead affects confidence in the assigned condition. This choice maintains compatibility with routine nourishment monitoring.

Uncertainty is assessed through a structured check rather than assigned a numerical score. The user first determines whether the available evidence is sufficiently reliable to assess the relevant requirement. Observation uncertainty requires verification when measurement quality or representativeness remains questionable. Interpretation uncertainty applies when reliable evidence does not support a sufficiently clear interpretation against the relevant requirement.

Implementation uncertainty is assessed after corrective action. It remains unresolved until subsequent monitoring confirms that the intended operational condition has been restored. A deviation is confirmed only when the evidence is reliable and its interpretation is sufficiently clear. The decision remains uncertain until additional evidence resolves the identified source of uncertainty.

2.4 Condition assessment and decision rules

Each indicator is assessed against the evidence available for the corresponding project stage. Numerical thresholds can originate from design specifications, contracts, permits, or regulatory requirements [32-33, 43, 44]. The framework does not replace these project-specific limits. It defines how their interpretation contributes to a management response.

Four operational conditions were considered: **acceptable, uncertain, correctable deviation, and critical**. An acceptable condition requires no additional action beyond routine monitoring. An uncertain condition indicates that available evidence remains insufficient for a reliable decision. A correctable deviation identifies confirmed non-compliance that can be addressed without full reassessment.

Classification first considers whether the available evidence is sufficient to assess the relevant requirement.

Insufficient evidence leads to an uncertain condition and requires further verification. When a deviation is confirmed, its correctability determines the subsequent classification. A deviation is classified as correctable when compliance can be restored within the applicable project requirements.

A deviation becomes critical when correction is no longer feasible without reassessment or when a mandatory requirement is exceeded. Persistent deviations may also become critical when continued operation increases adverse consequences. This sequence separates uncertainty in the evidence from confirmed non-compliance and provides a consistent basis for classification.

A critical condition represents a serious or persistent deviation requiring stronger intervention. Its classification depends on the consequence of continued operation and applicable project requirements. Critical conditions may arise within any of the three decision dimensions. Legal or permit requirements always take precedence over the general framework [43, 44].

Four responses correspond to these conditions: **continue, verify, modify, and stop/reassess**. The response level increases with evidence and potential consequences. Verification is therefore distinct from corrective intervention. This distinction prevents unnecessary modification when the primary problem is insufficient information.

Thresholds remain project-specific, but their role in classification is consistent. Examples include sediment-compatibility limits established during design [10, 45] or turbidity limits defined by environmental permits. Construction tolerances may provide equivalent thresholds for placed volume or beach geometry. Exceedance does not automatically imply a critical condition unless the applicable requirement or consequence justifies that response.

Thresholds should be established before operational assessment whenever formal limits are available. Their source should also be recorded to preserve traceability. Regulatory limits and permit conditions take precedence when applicable. Otherwise, project specifications or documented baseline conditions may define the relevant decision threshold. Thus, threshold calibration should reflect the indicator and the consequence associated with exceedance. The framework does not redefine these limits, but it requires their decision role to be explicit before classification.

2.5 Non-compensatory decision logic

The framework uses a non-compensatory rule for critical requirements. Technical, environmental, and operational indicators are therefore not combined into a single weighted score. Performance in one dimension cannot neutralize a critical condition in another. This rule preserves the decision significance of mandatory requirements.

This approach differs from many MCDA applications used for coastal planning. Complete aggregation methods combine criteria to obtain an overall measure of alternative performance [17-22]. Outranking approaches instead compare alternatives while retaining preference relationships among criteria [17]. Both approaches are valuable when the objective is to compare or rank competing management options [17-22].

The present problem has a different structure. During construction, some criteria act as operational constraints rather than preferences. A critical environmental condition requires attention even when technical performance is satisfactory. Similarly, unacceptable sediment cannot be justified by high dredging productivity.

The non-compensatory rule applies only to conditions classified as critical. Correctable deviations remain subject to project context and corrective capacity. Trade-offs may therefore be considered when no mandatory requirement is violated. This preserves engineering flexibility without allowing critical conditions to be offset by satisfactory performance elsewhere.

Compensatory reasoning may also support the selection among several feasible corrective responses. In such cases, MCDA or outranking methods can complement the framework by comparing alternatives that already satisfy mandatory requirements [17-18, 22]. The non-compensatory rule therefore determines when compensation is unacceptable rather than excluding trade-offs from routine project management.

2.6 Decision sequence and reproducibility

The decision procedure follows the same sequence for every evaluated condition. First, the relevant project objective and indicator are identified. Second, the available evidence and its uncertainty are assessed. Third, the operational condition is classified.

The corresponding response is then selected using the predefined decision rules. Conditions from the remaining dimensions are checked before implementation. A critical condition can override otherwise acceptable project performance. The selected action is subsequently evaluated through continued monitoring.

This sequence provides a structured and traceable record of the decision process. Each assessment documents the indicator and the evidence used to evaluate it. The identified uncertainty source and resulting condition are also recorded. When verification is required, the additional evidence and subsequent classification are documented before further action. This record allows the reasoning behind each decision to be traced by different project teams. Project-specific thresholds remain documented separately from the general decision logic [43, 44].

2.7 Illustrative application

Four representative situations were used to examine the internal behaviour of the framework. They address uncertain sediment representativeness, confirmed sediment incompatibility, environmental disturbance, and poor post-nourishment performance. The scenarios cover different project stages and decision dimensions. They also include cases with conflicting indicators.

Each scenario was evaluated using the same procedure described in Section 2.6. The available evidence was identified first. Its uncertainty and operational significance were then assessed. Finally, the condition class and corresponding management response were determined.

The scenarios provide an illustrative application rather than independent empirical validation. Their purpose is to examine the consistency and practical interpretation of the decision rules. Where suitable observations were available, the scenarios were linked to documented nourishment experience. This provides empirical context for selected indicators and conditions but does not validate the framework itself. No statistical performance measures were derived from these examples. External validation against documented management decisions is therefore considered a subsequent development stage.

3. Results

3.1 Decision criteria across the nourishment lifecycle

The framework identified three groups of indicators for operational decision making. These groups are technical, environmental, and operational. Each group supports different project objectives and management actions. Their relevance changes throughout the nourishment lifecycle.

Technical indicators describe sediment suitability and physical project performance. They include sediment representativeness, grain-size compatibility, placed volume, achieved geometry, and later morphological response [8-13, 29, 37, 38]. These variables support material acceptance, construction control, and post-project assessment. Their importance is already well established within nourishment quality-control practice [7-13, 34, 37, 38].

Table 1. Decision indicators describing technical performance, environmental effects, and operational execution across the beach nourishment lifecycle

Indicator	Project stage	Main evidence	Decision relevance
TECHNICAL physical performance and compliance			
Sediment representativeness	Planning/Dredging	Samples and sampling records	Reliability of characterization
Grain-size compatibility	Planning/Dredging	Grain-size distributions	Borrow-material acceptance
Placed volume	Placement/Post-construction	Topographic/bathymetric surveys	Construction compliance
Achieved beach geometry	Placement/Post-construction	Profiles, GNSS, UAV	Design compliance
Post-nourishment response	Monitoring/Maintenance	Repeated surveys	Performance/maintenance
ENVIRONMENTAL effects and environmental constraints			
Turbidity	Dredging/Placement	Turbidity monitoring	Short-term disturbance
Suspended sediment concentration	Dredging/Placement	Water samples/sensors	Suspended sediment load
Plume behaviour	Dredging/Placement	Visual/instrumental monitoring	Extent and persistence
OPERATIONAL execution and process control			
Dredging productivity	Dredging	Production records	Operational efficiency
Placement positioning	Placement	GNSS/construction records	Placement accuracy
Material balance	Dredging/Placement	Dredging/survey records	Quantity consistency
Operational continuity	Dredging/Placement	Daily records	Execution reliability

Environmental indicators describe conditions that can constrain dredging or placement [14, 16, 32, 33]. Turbidity, suspended sediment concentration, and plume behaviour are common examples [14]. Their significance depends on local regulation, background conditions, and environmental sensitivity [15, 16, 32, 33]. Previous nourishment studies have shown the value of plume extent and persistence for assessing operational disturbance [7, 14].

Operational indicators describe how efficiently and accurately the works are executed [11, 31-34, 39]. They include dredging productivity, placement accuracy, positioning, volume control, and operational continuity [34]. These indicators help separate design problems from execution problems. They also provide direct evidence for corrective action.

Table 1 summarizes the resulting indicator structure. No universal numerical limits are proposed. Thresholds must remain linked to contracts, permits, technical specifications, or local regulation [31-32, 43, 44]. The framework instead defines how those thresholds affect management decisions.

The indicators do not all perform the same function. Some represent formal compliance requirements. Others identify uncertainty, changing conditions, or possible loss of performance. Their interpretation therefore depends on both evidence and project context.

3.2 Decision structure and condition classes

The resulting framework links six elements within a repeated decision sequence. These are objectives, monitoring data, indicators, uncertainty, condition assessment, and operational response. Subsequent monitoring closes the process after each action. Figure 1 shows how the six decision elements are implemented through seven procedural steps and subsequent feedback.

The three decision dimensions remain separate during condition assessment. They are integrated only when the management response is selected. This prevents the origin of an uncertain, correctable, or critical condition from becoming hidden. It also supports direct traceability from evidence to action.

Thus, the framework distinguishes four operational conditions: **acceptable, uncertain, correctable deviation, and critical**. These classes describe the management significance of available evidence. They do not represent probability ranges. Their interpretation is summarized in Table 2.

Table 2. Condition classes linking monitoring evidence, decision interpretation, and management response

Condition class	Evidence	Decision interpretation	Management response
Acceptable	Evidence is consistent and sufficient	Project requirement is satisfied	CONTINUE
Uncertain	Evidence is incomplete, inconsistent, or insufficient	Compliance cannot yet be confirmed	VERIFY
Correctable deviation	Non-compliance is confirmed but manageable	Performance can be restored through corrective action	MODIFY
Critical	Serious or persistent deviation is confirmed, or a mandatory limit is exceeded.	Continued operation may increase adverse consequences	STOP/REASSESS

The distinction between uncertainty and confirmed deviation is important. An uncertain result does not demonstrate project failure. It instead indicates that the available evidence is insufficient to support a definitive decision. Verification therefore becomes an explicit management response.

A correctable deviation differs from a critical condition. Both indicate unacceptable performance, but their operational consequences differ. Correctable deviations can often be addressed without suspending the entire operation. Critical conditions require a stronger response.

The framework follows a non-compensatory rule for these critical conditions. Technical, environmental, and operational results are not averaged into one performance score. A critical condition can therefore determine the response independently. Good performance elsewhere cannot neutralize that requirement.

Figure 2 places this logic within the nourishment lifecycle. The five stages are planning, dredging, placement, post-construction monitoring, and maintenance. Different indicators dominate different stages. However, the same decision logic applies throughout the process. Figure 2 shows how the three decision dimensions contribute across the different stages of the nourishment lifecycle.

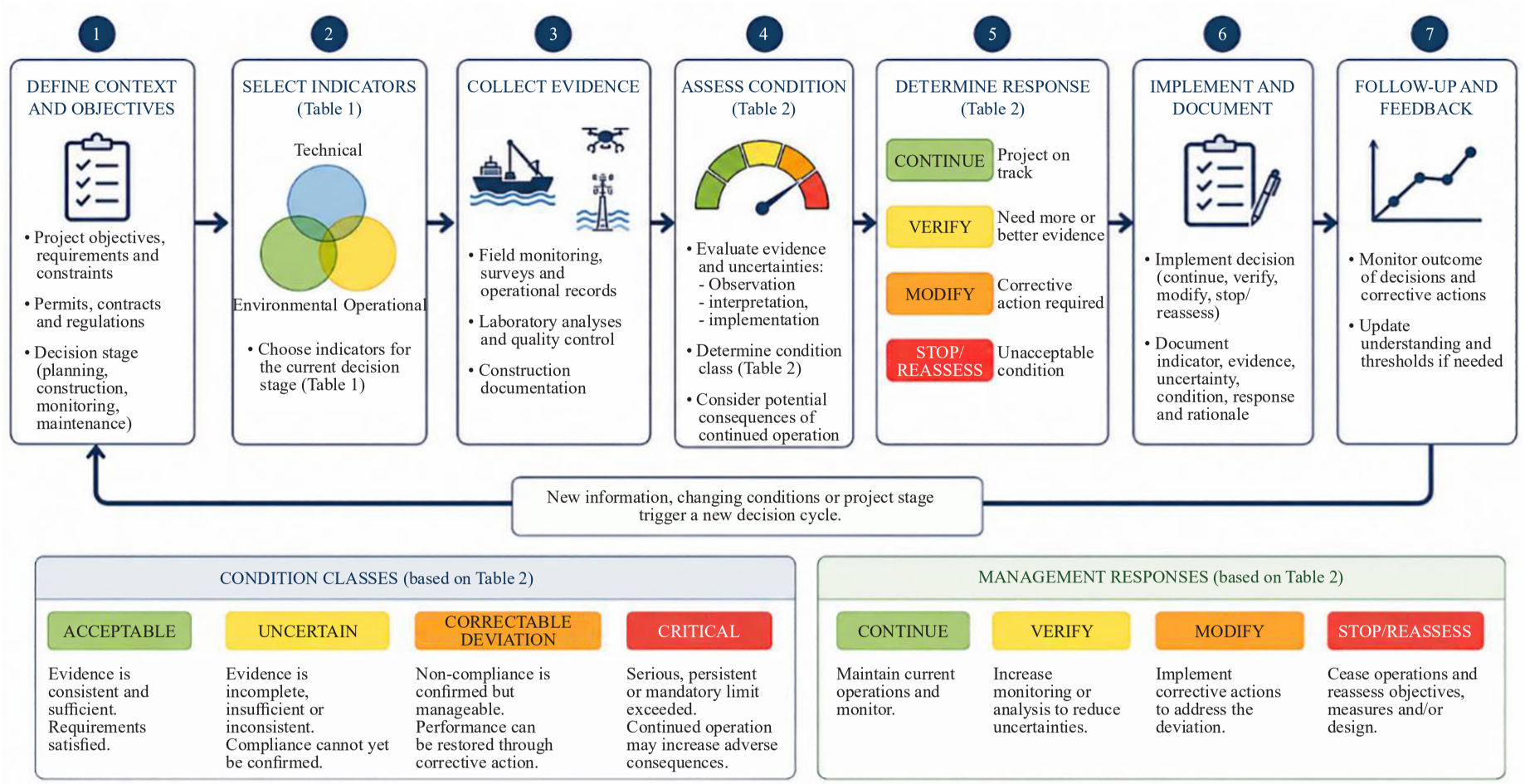


Figure 1. Risk-informed decision process linking monitoring information with operational responses during beach nourishment

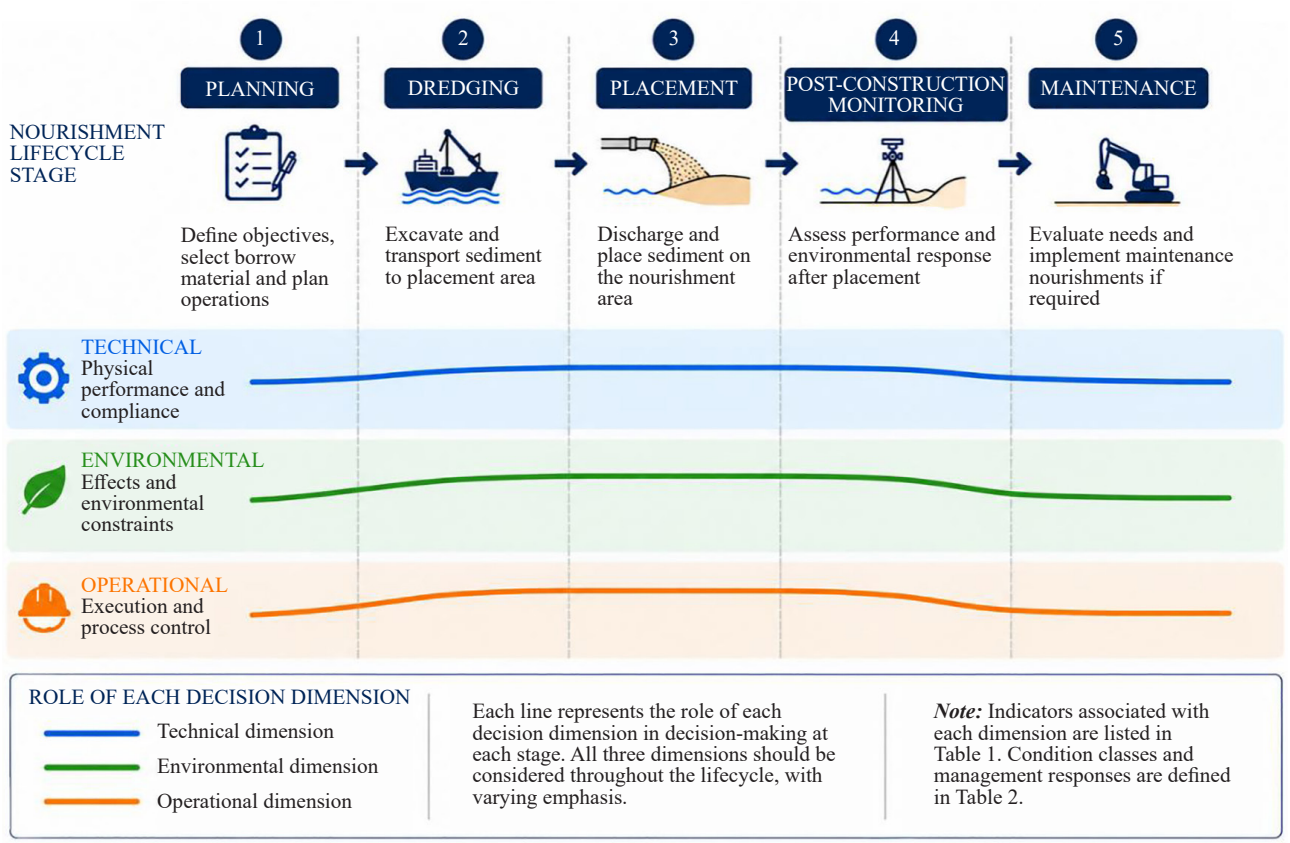


Figure 2. Technical, environmental and operational decision dimensions across the beach nourishment lifecycle

Technical criteria are important from sediment selection to post-construction assessment [8-13, 29, 38]. Environmental criteria are most active during dredging and placement [14-16, 32]. Operational criteria dominate construction and verification activities [11, 32-34]. Their relative importance can therefore change without changing the general framework.

3.3 Illustrative application of the decision rules

Four representative situations were used to examine the decision logic. They cover sediment characterization, material acceptance, environmental control, and post-nourishment performance. Each scenario was evaluated using the same sequence. Figure 3 summarizes the resulting response pathway.

Scenario 1. Uncertain sediment representativeness

A sediment sample satisfies the adopted grain-size requirement. However, available information questions whether the sample represents the dredged material [29]. The analytical result is therefore insufficient for final acceptance. The condition is classified as uncertain.

The resulting response is **VERIFY**. Additional representative sampling is required before confirming sediment suitability. This response separates uncertainty in evidence from confirmed sediment incompatibility. It avoids rejecting suitable material on weak evidence.

Scenario 2. Confirmed sediment incompatibility

Representative sampling indicates that the borrow sediment fails to meet the adopted suitability criteria for beach nourishment [45]. The problem is therefore no longer related to uncertainty. Continued use of the material may affect nourishment performance. The condition is classified as a correctable deviation when another suitable source remains available.

The corresponding response is **MODIFY**. Possible actions include changing the borrow sector or adjusting sediment selection. A stronger response may be required if no suitable material remains available. The management action therefore depends on corrective capacity. If no compliant borrow source or corrective option remains available, the condition becomes critical and the response changes to **STOP/REASSESS**.

Scenario 3. Environmental disturbance during satisfactory construction

Sediment compatibility and construction performance remain within the expected range. Environmental monitoring, however, identifies elevated turbidity or persistent plume behaviour. The indicators therefore provide conflicting assessments. Technical performance alone cannot determine the response.

An uncertain environmental observation first

leads to **VERIFY**. A confirmed correctable deviation leads to **MODIFY**. A persistent critical exceedance requires **STOP/REASSESS**. Technical and operational performance do not compensate for the environmental condition.

This scenario is supported by observations from dredging and nourishment at Trafalgar and El Palmar [14]. Field monitoring documented plume extent and persistence during the works. The study also examined relationships between turbidity and suspended sediment. These observations provide an empirical basis for the environmental indicators represented in this scenario. However, the original project was not managed using the present framework. The example therefore supports indicator relevance rather than providing retrospective validation of the decision rules.

Scenario 4. Acceptable construction followed by poor beach response

Construction surveys confirm the planned volume and geometry. The works therefore satisfy the immediate construction requirements. Later monitoring, however, shows an unexpected loss of beach performance. Construction compliance and subsequent behaviour then provide different assessments.

The first response may be **VERIFY**, especially during early morphological adjustment. Persistent poor performance requires **STOP/REASSESS** and may justify maintenance. This scenario shows that project completion does not represent the end of the decision process. Post-construction monitoring remains part of nourishment management [12, 13, 38, 41, 42, 46, 47].

The four scenarios demonstrate how similar observations can lead to different actions under different levels of certainty. They also show why several dimensions should be considered together. Each response remains linked to the condition that triggered it. No composite numerical score is required.

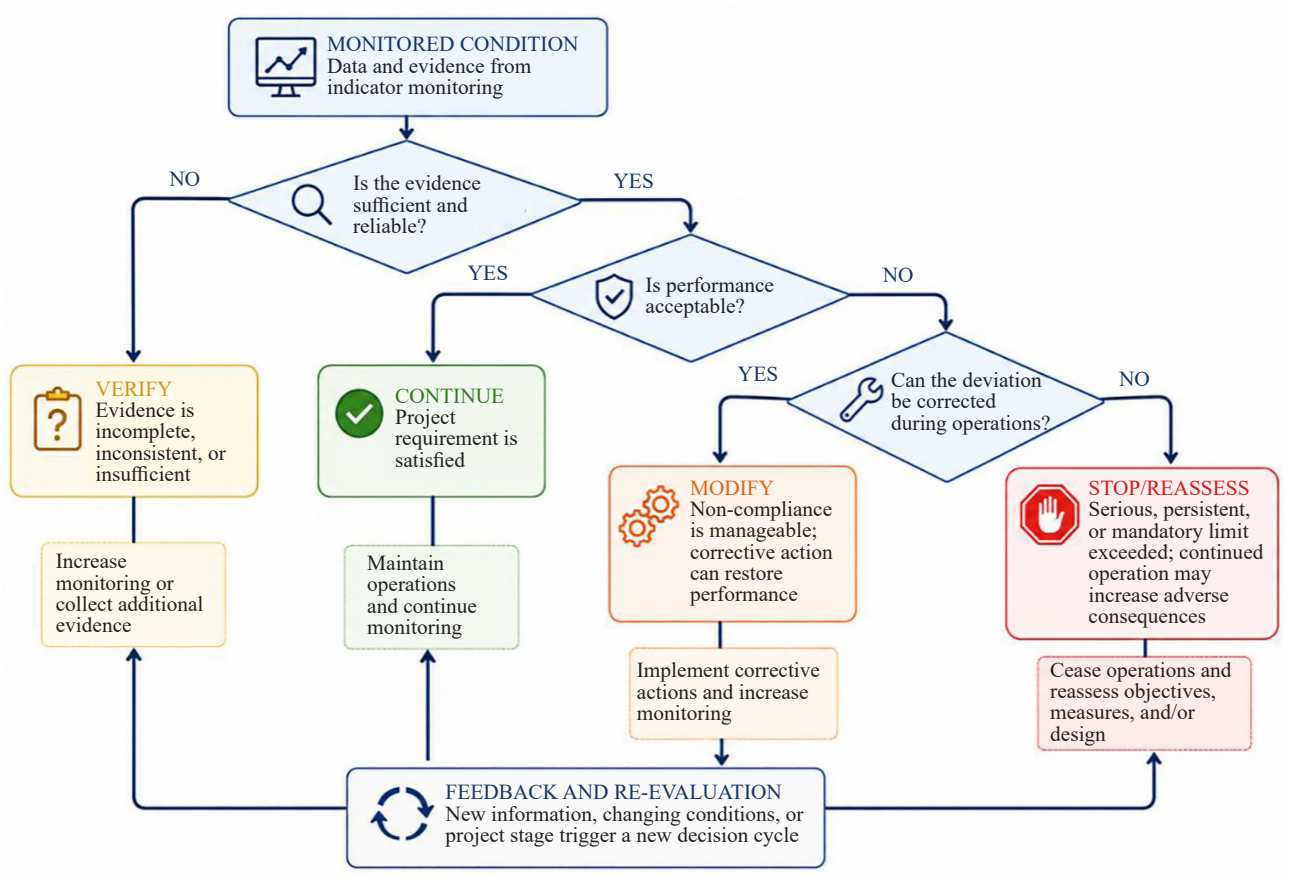


Figure 3. Decision pathway from observed conditions to continue, verify, modify, or stop/reassess responses

4. Discussion

4.1 Operational decision support as a distinct coastal management problem

The proposed framework addresses a specific stage of coastal decision making. It does not compare alternative protection strategies. Instead, it supports decisions once nourishment has already been selected. The focus is therefore operational rather than strategic.

This distinction separates the present approach from most coastal MCDA applications. Sauve et al. [17] used PROMETHEE to rank coastal defence measures with stakeholder-defined criteria. Skidmore and Cohon [19] used MCDA to compare managed-retreat policies under competing objectives. These approaches are suitable when several alternatives must be prioritized [17-19, 22].

Operational nourishment control involves another question. Managers must decide how to respond when monitored conditions change during the same project. These decisions are repeated during dredging, placement, monitoring, and maintenance [5-7, 36]. The framework therefore treats nourishment management as a sequential process.

This sequential interpretation is consistent with previous decision-analysis studies. Little and Lin [27] presented a structured approach to evaluating climate adaptation options under long-term uncertainty. Their study illustrates how decision analysis can support the comparison of management alternatives. The present framework applies the same general logic at the operational scale.

The contribution is therefore not a new optimization or probabilistic risk-analysis method. Instead, it lies in the operational classification of evidence after nourishment has already been selected. This procedure aims to improve consistency and traceability across repeated operational decisions.

4.2 Non-compensatory decisions and critical conditions

Many coastal decision models combine criteria through weights or preference functions [17-19, 22]. These methods are useful when trade-offs among alternatives are acceptable. Recent applications have integrated technical, environmental, economic, and social factors [17-19, 22]. Similar approaches have also been applied to coastal adaptation planning and infrastructure selection.

However, some nourishment requirements do not behave as preferences. They act as operational constraints. A serious environmental exceedance cannot be offset by efficient dredging [15-16, 43, 44]. Confirmed sediment incompatibility also requires action despite satisfactory performance elsewhere [10, 31, 45].

For this reason, the framework adopts a non-compensatory rule for critical conditions. The rule preserves the meaning of each decision dimension. It also prevents an aggregated score from hiding the cause of intervention. This is particularly relevant for regulatory and contractual limits.

This restriction does not imply that all nourishment decisions are non-compensatory. Trade-offs may remain legitimate when deviations are correctable and feasible alternatives remain available. MCDA methods can therefore complement the framework when several acceptable management responses must be compared. Outranking approaches may also support decisions where partial compensation remains meaningful. The proposed rule is narrower and prevents compensation only when continued operation conflicts with a critical requirement. Conversely, compensatory methods remain useful when trade-offs among feasible alternatives have a clear management meaning.

This distinction may also help reduce methodological complexity. A weighted model would require criteria weights and additional expert input. That additional effort is unnecessary for many operational decisions. The proposed rule instead retains direct links between conditions and actions.

4.3 Uncertainty, verification, and adaptive response

A second contribution is the separation of uncertainty from confirmed non-compliance. This distinction is important during routine monitoring. Weak evidence should not automatically trigger the same response as a confirmed problem. The **VERIFY** response was introduced to represent this intermediate state.

Sediment sampling provides a clear example. Laboratory analysis may be precise while the sampled material remains poorly representative [29]. In such cases, the main problem concerns confidence in the evidence. Additional sampling is more appropriate than immediate rejection.

Environmental monitoring presents similar situations. Short-term turbidity increases may not indicate persistent adverse conditions [14]. Their interpretation depends on duration, magnitude, background variability, and permit requirements [14, 16, 43, 44]. Verification can therefore prevent premature operational changes.

VERIFY is maintained only while the available evidence is insufficient to assess compliance. Additional observations must resolve the identified uncertainty and allow comparison with the applicable requirement or threshold. If compliance is confirmed, operations CONTINUE. If non-compliance is confirmed, the response changes to MODIFY when correction remains feasible. A mandatory exceedance or non-correctable condition requires STOP/REASSESS.

This logic also supports adaptive management [36]. Corrective actions are followed by continued monitoring. Their effectiveness can then be evaluated using the same

decision structure. The process therefore remains open after intervention.

Risk-informed coastal management provides a broader context for this approach. Jongejan et al. [30] showed the importance of uncertainty and consequences in coastal risk decisions. Their work used a more formal probabilistic structure. The present framework operates at a simpler operational level.

The term risk-informed is therefore used deliberately. The framework does not estimate failure probability or propagate uncertainty quantitatively. Instead, uncertainty affects the confidence placed in the available evidence before a response is selected. Potential consequences then influence the required level of intervention.

Quantitative uncertainty analysis requires sufficient data to estimate the uncertainty associated with each input. Routine nourishment monitoring does not consistently provide such data, especially for operational observations. Introducing probability distributions without adequate data would add assumptions that cannot be supported by the available evidence. The framework therefore addresses uncertainty by determining whether the available evidence is sufficient to support a decision.

4.4 Practical implementation, transferability, and limitations

The framework was designed for information already collected during nourishment control. This reduces the need for additional monitoring or specialist analysis. Most indicators can be obtained from sediment records, surveys, environmental monitoring, and construction logs. These monitoring sources are widely used to assess nourishment construction and subsequent beach response [12, 13, 37, 38, 46-48]. The main contribution concerns how these data are interpreted.

The framework also separates decision logic from numerical thresholds. This improves transferability among projects and regulatory systems. Sediment limits and environmental criteria can vary among coastal settings [43, 44]. Contractual tolerances may also differ. Comparable nourishment practices have been adapted to different physical and institutional settings [6-7, 49]. The consequences of the same observed condition may also depend on coastal exposure and projected changes in water levels or wave run-up [50]. Long-term nourishment experience also shows that implementation practices must be adapted to local coastal and management conditions [51]. Extreme sea levels may also affect coastal exposure and the resilience of adjacent infrastructure [52]. Management requirements may also differ substantially in urban beaches, where erosion affects infrastructure, recreational use, and maintenance needs [53].

However, threshold definition remains essential for practical implementation. Applicable limits should therefore be established and documented before operational classification whenever possible. Regulatory requirements and project specifications provide the primary basis for threshold selection. Where formal limits are unavailable, documented baseline conditions may support project-specific calibration.

The present framework extends this principle by requiring project-specific thresholds to be documented before classification.

The framework may also improve communication among project participants. Contractors, consultants, environmental teams, and public agencies often use the same data differently. Explicit condition classes can reduce disagreement about the meaning of observations. Documented responses can also improve project traceability.

Several limitations remain. First, the framework has not been validated against management decisions from independent nourishment projects. The scenarios primarily examine internal consistency and should not be interpreted as empirical validation. Scenario 3 is supported by field observations from a documented nourishment project [14]. However, those observations support the relevance of selected indicators rather than the performance of the proposed decision framework.

Second, condition classification still requires engineering judgement, particularly where coastal response and intervention effects remain uncertain [28, 42]. This is unavoidable when thresholds are incomplete or observations conflict. The framework structures that judgement but does not eliminate it. Project-specific regulations also remain dominant.

Third, the current framework does not include stakeholder preferences or economic optimization. These factors may become important in strategic decisions. They could be incorporated later through MCDA or probabilistic methods. Such extensions should preserve the treatment of critical non-compensatory conditions.

Future work should therefore focus on practical testing rather than additional methodological complexity. Completed nourishment projects could be used to compare documented decisions with framework recommendations. Independent practitioners could also apply the framework to the same evidence to assess consistency in condition classification. These steps would provide stronger evidence of reproducibility and external validity.

The framework should remain simple enough for routine use. Its value depends on transparent links between evidence, condition, response, and outcome. Additional complexity would only be justified if it improves those decisions. Otherwise, simplicity is an operational advantage.

5. Conclusions

Beach nourishment requires repeated decisions based on technical, environmental, and operational information. However, monitoring data do not always translate directly

into consistent management actions. This study proposes a risk-informed framework to structure that transition. The approach is intended for operational decisions after nourishment has been selected.

The framework distinguishes four conditions: **acceptable, uncertain, correctable deviation, and critical**. These conditions lead to four responses: **continue, verify, modify, and stop/reassess**. This structure separates uncertain evidence from confirmed non-compliance. It therefore supports responses that are proportional to the available evidence.

A non-compensatory logic is applied to critical conditions. Good performance in one dimension cannot offset a critical requirement in another. This principle is especially relevant for environmental limits and essential technical requirements. It also avoids the loss of information associated with a single aggregated performance score.

The framework uses indicators already available through common nourishment monitoring and quality-control activities. Project-specific thresholds remain defined by design requirements, contracts, permits, and applicable regulations. The proposed approach therefore adds decision structure rather than additional monitoring requirements. This feature should facilitate its application across different project settings.

The framework does not replace engineering judgement or formal probabilistic risk assessment. Instead, it makes operational reasoning more explicit and traceable while providing a structured basis for reproducible application. Continued monitoring also allows decisions and corrective actions to be reassessed through feedback. This supports an adaptive approach throughout the nourishment lifecycle.

The main limitation is the lack of independent validation across completed nourishment projects. The illustrative scenarios demonstrate the internal operation of the framework but not its operational effectiveness. Future work should therefore prioritize practical testing with documented projects and experienced practitioners. Such validation may refine decision triggers without increasing unnecessary methodological complexity.

Declaration of generative AI use

The authors declare that ChatGPT (OpenAI) was used as an AI-assisted tool during the preparation of this manuscript. AI tools were limited to the following purposes: language improvement. All AI-assisted outputs were critically reviewed, verified, and revised by the authors. Generative AI tools were not used to replace the authors' scientific judgment, generate unsupported scientific claims, interpret results independently, or assume responsibility for any part of the research. The authors remain fully responsible for the originality, accuracy, integrity, and ethical compliance of the manuscript.

Author contributions

Conceptualization, J.J.M.-P., P.P. and A.C.; methodology, J.J.M.-P., P.P. and A.C.; formal analysis, P.P., A.C. and F.C.; investigation, P.P., F.C. and B.J.; resources, J.J.M.-P. and B.J.; writing—original draft preparation, J.J.M.-P., P.P. and A.C.; writing—review and editing, F.C. and B.J.; visualization, A.C. and F.C.; supervision, J.J.M.-P. All authors have read and agreed to the submitted version of the manuscript.

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Conflicts of interest

The authors declare no conflicts of interest.

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