DECISION SUPPORT TOOLKIT IN EARLY DESIGN PHASE: A LIVING WALL SYSTEM FOR GREYWATER TREATMENT AND REUSE IN MOUNTAIN ENVIRONMENT

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Abstract. Mountain regions are increasingly affected by seasonal droughts driven by shifts in precipitation patterns and rising average temperatures, which are sometimes accompanied by peak tourist seasons, placing significant pressure on local water resources and infrastructure. This study presents a conceptual framework for a tool to guide the design of a nature-based solution (NBS) for water management: a Living Wall System (LWS) for greywater treatment and reuse in mountain environments. The aim of the study, which is part of the Nature-based Solutions for Mountain Villages (NBS4MOV) project, is to provide a solid groundwork for a decision-support tool to be used during the early design phase and to promote and facilitate the adoption of the proposed LWS in a replicable and scalable way. A performance-based design methodology is adopted to integrate water management, engineering, and architectural needs, as well as specific requirements for a LWS in the complex mountain environment where operational constraints are more pronounced. First, the architectural features to be considered during the early stages of the integrated LWS design process are identified. Then, a selection process defines transportability, modularity, replicability, scalability, and reversibility as key needs for system development. To systematically develop the decision support tool, for each identified need, corresponding requirements are defined and linked to performance specifications to guide implementation. The envisioned system is intended to be accessible and effective for non-expert users by collecting technical and performance-related data indirectly. Finally, a dedicated matrix is developed to manage a wide range of information and to enable performance data to be evaluated in relation to each other. The output is presented as a structured system of questions with related rules, enabling the generation of a report containing design guidelines, technical specifications for each category, and relevant warnings.

Keywords: performance-based approach, decision-making tool, living wall system, mountain valleys;

Introduction

Seasonal droughts are becoming more frequent in mountainous areas due to changes in rainfall patterns and rising average temperatures (Ioan, 2025), often exacerbated by periods of high tourist activity, which strain local water supplies and infrastructure (Rogowski, 2025). Moreover, although demographic decline linked to limited services and economic opportunities continues to affect remote mountain villages, the recent expansion of digital infrastructure and remote work models offers new scenarios for repopulation and socio-economic revitalisation of these areas (Polin et al., 2024). Given these considerations, effective water resource management is essential to promote tourism development and repopulate mountain areas while ensuring the hydrogeological safety of these territories. Nature-based Solutions (NBS) can significantly contribute to this objective by providing multiple ecosystem services, including local water treatment (Pereira et al., 2023). Within this framework, the NBS4MOV project (2023-2025) aimed to prototype and install an NBS system for greywater treatment. The outcome was a first prototype of a modular stand-alone Living Water System (LWS) for the treatment and local reuse of domestic greywater, excluding wastewater from toilet flushing, based on the most recent literature on this emerging technology (Pucher et al., 2025; Prodanovic, 2025; Masi, 2025). The project highlighted the importance of involving both professionals responsible for NBS design and implementation, as well as non-technical users. However, it also revealed that initial interactions with a professional team could act as a barrier for private individuals or local administrators due to perceived economic and commitment-related constraints. Therefore, there is a clear need for tools that facilitate the initial assessment and decision-making process, allowing users to estimate and plan solutions tailored to their specific needs and the characteristics of the installation sites. In the context of NBS, existing tools designed to support urban climate adaptation planning are primarily targeting technical users such as urban planners, engineers, and environmental specialists. Moreover, current tools often require substantial technical knowledge to navigate effectively, creating barriers for non-expert users (Voskamp, 2021).

Considering the above, the work presented in this paper represents the early stages of developing a decision support tool as part of the NBS4MOV project. The primary aim is to explore and analyse how a non-expert user could identify appropriate system performance requirements without directly engaging with complex technical methodologies or possessing specialized expertise. While technical users can define needs and performance goals directly, this work focuses on conceptualizing how the tool could be made accessible and effective for non-expert users as well. The proposed tool is intended to provide access to technical information for both user types and is being developed using a performance-based design approach, which is particularly valuable given the high complexity of mountain environments. To manage a wide range of information and enable comparative performance evaluation, a dedicated matrix structure has been conceptualized with defined performance categories. The intended functionality would allow each user interaction to trigger the automatic extraction of one or more design requirements, which would then be compared with similar ones within the same performance category. In conclusion, the tool could enable access to technical information for both technical and non-technical users, thus potentially facilitating the dissemination and adoption of the proposed LWS for water management in mountain villages. The envisioned system would support context-sensitive solutions by accounting for needs that vary according to geographical location and site-specific conditions. Future development

phases will focus on implementing and validating this preliminary conceptual framework.

Methodology

The research initially explores how a professional designer approaches the complexity of designing a Living Wall System in a mountain region. In particular, it analyses the procedural steps required to design, size, and evaluate architectural solutions according to different requirements. The conventional design process followed by technical experts within the disciplinary framework of Architectural Technology was therefore analysed to identify which phases could be automated through the development of a dedicated tool. The definition of the performance hierarchy and the associated constraints have been calibrated on mountain settlements, where environmental, logistical, and socio-technical limitations are more pronounced.

The performance-based design approach served as the core methodology aimed at ensuring building quality by responding to both client and user needs. Although not comprehensively codified in a single standard, this approach primarily refers to two Italian norms: UNI 8289:1981, which defines categories of user requirements, and UNI 8290 series, especially UNI 8290-1 and UNI 8290-2, which define the technological system, categorise technological units and technical elements, and provide criteria for their identification.

Based on the performance-based methodology, the following phases were identified as representative of a design process:

1. identification of client and end users of the building system;

2. classification of needs categories;

3. definition of the requirements related to the needs;

4. specification of performances through appropriate descriptors (attributes and/or variables characterizing performance levels);

5. determination of which technical and/or spatial elements provide the required performance;

6. development of the design solution based on its ability to satisfy the defined performance program.

The performance-based methodology described above refers to a building system conceived as an assembly of technological elements and components (Zanchetta et al., 2017). In the case of designing a LWS, this system must be considered a technological element within the broader building organism (Giordano et al., 2017). Consequently, the conventional performance-based process is adapted and simplified to fit this specific design context. Figure 1 presents the phases of the simplified performance-based approach.

The simplified approach is articulated through the following phases:

1. identification of the relevant need categories, accounting for all the characteristics that the element may exhibit in relation to the various life-cycle stages (e.g., transportation, installation, use, maintenance, and disassembly) and to the different user groups (end users of the product and the owner);

2. definition of specific requirements (both functional and technical) for each need category;

3. specification of the performance that the component must achieve in operation for each technical requirement (through the determination of attributes and/or variables that describe its performance).

In particular, typical constraints of mountain environments, such as limited site accessibility, strong seasonal variability in use, and the prevalence of existing buildings, were defined. These conditions informed the selection of key needs, including transportability (e.g., through helicopter), modularity, and reversibility of the system (resulting in non-invasive interventions on existing building stock).

As shown in Table 1, for each need category, multiple requirements were defined, together with their corresponding performance specifications with reference to the scope of the Living Wall System and the mountainous context.

Results

Preliminary conceptual framework for the tool

The adopted strategy establishes a question-based system in which user responses identify or exclude specific requirements. Through a sequence of questions, the user interacts with the tool intuitively, progressively generating a corresponding set of performance and technical characteristics for the Living Wall System. The sequential question system thus forms the core of user-tool interaction. Different types of interaction have been explored, each of which automatically produces an outcome in terms of specific need or technical requirement. These represent the way the user interacts with the system. They may consist of multiple-choice inputs from a predefined list, numerical entry, or map-based navigation to select a geographic point.

Since multiple questions may generate performances of the same category, the system must automatically yield overlapping specifications within the same performance domain (e.g., two different dimensional constraints). An additional development phase was required to avoid inconsistencies in overlapping performances. All performance parameters were categorized into performance classes (e.g., dimensional, material, assembly-related). This classification enables the comparison of performances of the same domain and the definition of hierarchies among them. The diagram in Figure 2 illustrates how the horizontal matrix structure enables each user's response to generate a specific performance output, and how the resulting performances are grouped within the same performance classes. Those potential conflicts between outputs were analysed, leading to the formulation of methods for identifying the prevailing option or, in more complex cases, for combining multiple outputs.

Table 2 shows the way the system interacts with conflicts. Specifically, this was achieved by assigning comparable numerical scores within each class, enabling each performance to be ranked accordingly. The hierarchical scoring system ensures that, within each performance class, only one final

performance can be selected.

Figure 3 provides a schematic overview of the selection process: two different questions may generate outputs belonging to the same performance class, and through the ranking system, only the most restrictive one is retained.

To indirectly include or exclude all requirements analysed in the performance-based phase, a set of questions was developed. The user interacts with predefined questions whose answers correspond to specific outputs. Each question is designed with a set of possible answers, each linked to a corresponding output in terms of need, requirement, or performance. This procedure, thanks to the performance-based scheme (Table 1), allows the automatic identification of a specific performance starting from a questionnaire. Table 3 presents the question categories, the type of information required, and the corresponding output for each of them. This approach follows the methodology illustrated in Figure 2 (blue squares), where each identified performance is associated with a response that justifies its inclusion.

Figure 4 shows the relation between the performance-based approach and the envisioned tool. The information generated by the questionnaire mirrors the type and structure of outputs typically produced by an expert designer, demonstrating the effectiveness of the proposed method in simplifying early-stage decision-making.

Conclusions

The study aims to translate a performance-based approach into a question-based system that guides non-expert users to the indirect definition of the performance attributes required to preliminarily size and describe a Living Wall System thought to be installed in mountain contexts characterised by heightened environmental and operational constraints

The methodological framework developed in this research constitutes a replicable model for other technological building systems. By establishing explicit rules, hierarchical structures, and performance classes, the process can be expanded or adapted to different design needs and intervention scales. This highlights the broader applicability of the approach within digitalised design workflows.

Despite its potential, the system cannot replace the expertise of a qualified professional. The quality and reliability of the outputs depend on the formulation of the predefined questions, and the absence of detailed contextual, technical, and regulatory inputs limits the results to preliminary estimations. Professional judgement remains essential for critically reviewing automated outcomes and refining them within a comprehensive design process.

Given its modular structure, the system can be extended to incorporate additional disciplinary domains, such as structural, energy, hydrological, or bioclimatic analysis, thus enhancing the depth and reliability of future assessments. The work presented here also provides the foundation for the development of an operational software tool based on defined rules and performance hierarchies. Future research could focus on validating the system through real-world case studies and on implementing more advanced decision-making algorithms to improve the robustness and accuracy of the tool.

By grounding the development of the toolkit in the constraints of mountain contexts, characterised by limited accessibility, seasonal variability, and non-specialist users, the proposed approach demonstrates how highly constrained environments can serve as a robust testing ground for decision-support methodologies applicable also to more favourable contexts.

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Figures

Figure 1 - Simplified scheme of performance-based methodology adopted.

Figure 2 - Horizontal matrix structure. Black squares are performance-based analysis, in blue the question-based tool, and in red performance classes to compare the output of similar constraints.

Figure 3 - Schematic representation of the selection process of an output from the question-based tool.

Figure 4 - Schematic relation between the performance-based approach and the tool.

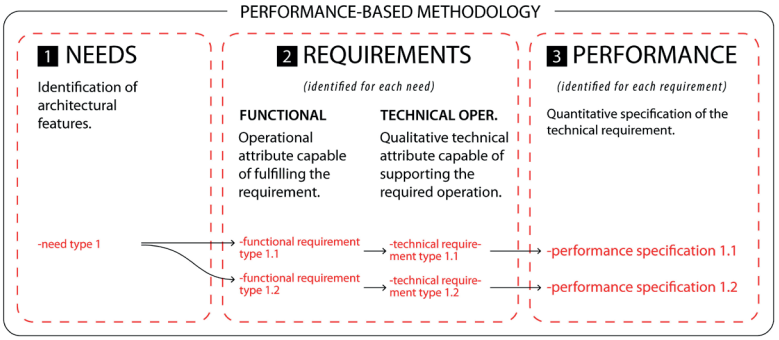
Tables

Table 1. Performance-based analysis for a LWS in a mountain region.

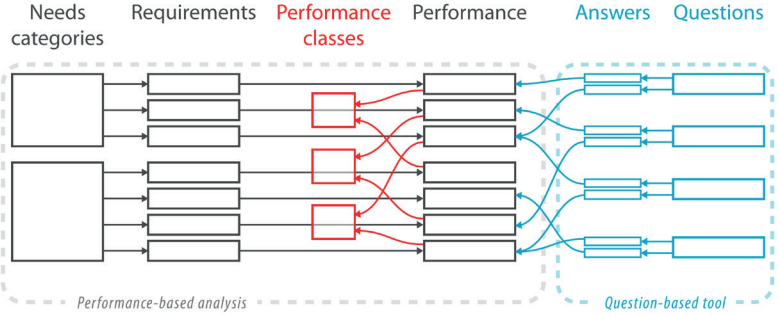
Table 2. Performance classes specification and score assignment.

Table 3. Question scheme

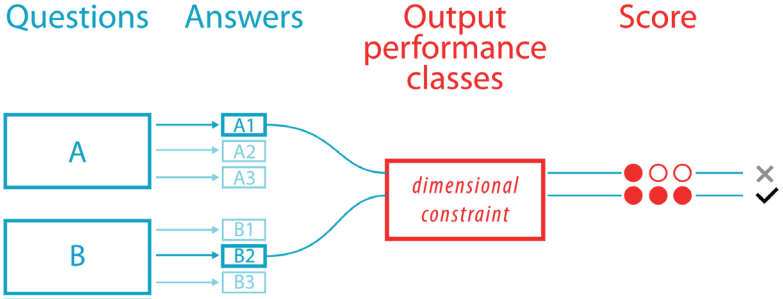
1.


PERFORMANCE-BASED METHODOLOGY
1 NEEDS
Identification of architectural features.
2 REQUIREMENTS
(identified for each need)
FUNCTIONAL
Operational attribute capable of fulfilling the requirement.
TECHNICAL OPER.
Qualitative technical attribute capable of supporting the required operation.
3 PERFORMANCE
(identified for each requirement)
Quantitative specification of the technical requirement.
-need type 1
-functional requirement type 1.1
-functional requirement type 1.2
-technical require-ment type 1.1
-technical require-ment type 1.2
-performance specification 1.1
-performance specification 1.2

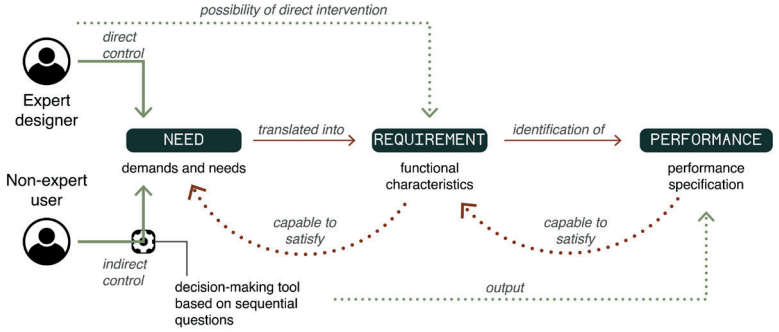
2.


Needs categories
Requirements
Performance classes
Performance
Answers
Questions
Performance-based analysis
Question-based tool

3.


Questions
Answers
Output performance classes
Score
A
B
A1
A2
A3
B1
B2
B3
dimensional constraint

4.


possibility of direct intervention
direct control
Expert designer
NEED
translated into
REQUIREMENT
identification of
PERFORMANCE
demands and needs
functional characteristics
performance specification
Non-expert user
capable to satisfy
capable to satisfy
indirect control
decision-making tool based on sequential questions
output

1.

Need	Requirement	Performance
Modularity	Standard dimensions	(1.1) 60 cm modules
	Hydraulic connection interfaces	(1.2) Segmentation of tanks and linking points between purified water storage units
	Fasteners	(1.3) Anchoring system compatible with traditional masonry surfaces
	Materials	(1.4) Specifications on weight, UV and frost resistance, and corrosion-free performance
	Mounting and dismounting system	(1.5) Design for disassembly specifications
Reversibility		
	Mounting and dismounting system	(2.1) Design for disassembly specifications
	Prefabrication	
Scalability	Modularity	(2.2) Elements and components will be pre-assembled for dry installation. Interlocking or screw-assisted fastening systems are preferred.
	Modularity	(2.3) 60 cm modules
Transportability	Mounting and dismounting system	
	Weight	
		(3.1) 60 cm modules
		(3.2) Design for disassembly specifications, maximum spacing between modules ≤ 5 cm; hydraulic and structural continuity without loss of efficiency.
	Transportation system	
	Mounting and dismounting system	
Efficiency	Prefabrication	(4.1.1) by hand <25-30 kg; 80x60x40 cm
	Dimensioning	(4.1.2) van <1200-1500kg; 3.7x1.8 m
		(4.1.3) truck <9000-25000kg
		(4.1.4) light helicopter <1000-1200 kg
		(4.2) On EUR 1 EUROPALLET, elements < 1.2x0.8 m, <1000–1500 kg.
		(4.3) Tool-less or minimal-tool assembly system, installable by non-experts.
		(4.4) Elements and components will be pre-assembled for dry installation. Interlocking or screw-assisted fastening systems are preferred.
		(5.1) The module has a capacity of 48 L/day; add modules as needed to cover the greywater consumption of the facility.

2.

Performance	Performance classes	Conflicts	Score
(1.1) 60 cm modules	dimensional	yes	1/3
(1.2) Segmentation of tanks and linking points between purified water storage units	structural	no	x
(1.3) Anchoring system compatible with traditional masonry surfaces	anchors	no	x
(1.4) Specifications on weight, UV and frost resistance, and corrosion-free performance	material	no	x
(1.5) Design for disassembly specifications	assembly	yes	3/3
(2.1) Design for disassembly specifications	assembly	yes	1/3
(2.2) Elements and components will be pre-assembled for dry installation. Interlocking or screw-assisted fastening systems are preferred.	structural	no	x
(2.3) 60 cm modules	dimensional	yes	2/3
(3.1) 60 cm modules			
(3.2) Design for disassembly specifications, maximum spacing between modules ≤ 5 cm; hydraulic and structural continuity without loss of efficiency.	structural	yes	2
(4.1.1) by hand <25-30 kg; 80x60x40 cm	dimensional	yes	3/3
(4.1.2) van <1200-1500kg; 3.7x1.8 m	dimensional	yes	3/3
(4.1.3) truck <9000-25000 kg	dimensional	yes	3/3
(4.1.4) light helicopter <1000-1200 kg	dimensional	yes	3/3
(4.2) On EUR 1 EUROPALLET, elements < 1.2x0.8 m, <1000–1500 kg.	dimensional	yes	3/3
(4.3) Tool-less or minimal-tool assembly system, installable by non-experts.	assembly	yes	2/3
(4.4) Elements and components will be pre-assembled for dry installation. Interlocking or screw-assisted fastening systems are preferred.	assembly	yes	2/3
(5.1) The module has a capacity of 48 L/day; add modules as needed to cover the greywater consumption of the facility.	structural	no	x

3.

Category	Type of information requested	Output obtained	What it is used for
Territorial Information	Location	Coordinates	Shading analysis
End Users	Capacity	Number of users	LWS sizing
Site Accessibility	Means of transport	Vehicle type	Maximum component dimensions
Available walls for installation	Orientation	Cardinal Direction	Bioclimatic Analysis
	Dimensions	Available vertical area	Preliminary sizing
	Features	Wall Typology	Anchoring system
		Presence of windows	Modularity of structure
	Nearby obstacles	Dimensions and location	Bioclimatic Analysis
Use Phase	Relocation to other sites	Transportability features	Design for disassembly features

