Re-Zero: Modular Logic in Domestic Bio-filtration

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Abstract (English)

In sustainable home infrastructure, the Zero Mile research prototype explores the recycling of Dishwasher Wastewater (DWW) through biofiltration and domestic reuse. While technically feasible, such slow and biologically mediated processes often remain difficult for users to interpret in everyday contexts due to their temporal opacity and limited perceptual feedback. This creates an interpretive gap between system operation and user understanding, challenging users' ability to interpret system states and sustain engagement over time.

To address this condition, this project investigates the design of an interpretive interaction layer for the Zero Mile system, aiming to render biofiltration processes perceptible, understandable, and maintainable within domestic environments. Building upon the existing prototype, the research introduces a modular design strategy that decomposes the system into functional units —including biofiltration, water storage, and cultivation—enhancing spatial adaptability and maintenance accessibility. The accompanying digital interface translates slow biological rhythms and infrastructural states into actionable and low-cognitive-demand forms of awareness, clarifying boundaries of responsibility between user care and autonomous system operation.

Through a multi-dimensional information architecture, the interface reframes the perception of wastewater recycling as an ongoing ecological process rather than a hidden technical function. While the Home and Care interfaces support interpretive understanding of system operation and maintenance readiness, the Garden interface exposes the tangible outcomes of the cycle through plant growth and irrigation feedback. This perceptual coupling between invisible treatment and visible cultivation fosters experiential credibility and sustained engagement.

By extending the Zero Mile prototype through modular restructuring and interpretive interface design, the project demonstrates how interaction design can support the domestication of slow ecological infrastructures. The research contributes a design perspective on bridging biological processes and everyday interpretation, highlighting the role of interfaces in enabling long-term coexistence between households and living water systems.

Keywords: DWW Recycling; Biofiltration; Modular Architecture; Interpretive Interaction; Domestic Sustainable Infrastructure

Abstract (Italiano)

Nell'ambito delle infrastrutture domestiche sostenibili, il prototipo di ricerca Zero Mile esplora il riciclo delle acque reflue di lavastoviglie (DWW) attraverso la biofiltrazione e il riutilizzo domestico. Sebbene tecnicamente fattibili, questi processi lenti e biologicamente mediati spesso rimangono difficili da interpretare per gli utenti nei contesti quotidiani a causa della loro opacità temporale e del feedback percettivo limitato. Ciò crea un divario interpretativo tra il funzionamento del sistema e la comprensione da parte dell'utente, mettendo alla prova la capacità di questi ultimi di interpretare gli stati del sistema e di mantenere l'impegno nel tempo.

Per affrontare questa condizione, questo progetto studia la progettazione di un livello di interazione interpretativa per il sistema Zero Mile, con l'obiettivo di rendere i processi di biofiltrazione percepibili, comprensibili e manutenibili all'interno degli ambienti domestici. Basandosi sul prototipo esistente, la ricerca introduce una strategia di progettazione modulare che scompone il sistema in unità funzionali, tra cui biofiltrazione, stoccaggio dell'acqua e coltivazione, migliorando l'adattabilità spaziale e l'accessibilità alla manutenzione. L'interfaccia digitale di accompagnamento traduce i ritmi biologici lenti e gli stati infrastrutturali in forme di consapevolezza attuabili e a basso fabbisogno cognitivo, chiarendo i confini di responsabilità tra la cura dell'utente e il funzionamento autonomo del sistema.

Attraverso un'architettura informativa multidimensionale, l'interfaccia riformula la percezione del riciclo delle acque reflue come un processo ecologico continuo piuttosto che come una funzione tecnica nascosta. Mentre le interfacce Home e Care supportano la comprensione interpretativa del funzionamento del sistema e della prontezza alla manutenzione, l'interfaccia Garden espone i risultati tangibili del ciclo attraverso la crescita delle piante e il feedback sull'irrigazione. Questo accoppiamento percettivo tra trattamento invisibile e coltivazione visibile promuove la credibilità esperienziale e un coinvolgimento duraturo.

Estendendo il prototipo Zero Mile attraverso una ristrutturazione modulare e la progettazione di un'interfaccia interpretativa, il progetto dimostra come l'interaction design possa supportare l'addomesticamento di infrastrutture ecologiche lente. La ricerca fornisce una prospettiva progettuale sul collegamento tra processi biologici e interpretazione quotidiana, evidenziando il ruolo delle interfacce nel consentire la coesistenza a lungo termine tra famiglie e sistemi idrici vivi.

Parole chiave: Riciclo DWW; Biofiltrazione; Architettura modulare; Interazione interpretativa; Infrastruttura nazionale sostenibile

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Introduction

The increasing global focus on water scarcity has accelerated the integration of circular water systems within domestic environments. Among various household water sources, Dishwasher Wastewater (DWW) represents a significant yet underutilized resource, rich in nutrients and potential for reuse. While advancements in biofiltration technology have made it technically possible to purify DWW for domestic irrigation, a critical gap remains between functional technology and human acceptance. The Zero Mile research prototype explores this recycling potential, yet such slow and biologically mediated processes often remain difficult for users to interpret in everyday contexts due to their temporal opacity and limited perceptual feedback. Without a clear understanding of the system's internal state or maintenance requirements, users often face an interpretive gap that challenges their ability to assess system reliability, potentially leading to a lack of trust and eventual abandonment of the technology.

This research addresses the challenge not by refining the biological process itself, but by designing the "interpretive layer" for the Zero Mile system. The project identifies two primary barriers to domestic adoption of this sustainable infrastructure: structural rigidity and cognitive opacity. Traditional prototype systems are often centralized and bulky, making them difficult to integrate into the fragmented spaces of a modern kitchen. Furthermore, the lack of intuitive feedback makes it nearly impossible for a layperson to distinguish between a functioning system and one requiring urgent intervention.

To bridge this gap, this project proposes a modular physical structure combined with a digital interaction layer for the Zero Mile prototype. By deconstructing the system into functional modules—such as biofiltration, water storage, and planting—the infrastructure achieves higher spatial adaptability and maintenance accessibility. Simultaneously, the digital interface serves as a cognitive bridge, translating complex biological rhythms into actionable daily information. The objective is to transform the DWW purification system from a complex "black box" device into a readable, coexistent ecological member of the household. By clarifying the boundaries of responsibility and making the value of the water cycle visible through plant growth, this design fosters a long-term symbiotic relationship between the user and the domestic ecosystem.

Chapter 1. Research Framework

1.1 Research Background & Motivation

We currently live in a socio-technical system largely shaped by a linear model of "take–make–dispose", which is particularly evident in domestic everyday life (Ellen MacArthur Foundation, 2015). Within this context, the consumption and waste of water and food represent two closely related environmental challenges. Household appliances, especially dishwashers, consume approximately 9-12 liters of clean water per cycle while producing wastewater rich in nutrients such as nitrogen and phosphorus (Congestri et al., 2020). This wastewater is typically discharged directly into the sewage system, where it becomes waste requiring additional energy for treatment.

At the same time, urban residents are showing increasing interest in fresh, locally produced food, often referred to as "zero-mile" food. This has led to the growing adoption of small-scale domestic food production practices, such as balcony gardening and indoor cultivation (Specht et al., 2014; Orsini et al., 2020). Although these two processes—household wastewater generation and domestic food production—are usually treated as separate, they together suggest the potential for a closed-loop system in which wastewater can be reconsidered as a resource rather than a by-product. Such nutrient recovery systems align with circular economy principles by transforming waste streams into productive inputs, thereby reducing both resource extraction and environmental discharge (Schröder et al., 2019).

Within this context, the Zero Mile System, led by Professor Fiammetta Costa at Politecnico di Milano, explores the reuse of dishwasher wastewater through an innovative biofiltration system that enables irrigation of edible plants (Costa & Nebuloni, 2021). Previous research has demonstrated the technical and biological feasibility of such a domestic water–food loop, including the microbial consortium's capacity to reduce nitrogen and phosphorus loads by up to 70% and 50% respectively (Alabiso et al., 2023), as well as its environmental benefits and social acceptance among potential users (Costa et al., 2018). However, while the system has been validated at experimental and prototype levels, its integration into diverse and everyday domestic environments remains a critical challenge. Bridging the gap between an engineering prototype and a usable domestic product requires a design-oriented investigation, which forms the starting point of this research.

The central design challenge, therefore, is not whether such a system can work biologically, but how it can become domestically adaptable, perceptually acceptable, and experientially legible within the varied spatial, functional, and cultural contexts of contemporary home environments.

1.2 Problem Focus

Although the Zero Mile prototype has demonstrated the effectiveness of its core technology (Alabiso et al., 2023; Congestri et al., 2020), user-centered research conducted by Costa and colleagues has revealed several key design challenges that limit its wider adoption when the system is considered for real domestic applications (Costa & Nebuloni, 2021; Costa et al., 2018). Focus group studies with potential users highlighted concerns regarding spatial requirements, aesthetic integration, and maintenance complexity (Costa & Nebuloni, 2021). These challenges limit the system's potential for positive user experience and hinder its transition from laboratory prototype to domestic product. Based on an analysis of the existing literature and empirical user feedback, these challenges can be summarized in three main aspects.

Beyond these user-facing challenges, a closer examination of the prototype reveals a deeper structural issue rooted in the system's architectural integration. In the current configuration, multiple functional domains—including wastewater treatment, irrigation supply, and dishwasher water provision—are tightly coupled within a single hydraulic and control infrastructure. While this integration supports experimental validation and internal resource circulation, it also creates rigid dependencies between core treatment functions and auxiliary service flows. As a result, individual components cannot be easily repositioned, replaced, or independently configured without affecting the overall system operation. This architectural coupling contributes significantly to spatial inflexibility, maintenance complexity, and configuration constraints observed by users, highlighting the need for a restructuring of the system architecture that allows functional separation while maintaining coordinated operation.

In addition to spatial and architectural constraints, these challenges also introduce a deeper experiential gap. The system's biological processes remain largely invisible, its operational rhythm is difficult for users to anticipate, and maintenance responsibilities are not clearly understood. As a result, the transition from laboratory prototype to domestic product is hindered not only by structural integration issues but also by limited system legibility in everyday use.

Taken together, these observations indicate that the barriers to domestic adoption are not isolated issues but interconnected challenges spanning spatial configuration, system integration, and everyday user interaction. To clarify the design implications of these barriers, the identified concerns can be synthesized into three primary categories that structure the following analysis.

- Limited spatial adaptability and flexibility
  The original prototype is designed as a relatively fixed and integrated system, which makes it difficult to adapt to the wide variety of domestic contexts, including differences in kitchen layouts, available space, and everyday lifestyles. Focus group discussions revealed that spatial concerns extended beyond mere physical dimensions: participants cited issues related to the system's size and placement requirements, maintenance challenges such as managing fallen leaves and organic waste, hygiene concerns including potential pests and odors, and safety risks such as electrical/water system failures and children climbing on plant racks (Costa & Nebuloni, 2021). These interconnected spatial, functional, and safety considerations demonstrate that flexibility must be designed into the system architecture itself (Norman, 2013), rather than expecting users to simply "make room" for a fixed installation. The current prototype's inflexibility limits its applicability to a narrow range of domestic situations, thereby restricting its potential for wider adoption.

- Limited domestic integration and perceived acceptance
  As a system that combines water treatment and plant cultivation, the current form of the Zero Mile prototype is often perceived as an experimental installation rather than a domestically integrated appliance. Aesthetic evaluations based on images of the prototype (Fig. 1)(Fig. 2) revealed mixed reactions. Concerns were raised primarily regarding the relatively large dimensions of the vertical planting wall and the unfinished appearance of container components. Conversely, some participants associated the system with innovative architectural features(Costa & Nebuloni, 2021, p. 48). This polarization in perception suggests that the system currently resonates more strongly with early adopters than with the broader domestic context. Questions therefore arise regarding how such a system can be integrated more comfortably into everyday living environments while retaining its distinctive character, particularly when its presence is perceived as a single dominant installation.

- Complexity of user experience and maintenance
  The biofilter, as the core component of the system, requires observation, maintenance, and potentially cleaning. These activities need to be designed in a way that is intuitive and manageable for non-expert users. However, current interaction paradigms—such as monitoring microbial health, adjusting light exposure, and performing periodic cleaning—remain opaque to laypersons (Costa & Nebuloni, 2021). In addition, system operation and feedback—such as water quality indicators and plant growth status—must be communicated clearly to reduce the learning effort and psychological barriers for users. As Forlizzi(2018) notes, successful integration of complex technologies into domestic spaces depends on designing interactions that align with existing household routines and require minimal cognitive overhead.

Figure 1. Prototype (Source: THE JETSONS' KITCHEN, 2021)

Figure 2. Prototype (Source: From greyto green, 2023)

These challenges do not undermine the value of the original research. Instead, they point to the next level of questions that must be addressed in the process of transforming a validated prototype into a domestic product. At their core, these are issues related to system architecture, product form, and human–system interaction—domains that fall squarely within the scope of design research. Addressing these challenges through design-driven methods can bridge the gap between technological feasibility and domestic desirability, ultimately enabling the Zero Mile system to realize its potential as a scalable circular economy solution.

While these challenges have been introduced here from a high-level design perspective, they require deeper investigation from multiple analytical angles. Chapter 2 expands this discussion by examining the Zero Mile system through technical system analysis, user research synthesis, and experiential interpretation. Through this multi-layered investigation, the identified challenges are translated into structured design requirements and intervention opportunities that form the foundation for the design development presented in later chapters.

1.3 Research Objectives

Based on the challenges identified above, this research adopts a design-driven approach to reconsider the Zero Mile system from the perspective of domestic integration and everyday use. The main objective of the study is to transform the system from an experimental prototype into a flexible, domestically adaptable, and user-comprehensible ecosystem. Rather than focusing on the redesign of individual components, the research emphasizes modular system restructuring and interaction design strategies that support long-term coexistence between users and the biofiltration process within the home.

To achieve this overall objective, the research is structured around two complementary design tasks:

- Developing a modular system architecture through functional decomposition.
  The system is analyzed and decomposed into a set of core functional modules—including pre-treatment, the biofilter core, cultivation units, and supporting hydraulic components. Relationships between modules are examined to enable flexible configuration scenarios that respond to diverse domestic spatial conditions, such as countertop integration, vertical arrangements, and distributed placement across different household areas. This task focuses on improving spatial adaptability, maintenance accessibility, and overall system configurability while preserving the biological performance established in prior research.

- Identifying user–system touchpoints and exploring the digital interaction framework.
  Building upon the modular architecture, the research investigates where user interaction becomes necessary, particularly in relation to system awareness, configuration understanding, and maintenance guidance. This task explores how a digital interface can support users in interpreting system states, understanding operational rhythms, and navigating maintenance activities within everyday domestic contexts.

Together, these tasks address both structural adaptation and experiential legibility, indicating the importance of an interaction layer that enables users to interpret system states, anticipate maintenance needs, and coexist with the ecosystem as part of daily household routines.

1.4 Thesis Structure

This research follows a "research through design" approach in which design practice itself is used as a method to explore and address the identified challenges. The overall process is structured as an iterative cycle of analysis, generation, development, and evaluation.

The structure of the thesis reflects this research process:

- Chapter 2 reviews the technical background and provides a critical analysis of the existing Zero Mile prototype. It outlines relevant analytical perspectives and user insights, establishing the functional and cognitive foundation for the project.

- Chapter 3 describes the design research methodology and the specific stages involved in the process, defining the Research through Design (RtD) framework and the evaluative criteria used to guide the modular and interactive development.

- Chapter 4 presents the physical modular strategy, documenting the functional decomposition of the system and the transition from a centralized prototype to a modular infrastructure. It details the rationale behind the spatial adaptability and maintenance accessibility of the new hardware logic.

- Chapter 5 focuses on the integrated interaction layer, proposing a digital interface that serves as a cognitive bridge. This chapter details how biological data is translated into user-centric feedback and how the system fosters a symbiotic relationship through daily interaction.

- Chapter 6 discusses the design evaluation and iterative reflections based on user walkthroughs and feedback. It employs qualitative methods to assess the design's success against the criteria established in Chapter 3.

- Chapter 7 summarizes the overall contributions of the research and outlines directions for future development, including potential pathways for technical validation, business model development, and scaling considerations.

Through this structure, the thesis aims to demonstrate how design can act as a key transformative force, translating an advanced circular economy concept into a tangible and desirable practice for everyday domestic life.

This research acknowledges its limitations in scale and scope: prototypes are evaluated with a small sample of users, and long-term functional validation of the biological system is beyond the study's scope.

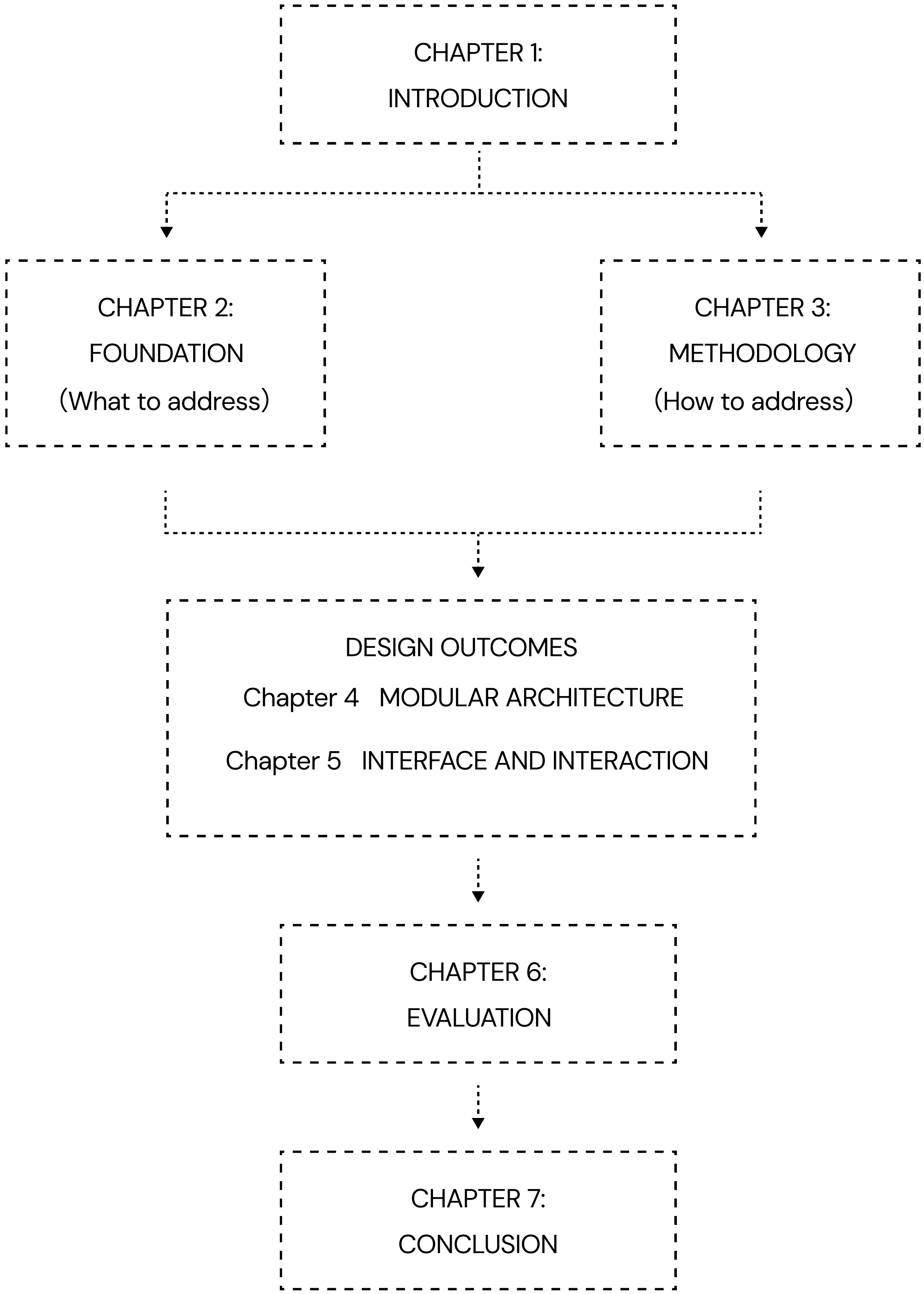


Figure 3. Thesis Structure Overview (Author's own illustration)

Chapter 2. Foundation

2.1 Technical Foundation

This design project does not start from a technological invention developed from scratch, but builds upon a solid foundation of interdisciplinary research. A research team led by Prof. Costa, Congestri, and their collaborators has, through a series of studies—including The Jetsons' Kitchen project and related academic publications—successfully validated the core technological pathway for recycling dishwasher wastewater at the domestic scale (Costa & Nebuloni, 2021; Alabiso et al., 2023; Congestri et al., 2020). This section synthesizes the key scientific findings that establish the feasibility of the Zero Mile concept, providing the technical foundation that defines the design space for subsequent investigation.

Key Technical Principles

Key findings from existing research can be summarized in three main aspects:

- Wastewater Characteristics and Reuse Potential
  Dishwasher wastewater contains plant nutrients (nitrogen and phosphorus) while maintaining low levels of pathogens and contaminants, making it suitable for reuse after treatment (Congestri et al., 2020; Alabiso et al., 2023). Unlike other greywater sources, DWW presents minimal safety risks when properly treated, establishing the feasibility of domestic-scale water recycling for food production.

- Biological treatment system
  The research team developed an engineered microbial consortium composed of filamentous cyanobacteria (Trichormus variabilis) and selected heterotrophic bacteria (such as Acinetobacter and Exiguobacterium). This consortium forms a suspended biofilm capable of efficiently removing nutrients from wastewater, functioning as the biological engine of the Zero Mile System.

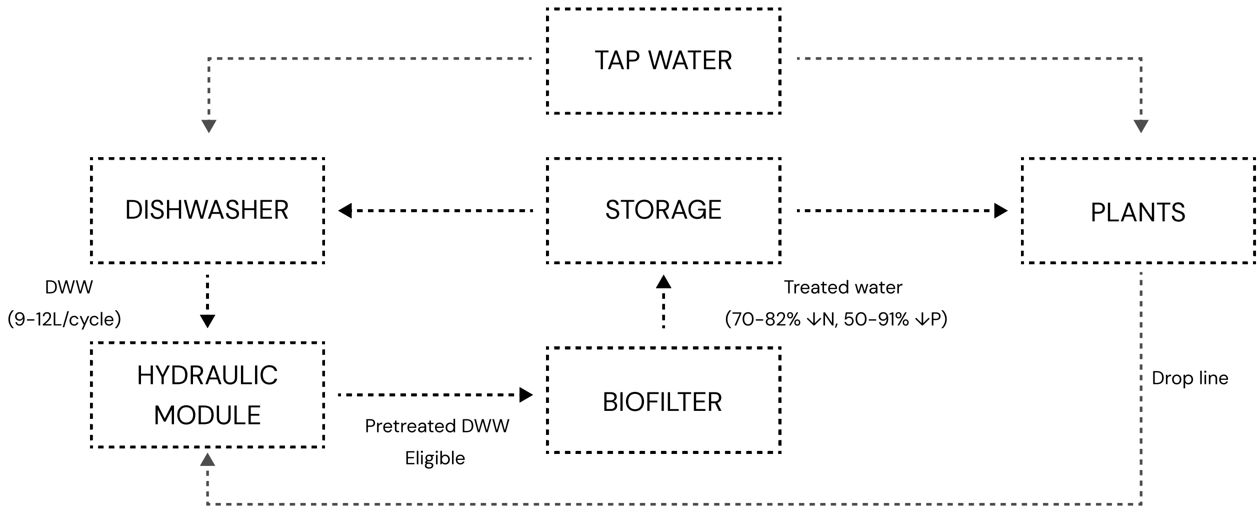


Figure 4. Zero Mile System Process (Author’s own illustration)

- Safe food production
  Crops irrigated with treated wastewater meet EU food safety standards, with no detectable pathogens (E. coli absent) and acceptable nitrate levels (Alabiso et al., 2023). Field trials confirm that the system produces safe, edible plants under real-world domestic conditions (Costa et al., 2024).

Technical Characteristics and Resulting Design Constraints

From a design perspective, these scientific findings translate into specific system requirements:

Technical Requirement	Design Implication (as fixed constraints)
Light dependency (130 μmol/m²/s)	The treatment process requires consistent light exposure, introducing spatial placement and environmental dependency constraints rather than flexible enclosure design.
Suspended biofilm (non-adherent)	The suspended biofilm structure reduces intensive mechanical maintenance but introduces sensitivity to operational disruption and irregular maintenance timing, requiring predictable maintenance awareness.
24-48 hour treatment cycle	The asynchronous treatment cycle introduces temporal decoupling between wastewater generation and reuse, requiring buffering mechanisms and user awareness of delayed and uncertain system feedback.
Alkaline tolerance (pH 9-11)	Chemical compatibility with typical dishwasher detergents reduces the need for user-driven chemical adjustment, supporting operational robustness within everyday domestic routines.
Periodic biological restart requirement (approximately every six months)	Introduces long-term maintenance discontinuity and lifecycle awareness needs, requiring mechanisms for maintenance anticipation, user notification, and communication of intervention periods

Table 1. Design Implication from Technical Requirement (Author's own table)

Scope Clarification

The purpose of this technical overview is to establish that the biological efficacy of the Zero Mile concept has been scientifically validated through rigorous research (Alabiso et al., 2023; Congestri et al., 2020; Costa et al., 2024). This thesis does not aim to revalidate or optimize the biological treatment process. Instead, it accepts these technical findings as reliable premises and focuses entirely on design-related challenges: how to translate this laboratory-validated system into a modular domestic product with clearly defined user touchpoints and intuitive interaction logic. The physical form and material design of the biofilter itself are not within the scope of this thesis; it is treated as a functional module whose user interactions (observation, maintenance notification) are designed.

2.2 Analysis of the Existing System

The most recent iteration of the Zero Mile system, documented by Sambinelli (2023), represents a significant advancement from earlier proofs-of-concept, integrating hydraulic treatment, cultivation infrastructure, and digital control into a semi-functional prototype. Developed under laboratory constraints, the system adopts a tightly integrated architecture optimized for experimental validation rather than domestic deployment.

Analyzing this configuration from a system architecture and domestic integration perspective reveals critical gaps between laboratory feasibility and domestic usability—gaps that frame the design challenges addressed in this thesis. This section examines the prototype at the subsystem level, identifying not only what it contains, but why its current form creates barriers for non-expert users.

2.2.1 Physical Configuration and Spatial Logic

Hydraulic module configuration

The hydraulic subsystem of the prototype is designed to fit within standard kitchen cabinet dimensions (approximately 60 × 60 × 85 cm), consolidating storage, filtration, pumping, sensing, and control components within a single enclosure. This compact integration includes dual storage tanks supporting both wastewater accumulation and treated water reuse, a network of solenoid valves regulating flow distribution, a circulation pump enabling system operation, and filtration and sensing elements that determine wastewater eligibility for treatment.

While this arrangement supports experimental validation by ensuring controlled hydraulic coordination, it also results in a dense infrastructural configuration in which tubing, electrical connections, and control hardware are spatially interwoven. Accessing individual components therefore requires partial enclosure disassembly, increasing maintenance complexity and limiting the possibility of independent module intervention.

Cultivation module configuration

The cultivation subsystem is vertically stacked directly above the hydraulic base, forming a unified structural assembly. The module comprises multiple planter units supported by an aluminum frame, integrated lighting elements required for plant growth, and a network of irrigation and drainage lines that return excess water to the treatment loop.

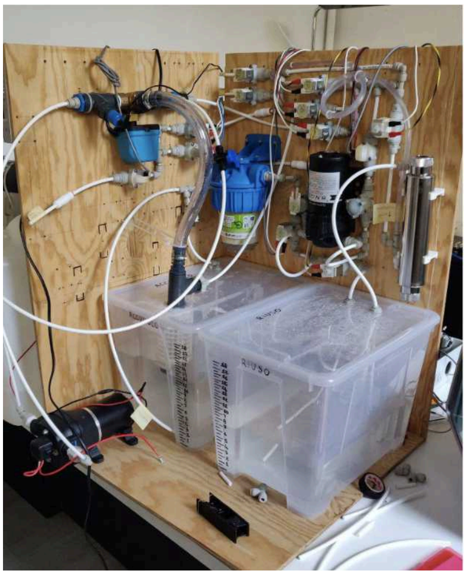


Figure 5. Hydraulic module (Source: From Grey To Green, 2023)

Figure 6. Cultivation module(Source: From greyto green, 2023)

Although the cultivation module is functionally dependent only on irrigation input and drainage return, its physical integration with the hydraulic base creates a fixed vertical configuration. This coupling constrains spatial adaptability by preventing independent placement of cultivation and treatment components according to environmental conditions, such as positioning plants near natural light sources while locating treatment infrastructure in concealed service areas.

Spatial implications

The prototype's tightly integrated configuration introduces structural constraints that limit spatial adaptability in domestic contexts. While the vertical arrangement supports coordinated system operation, it also restricts flexibility in placement, scaling, and maintenance accessibility.

Three forms of spatial rigidity can be observed. Spatial fixity arises from the system's vertical organization, which prevents horizontal deployment and exceeds typical countertop height, limiting compatibility with standard kitchen layouts. Scalar fixity reflects the coupling between treatment and cultivation capacities, preventing independent scaling of food production. Positional fixity further constrains adaptability, as components cannot be distributed according to environmental or functional needs, such as locating plants near natural light while concealing treatment infrastructure.

2.2.2 System Flows and Operational Logic

While the previous section examined what the system contains and how it is spatially arranged, this section focuses on how it operates. Understanding the sequence of water movement—from dishwasher intake to plant irrigation and return—is essential not only for technical comprehension but also for identifying where functional boundaries naturally occur.

In the current Zero Mile prototype, operational logic and physical configuration are not fully aligned. Components performing distinct functions are often physically bundled together, obscuring which parts of the system could operate independently and which require coordinated control. By tracing water movement across each stage of treatment, the analysis reveals patterns of dependency, independence, and transition that are not immediately visible from the physical configuration alone.

The system can be interpreted as a sequence of functional stages.

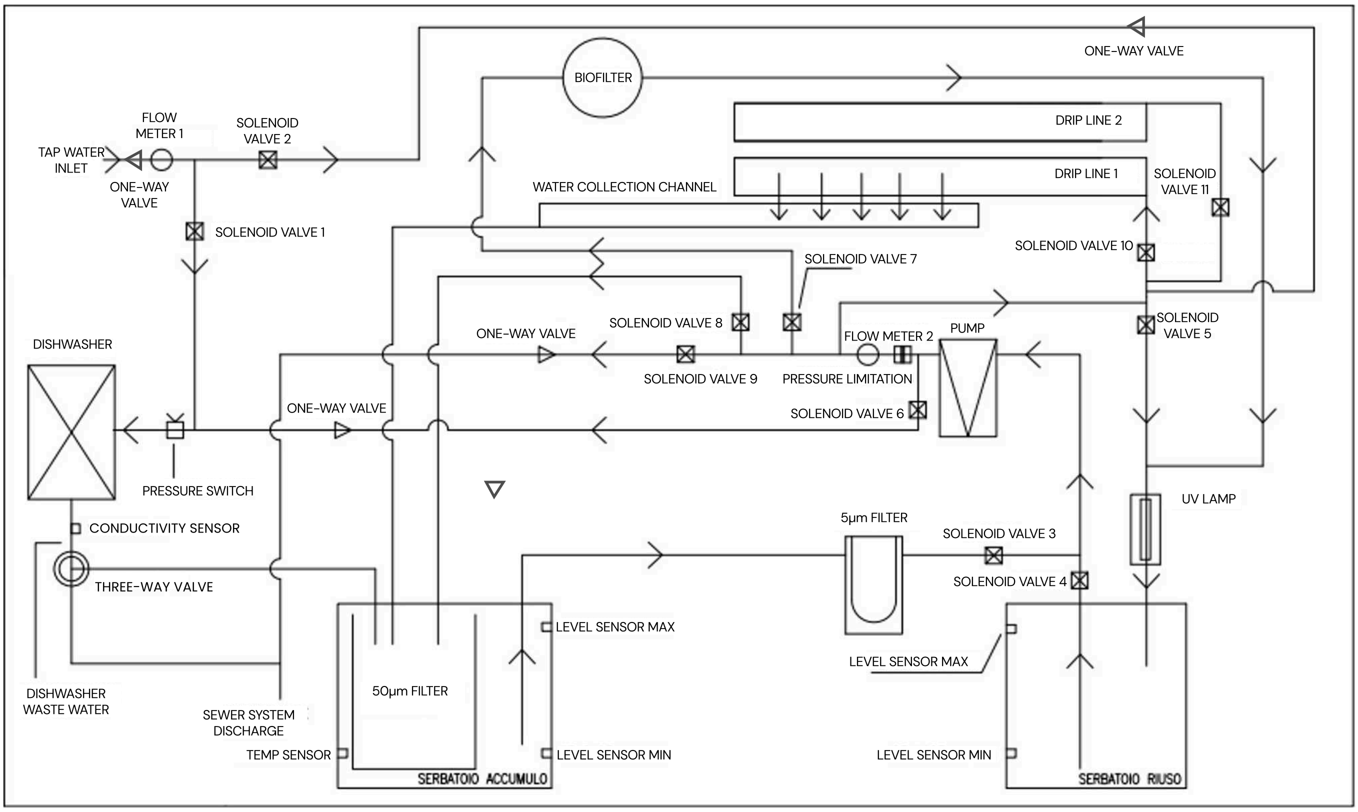


Figure 7. Kawe hydraulic module system diagram (Source: From greyto green, 2023, translated by author)

Stage 1: Intake Qualification and Coarse Filtration

Wastewater from the dishwasher first encounters a conductivity sensor and three-way valve. If salt/detergent levels are within acceptable range, water is routed toward the accumulation tank; if concentrations are too high, it is diverted directly to the sewer. Accepted water then passes through a 50 μm mechanical filter, removing coarse particulate matter before entering storage.

This stage operates independently of downstream processes. The decision to accept or divert depends only on the sensor reading at the moment of intake.

Stage 2: Buffered Storage

Accepted water enters the accumulation tank (22L), where it is stored until the treatment cycle is active. Level sensors monitor minimum and maximum fill levels, ensuring the pump does not run dry and that overflow is routed appropriately. A temperature sensor also monitors conditions that could affect downstream biological activity.

The tank is operationally passive—it stores water but does not actively process or route it. Its only dependencies are receiving water and supplying water when requested. These are simple interface relationships, not tight coupling.

Stage 3: Fine Filtration Prior to Biological Treatment

When the treatment cycle is active, the pump draws water from the accumulation tank and passes it through a 5 μm mechanical filter before entering the biofilter.

This stage is tightly coupled with pump operation. The filter itself is passive, but its function depends on water being actively pumped through it. The 5 μm filter and the pump form a functional pair.

Stage 4: Biological Treatment

Water enters the biofilter reactor, where a microbial consortium degrades organic contaminants over a controlled retention period. The reactor remains transparent to allow light penetration necessary for microbial vitality, and treated water exits through a regulated outlet before returning to the circulation loop.

From a functional perspective, the biofilter operates with a minimal set of dependencies. Its operation requires hydraulic input from the pump, an outlet returning treated water to the circulation path, and adequate light exposure, while remaining structurally and operationally independent from other system components.

Stage 5: Post-Treatment Disinfection

Treated water exiting the biofilter passes through a UV lamp before entering the reuse tank. The UV lamp is plumbed inline, downstream of the biofilter outlet and upstream of the reuse tank inlet. Its operation is coordinated with the pump and valve sequence.

The UV unit is hydraulically inseparable from the circulation path and therefore participates in the tightly coupled treatment sequence.

Stage 6: Treated Water Storage

Disinfected water enters the reuse tank (22L), where it is stored until needed for irrigation. Like the accumulation tank, the reuse tank is equipped with level sensors to monitor available supply.

Like Stage 2, this tank is operationally passive. It receives water from Stage 5 and supplies water to Stage 7 when requested. No active coordination is required.

Stage 7: Irrigation Distribution

Water is delivered to the cultivation module through a dual-mode logic. When reuse water is available, irrigation depends on pump-driven circulation. When reuse water is unavailable, a fallback tap-water path bypasses the circulation core, allowing independent operation. The two sources are mutually exclusive—they are not mixed, but selected based on availability.

This duality means that irrigation can function without the pump when tap water is used, but when relying on reuse water, it remains coupled to the circulation core.

Stage 7a: External Supply, Dishwasher Integration, and Overflow Management

This stage represents the interface between the internal reuse loop and external household infrastructure. Tap water enters the system through a monitored inlet regulated by a dedicated valve controlling supply to the dishwasher. In parallel, treated water from the reuse tank can be redirected toward the dishwasher through coordinated valve sequences. These two supply paths converge at a junction prior to the appliance, where a downstream pressure switch ensures stable delivery regardless of the active source. The two sources remain mutually exclusive and are selected through system logic rather than mixed.

Overflow management further reveals the active role of the circulation core in maintaining system stability. When the accumulation tank exceeds its capacity, excess water is actively discharged to the sewer through pump-driven flow and coordinated valve actuation. Similarly, surplus water in the reuse tank is redirected back to the accumulation tank via the circulation path. In both cases, overflow does not occur passively but requires intervention from the pump and valve control network.

From a functional perspective, this stage exhibits mixed dependency characteristics. Tap water supply is infrastructure-dependent but operationally independent, relying only on valve actuation without pump coordination. In contrast, reuse-to-dishwasher routing and both overflow pathways depend on the circulation core, sharing valve logic and pump operation. This configuration positions Stage 7 as a boundary condition where external infrastructure, safety regulation, and internal coordination intersect.

Stage 8: Return Flow Collection

Excess irrigation water that is not absorbed by the plants is collected in a channel beneath the planters and routed back to the accumulation tank. This return flow re-enters the treatment cycle, completing the closed loop.

The return flow is passive—it relies on gravity and does not require active pumping or valve coordination. The only requirement is a physical return line connected to the accumulation tank. Functionally, this stage is independent of the circulation core.

Analytical synthesis

The flow analysis highlights that the Zero Mile system is composed of subsystems with different degrees of functional coupling and autonomy. Rather than forming a uniformly integrated structure, some components operate as tightly coordinated infrastructural clusters, while others behave as passive storage elements or externally connected interfaces.

The following synthesis summarizes these recurring functional boundary patterns, providing an analytical foundation for the modular architecture developed in Chapter 4.

Pattern	Description	Evidence from stages
Tightly coupled circulation core	Pump, valves, UV lamp, and 5 μm filter form an interdependent network	Stages 3, 5, reuse-to-irrigation path (Stage 7), reuse-to-dishwasher path (Stage 7a), and both overflow paths depend on pump operation
Operationally passive storage	Accumulation and reuse tanks store water but do not actively route it	Stages 2 and 6 require only inlet/outlet connections and level monitoring—overflow is an exception that requires active intervention
Functionally independent biofilter	Biofilter requires only hydraulic connections, not structural or control integration	Stage 4
Dual-mode irrigation	Irrigation can be pump-dependent (reuse) or pump-independent (tap, fallback mode)	Stage 7
Infrastructure interface	Tap water supply and discharge paths are external-facing	Stage 7a

Table 2. Synthesis of Functional Boundary Patterns (Author's own table)

These patterns describe structural properties of the existing system rather than design decisions, clarifying which components may be separated and which must remain coordinated.

2.2.3 Missing Product Qualities

The technical analysis in 2.2.1 and 2.2.2 describes a system that is functionally complete but exhibits three characteristics that, from a product design perspective, represent significant gaps when evaluated against the expectations of a domestic appliance. These are not technical failures —the system works biologically—but architectural and interactional shortcomings that would hinder its adoption in everyday homes.

Legibility: The Absence of User-Facing Feedback
As documented across Stages 1–7a, the prototype monitors numerous parameters—conductivity, temperature, water levels, flow rates—yet provides no direct feedback to the user. Understanding the system's operational status requires connecting a laptop to the Arduino's USB port and inspecting serial console output. This complete lack of what Hallnäs and Redström (2001) term "ambient awareness"—the ability for a system to communicate status unobtrusively in the periphery of attention—places the Zero Mile prototype in stark contrast with established domestic technology conventions.

Successful household appliances communicate their state through intuitive signals: washing machines display cycle progress via LED patterns and audible tones; dishwashers illuminate "running" indicators; smart thermostats show current temperature at a glance. These interfaces allow users to understand whether an appliance is functioning normally, requires attention, or has encountered an error without active interrogation. The Zero Mile prototype, by operating as a black box that reveals its internal state only to those with programming expertise, creates a fundamental information gap. Users cannot distinguish between normal operation, states requiring attention, and failures without technical intervention—a condition that, in a domestic context, breeds uncertainty and undermines trust.

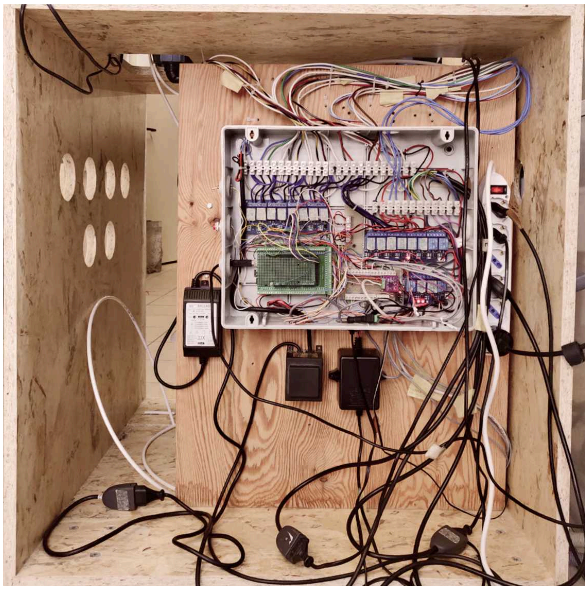


Figure 8. Control Module (Source: From Grey To Green, 2023)

Figure 9. Hydraulic module (Source: Author's own pic, 2025)

Modularity: The Rigidity of Functional Coupling

The flow analysis in 2.2.2 reveals that several functions exhibit functional separability—they could, in principle, operate independently if connected through clear interfaces:

- Storage tanks (Stages 2 and 6) are operationally passive, requiring only inlet/outlet connections and level monitoring
- The biofilter (Stage 4) requires only hydraulic connections and light access, with no structural dependency on the circulation core
- Irrigation distribution (Stage 7) can, in fallback mode, be supplied directly by tap water without pump involvement

Despite this functional independence, the current prototype fuses these elements into a single monolithic assembly. As shown in 2.2.1, the cultivation module is permanently stacked atop the hydraulic base, creating a 1.8 meter vertical structure that cannot be reconfigured horizontally. This rigidity has three concrete consequences: spatial fixity, scalar fixity and positional fixity.

The system therefore exists as a largely indivisible package—appropriate for experimental validation but poorly aligned with the spatial variability and incremental deployment required in domestic environments.

Repairability: The Fragility of Dense Integration

The dense packaging documented in 2.2.1—twelve solenoid valves, a pump, mechanical filters, sensors, and control hardware crammed into a 60 × 60 × 85 cm enclosure—creates significant barriers to maintenance and repair. Accessing any internal component requires removing enclosure panels and navigating a dense arrangement of tubing, valves, and electrical connections, with no clear service boundaries or designated access points.

Sambinelli (2023) provides concrete evidence of the consequences: tube connections became unfastened during transport between laboratories, causing complete system failure during testing phases. While this incident occurred in a research context, it highlights a fundamental design vulnerability—the entanglement of components renders the prototype susceptible to minor mechanical disturbances.

Repairing or diagnosing faults in this configuration typically involves disassembling enclosure elements, tracing complex tubing networks, identifying malfunctioning valves or sensors, and reassembling interconnected components without disrupting adjacent connections.

This level of complexity places routine maintenance beyond the capabilities of non expert users. Unlike conventional appliances where failed components can be accessed through service panels and replaced individually, the Zero Mile prototype's tightly integrated architecture treats the entire assembly as a single, fragile unit.

Architectural Clarity: The Entanglement of Treatment and Service Domains

Beyond the challenges of legibility, modularity, and repairability, the prototype exhibits a deeper architectural ambiguity regarding the boundaries between core treatment functions and infrastructure dependent service roles. As Stages 7 and 7a illustrate, wastewater treatment, irrigation supply, tap water distribution, and dishwasher provisioning are coordinated through a shared hydraulic and control structure—the same pump, valve network, and control logic serve multiple functional purposes simultaneously.

While this integration supports efficient experimental operation and internal resource circulation, it obscures the distinction between subsystems responsible for biological transformation and those responsible for distributing water to external endpoints. The reuse tank, for example, functions both as a storage buffer within the treatment loop and as a potential supply source for downstream services, without a clearly defined interface separating these roles. Similarly, the convergence of tap and reuse water paths—both for irrigation and dishwasher supply—relies on valve logic that is embedded within the same tightly coupled network as treatment circulation.

From a product architecture perspective, this lack of clearly articulated functional boundaries limits the system's adaptability and complicates both spatial configuration and maintenance planning. Without explicit architectural separation between treatment modules and service distribution subsystems, users and installers cannot easily reconfigure, replace, or extend individual components without affecting the broader system. Establishing clearer architectural boundaries and standardized interfaces is therefore essential to support modular deployment, flexible configuration, and long term product viability in domestic environments.

Summary

These missing product qualities—limited legibility, constrained modular adaptability, reduced repairability, and ambiguous architectural boundaries—do not originate from biological limitations but from the prototype's infrastructural integration strategy. Together, they reveal that the primary challenge is not technological feasibility but the translation of a validated treatment system into a domestically intelligible, adaptable, and maintainable configuration.

2.3 User Insights and Design Requirements

The technical and biological validation presented in Section 2.1 establishes that the Zero Mile system is scientifically feasible: the microbial consortium effectively removes nutrients, treated water meets food safety standards, and the biological pathway is robust.

However, the analysis of the existing prototype in Section 2.2 demonstrates that technical feasibility alone does not ensure domestic adoption. The prototype exhibits four architectural shortcomings—limited legibility, constrained modular adaptability, reduced repairability, and ambiguous architectural boundaries—that reflect its origin as a research platform rather than a consumer-oriented product.

As Norman (2013) suggests, successful product adoption depends not only on functional performance but on the alignment between system capabilities, user expectations, and everyday practices. Accordingly, this section examines how the architectural gaps identified in Section 2.2 are perceived and interpreted by potential users. Drawing on prior user studies conducted by Costa and collaborators (Costa & Nebuloni, 2021; Costa et al., 2018), Section 2.3.1 synthesizes key user perceptions, while subsequent subsections translate these insights into problem framing and actionable design requirements that guide the modular architecture proposed in Chapter 4.

2.3.1 User Perceptions and Concerns: Synthesis from Existing Research

Prof. Costa's research team conducted focus groups and interviews with potential users of the Zero Mile system. While participants expressed strong interest in sustainable water reuse and home food production, the studies reveal persistent uncertainties regarding how the current prototype would integrate into everyday domestic contexts.

These concerns cluster around three interrelated experiential dimensions: spatial uncertainty, perceptual integration, and operational opacity. Together, they describe how users interpret the prototype not as a household appliance but as an unfamiliar and difficult-to-situate technological object.

Spatial uncertainty

Participants frequently questioned whether the system could be accommodated within diverse kitchen environments. Concerns extended beyond footprint dimensions to include compatibility with cabinetry, coexistence with other appliances, and the accessibility of routine activities such as cleaning, harvesting, and water refilling under different placement scenarios. Feedback from engagement sessions further highlighted anxieties related to relocation, particularly in compact urban apartments where fixed installations are difficult to accommodate.

These perceptions reflect the constraints introduced by the vertically integrated configuration described in Section 2.2.1, which limits flexibility across heterogeneous domestic layouts.

Perceptual integration and product identity

User responses to the prototype's appearance were often framed in terms of familiarity and domestic appropriateness rather than aesthetic preference alone. Some participants described the system as visually "unfinished," while others associated it with experimental installations rather than everyday kitchen appliances. Participants repeatedly expressed the expectation that the system should appear understandable within the context of domestic technology and coexist with existing appliances rather than signal laboratory experimentation.

Several factors contributed to this perception, including visible tubing, utilitarian material choices, and the absence of recognizable interaction cues. Importantly, these reactions point to difficulties in interpreting the system's purpose and operational state within familiar domestic mental models.

Maintenance complexity and operational opacity

Participants also reported uncertainty regarding maintenance responsibilities and system operation, particularly concerning when intervention would be required and how routine upkeep should be performed. Rather than expressing fear of technical failure, users emphasized ambiguity surrounding everyday care activities, including organic waste management, hygiene considerations, and the timing of periodic actions.

The absence of accessible indicators of system status or biological activity contributed to this uncertainty. Participants frequently described the system as operating as a "black box," making it difficult to distinguish between normal operation, temporary states, and situations requiring attention.

Synthesis

These perceptions suggest that barriers to domestic adoption arise less from technical limitations than from the relationship between system configuration, perceptual interpretability, and everyday practices. Spatial rigidity, limited perceptual integration, and unclear maintenance rhythms shape how users understand the system's role within the home environment.

2.3.2 From User Concerns to Designable Problems

Building on the experiential observations outlined in Section 2.3.1, this section translates user perceptions into designable problem framings. Rather than prescribing specific product forms, the discussion identifies structural mismatches between system architecture, perceptual interpretation, and everyday domestic practices that must be addressed to support long-term adoption.

The analysis is organized around three complementary dimensions: spatial adaptability, experiential legibility, and maintenance intelligibility.

Spatial adaptabilty
User concerns regarding placement and accessibility reveal a misalignment between the prototype's fixed configuration and the variability of domestic environments. The issue is not the absolute size of the system but its limited capacity to support alternative spatial arrangements and negotiated placement within existing kitchen infrastructures. Vertically stacked components restrict horizontal redistribution and constrain the ability to adapt the relationship between cultivation and treatment functions.

This mismatch highlights the importance of configurability as an architectural property rather than dimensional reduction as a purely physical objective.

Experiential legibility
Difficulties in perceiving the system as a domestic appliance indicate a gap between system operation and user interpretation. Associations with laboratory equipment, unfamiliar material cues, and limited feedback mechanisms reduce users' ability to understand what the system is doing and why. The challenge therefore concerns the interpretability of system identity and activity rather than aesthetic refinement alone.

Perceived aesthetic disconnection can be understood as a manifestation of limited semantic integration, where the system's function and state are not readily communicated through recognizable domestic interaction cues.

Maintenance Intelligibility
Maintenance anxiety reflects uncertainty not primarily about technical procedures but about timing, responsibility, and intervention boundaries. Users struggle to anticipate when attention is required, how routine actions relate to ongoing biological processes, and which aspects of the system fall within their responsibility. The absence of accessible feedback regarding operational rhythms and periodic biological transitions reinforces this uncertainty.

This temporal ambiguity becomes particularly relevant for processes such as monitoring, cleaning, and biological restart events, which introduce discontinuities within otherwise continuous system operation.

Summary

These problem framings do not prescribe the redesign of individual components but instead clarify conditions for improving the relationship between system architecture, perceptual interpretation, and everyday practice. They establish the conceptual bridge between the diagnostic analysis and the design exploration.

2.3.3 User Expectations for Domestic Appliances as Design Criteria

Beyond the Zero Mile–specific concerns discussed in Section 2.3.1, potential users approach the system with expectations shaped by long-term interaction with domestic appliances. These expectations function not as arbitrary preferences but as culturally stabilised conventions that reduce cognitive load, support trust, and enable the seamless integration of technology into everyday life.

However, not all generic appliance expectations apply directly to the Zero Mile system. As clarified through supervisory discussions (Costa, 2026), the intended use model assumes professional installation and configuration, while users engage primarily through routine interaction and maintenance activities. This distinction frames which expectations remain relevant and how they should be interpreted.

Rather than presenting a checklist of requirements, the following discussion interprets key appliance expectations as normative reference points that complement the designable problems identified in Section 2.3.2.

Installation as an intelligible process
Although installation is performed by professionals, users expect the resulting configuration to appear coherent and interpretable rather than opaque. This expectation extends to the clarity of module relationships and the legibility of system structure after installation. Consequently, configurational outputs must support communication between professional assembly and everyday understanding, allowing users to perceive the system as intentionally organised rather than technically assembled.

Autonomy as the default operational state
Domestic appliances are typically expected to operate autonomously once installed, requiring intervention only for clearly defined tasks such as replenishment or maintenance. In the Zero Mile context, this expectation highlights the importance of distinguishing between routine biological processes that occur continuously and moments that genuinely require user action. The absence of this distinction risks transforming normal system behaviour into perceived malfunction or uncertainty.

Failure as guided deviation rather than interruption
Users anticipate that irregular conditions will be communicated in ways that support interpretation and action rather than abrupt cessation of function. This expectation reframes failure not as a technical breakdown but as a deviation within an otherwise continuous operational trajectory. Clear differentiation between user-resolvable conditions and those requiring professional intervention becomes essential to maintaining trust and perceived reliability.

Peripheral intelligibility of system state
Users expect to remain aware of an appliance's operational condition without continuous monitoring. Rather than requiring explicit inspection, domestic technologies typically communicate status through subtle, easily interpretable cues that support background understanding.

Perceptual coherence
Users expect technologies to visually and semantically belong within their domestic surroundings. This expectation concerns interpretability rather than stylistic refinement: materials, form relationships, and visible components collectively shape whether a system is perceived as a household appliance or as experimental infrastructure. The challenge therefore lies in aligning system identity with familiar domestic reference points while accommodating necessary technical transparency.

Maintainability (user-accessible)
Routine maintenance is expected to be both manageable and clearly bounded. Users anticipate knowing which actions fall within their responsibility, when such actions should occur, and how they relate to the system's broader operation. Ambiguity surrounding biological cycles, cleaning needs, or intervention timing undermines confidence and contributes to maintenance anxiety, reinforcing the intelligibility gap identified in Section 2.3.2.

Summary
Interpreted through the Zero Mile use model, these expectations establish a normative experiential baseline against which the prototype can be evaluated. They extend the designable problems identified in Section 2.3.2 by situating them within broader domestic appliance conventions, thereby clarifying the experiential conditions that the subsequent design requirements must address.

2.3.4 Derived Design Requirements

The preceding sections progressively established the foundation for design.

Section 2.3.1 synthesised user perceptions, highlighting spatial anxiety, limited system legibility, and uncertainty surrounding maintenance responsibilities. Section 2.3.2 translated these concerns into designable problems concerning configurability, experiential intelligibility, and the articulation of intervention boundaries. Section 2.3.3 further contextualized these problems within broader expectations associated with domestic appliances, including autonomous operation, accessible maintenance, and unobtrusive integration into everyday routines.

Building on these insights, this section consolidates the findings into a structured set of design requirements. Rather than prescribing specific product forms, the requirements define conditions that support spatial adaptability, improve users' understanding of system behaviour, and clarify maintenance responsibilities within domestic contexts.

The requirements are organised into two complementary dimensions:

- Functional requirements, addressing spatial configuration, component independence, and maintenance accessibility
- Experiential requirements, addressing system legibility, feedback communication, and users' ability to anticipate and understand intervention needs

Each requirement is explicitly traceable to preceding analyses and is assigned a priority level to support design decision-making where trade-offs are necessary.

Category	Requirement	Source	Priority
FUNCTIONAL			
F1	System must accommodate diverse spatial configurations: countertop, wall mounted, under cabinet	From configurable architecture problem and user spatial concerns	High
F2	System must allow the cultivation elements to be positioned independently from the water treatment components	From configurable architecture problem and user desire for placement flexibility	High
F3	Maintenance activities (biofilter cleaning, mechanical filter cleaning) must be physically accessible regardless of how the system is arranged	From maintenance boundaries problem and user concerns about maintenance access	High

Category	Requirement	Source	Priority
EXPERIENTIAL(UX)			
UX1	The system must communicate when user intervention is required and distinguish routine actions from abnormal conditions.	From intervention boundaries and maintenance uncertainty	Critical
UX2	Each distinguishable functional part of the system must have a defined user touchpoint type (digital / physical / none / service only)	From maintenance boundaries problem	Critical
UX3	The system must provide continuously available, low-effort cues indicating whether it is operating normally, temporarily inactive, or requiring attention.	From appliance expectation of passive awareness	Critical
UX4	The system must clearly differentiate user-serviceable maintenance activities from professional service interventions.	From repairability ambiguity and responsibility uncertainty	Critical
UX5	The system should communicate operational rhythms (e.g., monitoring, cleaning, restart cycles) so that users can anticipate routine interactions.	From maintenance anxiety and 6-month restart issue	High

Table 3. Design requirements derived from technical analysis, user research, and domestic appliance expectations.(Author's own table)

- Critical: requirements must be satisfied for the system to function biologically or to be usable by non expert users.
- High: requirements address primary user concerns identified in research and significantly impact usability or acceptance.
- Medium: requirements enhance experience or address secondary concerns but may be compromised if necessary to meet higher priority needs.

2.4 Design Paradigms and Case Studies

The design requirements established in 2.3.4 define what the redesigned Zero Mile system must achieve: configurable architecture, interaction legibility, clear maintenance boundaries, and intelligible system feedback. This section examines established design paradigms and commercial precedents that demonstrate how such qualities can be realized. These cases are not treated as models for replication but as analytical references that reveal transferable architectural and interaction principles informing the subsequent design exploration.

2.4.1 Modular Product Architecture and User-Accessible Design

Modular design—the decomposition of complex systems into discrete functional units with standardized interfaces—has been extensively theorized in product design literature. Salvador, Forza, and Rungtusanatham (2002) identify three fundamental types of modularity: component sharing (common parts across variants), component swapping (interchangeable units within a platform), and mix modularity (user-configurable combinations). Ulrich and Eppinger (2015) emphasize that effective modularity requires not only physical separability but also functional independence and interface standardization.

USM Modular Furniture System

Since the 1960s, the USM Haller system has employed a standardized ball-and-tube connector architecture that enables structural reconfiguration through discrete components. Shelving units are composed of panels, tubes, and connectors that can be assembled and rearranged without specialized tools, allowing configurations to evolve over time in response to spatial needs.

The system's long-term adoption demonstrates how clearly defined mechanical interfaces can support both configurability and structural stability. Rather than relying on fixed assemblies, the design externalizes modular logic through visible connection points, enabling users to understand how elements relate and how configurations can be modified

Figure 10. USM Haller furnitures (Source: USM official website https://us.usm.com/ (accessed in 2026))

Insight for Zero Mile is that standardized, tool-independent connection interfaces can support spatial reconfiguration while maintaining structural intelligibility, allowing users to anticipate how modules can be assembled, repositioned, or replaced over time.

Fairphone Modular Smartphone

The Fairphone exemplifies modular product architecture designed around component-level accessibility. Core elements—including the battery, camera modules, charging port, and speakers—are organized as discrete units that can be individually removed using standard fastening mechanisms. This segmentation externalizes maintenance structure, allowing users to identify replaceable components without disassembling the entire device.

Figure 11. Fairphone back structure (Source: Fairphone official website, https://shop.fairphone.com (accessed in 2026))

Rather than treating repair as an expert-only activity, the product distributes maintenance responsibility through explicit physical boundaries and accessible attachment methods. The architecture demonstrates how complex technical systems can support partial intervention by clearly differentiating between user-serviceable modules and components requiring specialized service.

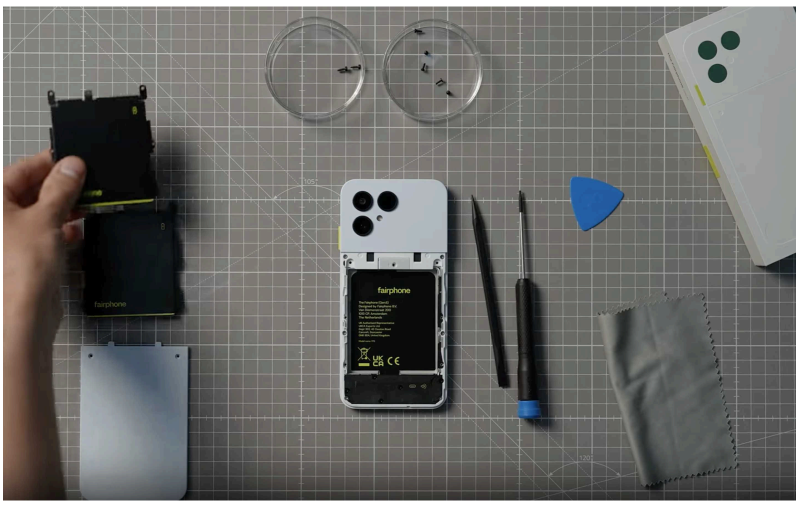


Figure 12. Process of changing battery of a Fairphone (Source: Fairphone official website, https://shop.fairphone.com/(accessed in 2026))

Insight for Zero Mile is that explicit physical segmentation and accessible attachment mechanisms can clarify maintenance responsibility, enabling users to recognize which components can be safely serviced and which require external intervention. Such architectural legibility can reduce maintenance uncertainty and support sustained engagement with complex domestic systems.

The IKEA METOD kitchen system demonstrates modular architecture organized around standardized structural units combined with a configuration interface that mediates between user preferences and feasible installation outcomes. Rather than requiring users to understand technical constraints directly, the system externalizes spatial planning through a digital configuration tool that translates layout decisions into a structured component specification.

Crucially, the platform separates configuration from installation responsibilities. Users engage primarily in spatial planning and selection, while physical assembly may be performed either independently or by professional installers. This division clarifies responsibility boundaries and reduces the cognitive burden associated with coordinating complex technical installations.

IKEA METOD Kitchen System

The system illustrates how modular product ecosystems can support user agency in configuration without transferring the full complexity of installation, enabling adaptable deployment across diverse domestic environments.

Figure 13. IKEA MOTHOD kitchen merchandise display (Source: IKEA official website, https://www.ikea.com/gb/en/cat/metod-kitchens-ka005/ (accessed in 2026))

Insight for Zero Mile is that a configuration interface that translates spatial preferences into an installation-ready component specification can mediate between user agency and professional deployment, reducing uncertainty while preserving flexibility in system configuration.

LEGO Building System

The LEGO building system exemplifies modular architecture grounded in strict interface standardization. Connection geometries have remained consistent across generations, allowing components produced decades apart to interoperate without modification. This stability supports incremental expansion and reconfiguration while preserving compatibility across the evolving ecosystem.

Rather than emphasizing flexibility alone, the system demonstrates how standardized interfaces enable long-term structural continuity. Users can extend, modify, and repair configurations without requiring redesign of existing components, reducing both technical risk and cognitive effort associated with system evolution.

The LEGO platform illustrates how interface stability can sustain adaptability over time, allowing complex assemblies to evolve through accumulation rather than replacement.

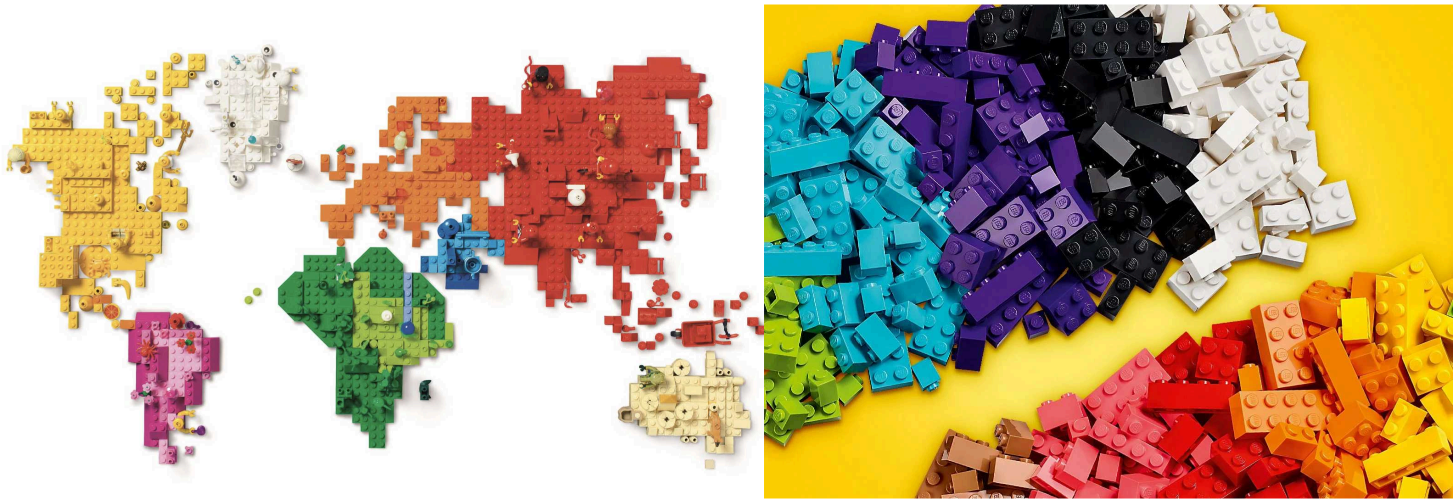


Figure 14. LEGO classical blocks (Source: LEGO official website, https://www.lego.com/(accessed in 2026))

Insight for Zero Mile is that stable and standardized module interfaces can support incremental system evolution, allowing components to be added, replaced, or reconfigured without destabilizing existing configurations and thereby reducing long-term adoption risk.

Summary

Across these examples, modularity emerges not only as a strategy for functional decomposition but as an architectural condition that supports user comprehension, maintenance clarity, and long-term system evolution. The cases demonstrate that modular systems become accessible when interfaces are standardized, service boundaries are legible, and configuration decisions are mediated through structured mechanisms.

2.4.2 Modular Cultivation Systems and Domestic Integration

Domestic cultivation as infrastructure

Recent domestic cultivation systems provide relevant precedents for integrating biological processes within everyday living environments. These products address challenges comparable to the Zero Mile context, particularly the need to externalise system state, communicate maintenance rhythms, and embed cultivation infrastructure within spatial and interactional conventions of the home.

Rather than emphasising technical control, such systems demonstrate strategies for mediating biological complexity through automation, distributed feedback, and carefully scoped user interaction.

Click & Grow Smart Garden

The Click & Grow Smart Garden exemplifies a cultivation system designed as a low-attention domestic appliance. The system adopts a plug-and-play operational model in which users insert plant cartridges, replenish water periodically, and rely on automated regulation of lighting, irrigation, and nutrient delivery. Core cultivation processes remain operationally abstracted, reducing the need for configuration or continuous monitoring.

The Click & Grow Smart Garden exemplifies a cultivation system designed as a low-attention domestic appliance. The system adopts a plug-and-play operational model in which users insert plant cartridges, replenish water periodically, and rely on automated regulation of lighting, irrigation, and nutrient delivery. Core cultivation processes remain operationally abstracted, reducing the need for configuration or continuous monitoring.

Figure 15. The Smart Garden 27 (Source: click & grow official website, https://www.clickandgrow.com/?srsltid=AfmBOopMKh2AyExBsq1LHsXqJH7f32gJKRCI-S_Iva7thtI0O_Bc5shP (accessed in 2026))

The case illustrates how biological processes can be operationally abstracted while still providing intelligible access to system state and maintenance timing. Separating background automation from optional informational interfaces offers a strategy for reducing perceived complexity without obscuring responsibility for routine intervention.

Rise Gardens

Rise Gardens presents a domestic cultivation system organized as a vertically stackable infrastructure, combining hydroponic modules with sensor monitoring and app-mediated feedback. The modular arrangement enables incremental expansion while preserving a stable operational core, supporting variation in cultivation capacity without requiring reconfiguration of underlying technical systems.

System feedback is mediated primarily through the companion application, which translates sensor measurements into actionable maintenance prompts rather than exposing raw operational data. This approach reframes system monitoring as episodic intervention, allowing users to engage with cultivation processes through interpretable tasks such as harvesting, refilling, or adjustment.

Figure 16. The Rise Garden 3 (Source: RiseGarden official website, https://risegardens.com/?srsltid=AfmBOorzeeljoMBf3VHKn_xL2QtXX__tggz-dCH28cJwH2QJGKfhnRhY (accessed in2026))

The case demonstrates how modular expansion can be decoupled from core treatment functions while maintaining intelligible maintenance communication. Translating system sensing into task-oriented prompts illustrates how informational mediation can support user engagement without increasing cognitive burden.

Rise Gardens

Across these cases, domestic cultivation is framed not as a technically intensive activity but as an infrastructural process mediated through automation and episodic user interaction. Modular organisation supports incremental adaptation, while selective abstraction of biological complexity enables systems to remain intelligible without requiring continuous oversight. These precedents highlight how operational decoupling, informational mediation, and spatial compatibility collectively contribute to the domestication of biologically driven infrastructures.

2.5 Design Opportunity

The preceding sections establish that the Zero Mile system is technically viable yet domestically unresolved. While the biological treatment process functions reliably, the current prototype exhibits spatial rigidity, limited experiential legibility, and ambiguous maintenance boundaries that hinder integration into everyday home environments.

Rather than indicating a need for further technical optimization, these limitations reveal a design translation challenge: how a laboratory-validated biological infrastructure can be reconfigured to support domestic adaptability, intelligible operation, and sustainable long-term engagement. This thesis therefore reframes the problem as one of architectural and interactional mediation between biological constraints and everyday household practices.

- **System architecture opportunity**
  The monolithic configuration of the current prototype limits spatial adaptability and independent scaling of system functions. This suggests an opportunity to reconceptualise the system as a configurable architecture composed of functionally distinct yet interoperable modules. By establishing stable interface relationships between components, the system can support diverse spatial arrangements while preserving treatment integrity.

- **Component interaction opportunity**
  At the level of individual functional elements, the absence of clearly articulated user touchpoints contributes to uncertainty regarding permissible interaction and maintenance responsibilities. This highlights the need to define module-specific interaction boundaries, clarifying which components invite user engagement, which remain observational, and which require professional servicing. Such differentiation enables users to interpret system structure through interaction rather than technical understanding.

- **Operational legibility opportunity**
  Users' uncertainty regarding system status and maintenance timing indicates an opportunity to externalize operational rhythms through accessible feedback and guidance. Rather than increasing technical transparency, the challenge lies in communicating system states, routine cycles, and intervention triggers in forms that support peripheral awareness and episodic engagement.

Scope and research boundaries

The three opportunity areas outlined above—configurable architecture, interaction boundaries, and operational legibility—define the scope of design exploration undertaken in this thesis. Each responds directly to the architectural and experiential gaps identified in the preceding analysis.

This research does not attempt to revalidate the biological treatment process, redesign material or structural aspects of the biofilter, or develop detailed engineering specifications. Instead, the contribution lies in articulating architectural and interaction strategies that mediate between existing technical constraints and domestic use contexts.

By delimiting the investigation in this manner, the thesis positions its outcomes as design research propositions that remain grounded in validated biological functionality while enabling future technical refinement and implementation.

Chapter 3. Methodological Approach

3.1 Research through Design Positioning

This thesis adopts Research through Design (RtD) as its core methodological framework. This choice is grounded in the premise that transitioning controlled biological systems from the laboratory to the volatile domestic environment requires more than technical optimization; it requires a systematic investigation into human-biological coexistence. Consequently, this research does not treat design as the production of a finalized consumer product, but as a primary mode of inquiry. In this framework, the design process functions as an iterative experiment where ideation, visualization, and materialization serve as methods to investigate the interdependencies between system architecture, user perception, and domestic routines.

This methodological positioning dictates a reflective translation of technical requirements. Rather than treating biological survival parameters as fixed engineering constraints, the research actively translates them into spatial and interactional propositions. For instance, the precise monitoring requirements of a bioreactor are reframed as "ambient feedback" within a domestic furniture component. This translation allows for the observation of how biological necessities—once embedded in household objects—shape user understanding and acceptance.

To bridge the gap between theoretical speculation and domestic reality, the research employs prototyping as a mode of reflective externalization. In an RtD context, prototypes are not precursors to a final product but "epistemic artefacts" that function as physical hypotheses. By situating these prototypes within simulated domestic contexts, the research exposes latent frictions—such as interpretive gaps in maintenance or biological status signals—that remain invisible during abstract analysis.

The prototype thus serves as a communicative medium, where generated feedback drives a continuous cycle of "making–reflection–revision". The objective of this process is not the optimization of a single artifact, but the synthesis of intermediate design knowledge in the form of Design Guidelines. These guidelines address system configurability, legibility of biological states, and the reduction of cognitive load in maintenance, providing a theoretical and practical framework for integrating biotechnology into domestic interiors.

3.2 Translating Requirements into Design Exploration

The design requirements formulated in Chapter 2 transcend mere technical specifications; they constitute the analytical foundation for the subsequent Research through Design (RtD) inquiry. These requirements establish a normative coordinate system for evaluating the translation of laboratory-scale technology into the domestic sphere. Rather than prescribing a static aesthetic form, they articulate performance boundaries—specifically spatial adaptability, clear intervention thresholds, and intelligible feedback—that the system must satisfy to transition from an experimental apparatus to a domestic inhabitant (Gaver et al., 1999).

Within the "Translation Funnel" framework (Zimmerman et al., 2007), these requirements represent the Scientific Domain. They function as a conceptual filter that refines the survival-oriented logic of the laboratory—characterized by controlled variables—into the multifaceted and unpredictable logic of the home. In this context, design exploration is reframed as a process of "material re-narration," where technical constraints are translated into relational properties between the user and the system.

To operationalise this translation, the research employs an Architectural Decomposition strategy at the "neck" of the funnel—the Design Intervention phase. This methodological step is vital: it deconstructs the existing Zero Mile prototype into three interrelated functional layers: the Life-Support Layer (core metabolism), the Interface Layer (human-biological communication), and the Spatial Support Layer (environmental integration). This decomposition allows for an independent investigation into spatial configurations and interaction touchpoints without compromising the validated biological core (Stappers & Giaccardi, 2017). By isolating these fragile experimental parameters, the designer can treat the system architecture as a modular field, exploring alternative topologies that align with the spatial and temporal rhythms of everyday life.

Throughout this iterative process, sketching, diagrammatic modelling, and scenario-based reasoning function as inquiry-driven tools rather than mere representational aids. These methods facilitate the rigorous examination of the funnel's three core iterative loops:

- Configurability Logics: Investigating the transition from centralized to distributed structures. This explores how modular components adapt to diverse household typologies, light patterns, and movement gradients (Brandes et al., 2009).

- Touchpoint Distribution: Mapping the physical manifestation of maintenance tasks. The goal is to transform "maintenance anxiety" into "rituals of domestic care," where user interventions are clearly bounded and intuitively prompted.

- Operational Rhythms: This involves externalizing the hidden metabolic cycles of the biological system—such as filtration stages, water quality transitions, and nutrient availability—into actionable digital feedback. This research investigates how the digital interface layer can serve as a cognitive surrogate for the invisible biological process. By employing dynamic data visualization, intuitive color coding, and ambient notifications, the design enables non-expert users to "read" the system's health status in real-time. The objective is to bridge the temporal gap between the slow biological rhythm and the fast-paced domestic routine, ensuring that system states are perceptually accessible without requiring deep biological knowledge.

The emphasis of this phase remains on the Relational Properties of the system—how components connect and how responsibilities are communicated. As they pass through the Translation Funnel, they evolve from controlled laboratory data into modular system architectures and interactional propositions. This provides the conceptual and visual evidence necessary to achieve Legibility, Configurability, and Maintenance Intelligibility in the final domestic bio-integrated system. This process ensures that the final system achieves the necessary levels of Legibility, Configurability, and Maintenance Intelligibility, effectively bridging the gap between advanced bio-technology and domestic practice.

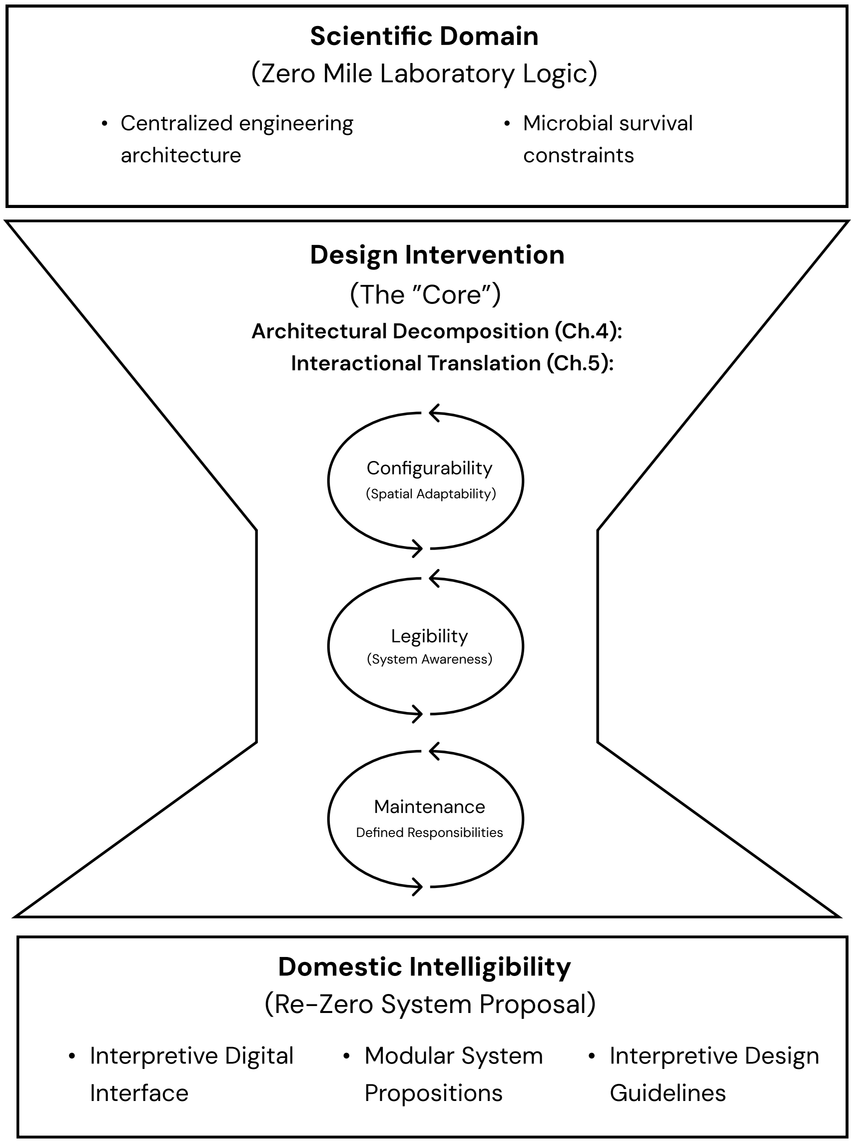


Figure 17. The RtD Translation Funnel: Deconstructing Bio-filtration Systems into Modular and Interactional Propositions.(Author's own illustration)

3.3 Prototyping as Reflective Externalization

In this research, prototyping functions not as a pursuit of final engineering performance, but as a reflective instrument for evaluating the logical coherence of design propositions. Within the framework of the "Translation Funnel," prototyping is situated at the core of Design Intervention, manifesting through digital User Interfaces (UI) and modular system architectures. As "epistemic artefacts," these prototypes aim to externalize hidden system logics, making abstract assumptions explicit and tangible. Through this process, the researcher can systematically reflect on whether these mediums effectively bridge the interpretive gap between laboratory technology and the domestic context.

The evaluation process involves a deep reflective analysis against the requirements established in Chapter 2. To ensure a rigorous assessment, the research identifies three key evaluative dimensions that correspond to the iterative loops of the translation funnel:

- Legibility: UI as a Communicative Translator:
  This criterion evaluates how the interaction interface translates hidden metabolic rhythms—such as nutrient flow and biological status—into an intuitive visual language. In this dimension, the UI acts as a "translator" rather than a mere display. To assess whether the interface enables users to read the system's life rhythms through color, dynamics, or layout logic without requiring specialized expertise. It examines the success of unobtrusive communication in reducing the user's cognitive effort to monitor the biological system.

- Maintenance Intelligibility: Defining Interaction Boundaries:
  This criterion focuses on the demarcation of responsibility boundaries within the system architecture. Even in the absence of a final physical product, the proposed model architecture must guide users to intuitively identify "human-machine touchpoints." To evaluate whether the system's modular form clarifies which areas allow human intervention and which zones are autonomously managed. This physical and digital demarcation aims to lower the cognitive load of maintenance by embedding operational logic into the system's structure.

- Configurability: Spatial and Functional Negotiation:
  This assesses the system's flexibility within dynamic and fragmented domestic settings. It examines the relationship between the interface logic and the modular footprint. To evaluate whether the system can adapt to different usage scenarios and household typologies without disrupting core biological functions. It investigates the spatial negotiation between the infrastructure’s requirements and the user’s everyday living patterns.

This reflective mode of evaluation allows "intermediate knowledge" to emerge through comparison and iteration. The value of these prototypes lies not in their industrial completion, but in their role as "material arguments" that reveal interaction frictions invisible through theoretical reasoning alone. This approach prioritizes domestic integration through interface interaction and foundational architecture, establishing the basis for the design explorations presented in Chapters 4 and 5.

Chapter 4. Modular Structure

4.1 Functional Unit Decomposition

4.1.1 Implications of Monolithic Integration

The current Zero Mile prototype, while functionally complete, presents itself as a single integrated assembly. Hydraulic infrastructure, biological treatment, cultivation elements, and sensing components are consolidated within a vertically organised structure that does not support spatial reconfiguration, incremental scaling, or partial servicing without disassembling the system as a whole.

From a research perspective, this integration was necessary to ensure process stability and validate the biological treatment pathway under controlled conditions. The concentration of subsystems within a unified structure reduces environmental variability and simplifies experimental monitoring. However, when the system is considered as a candidate for domestic adoption rather than laboratory validation, this same integration introduces architectural constraints that shape how the system can be positioned, understood, and maintained in everyday settings.

Importantly, these constraints do not arise from technological complexity but from the way functional dependencies are materialized. The prototype embeds heterogeneous processes—biological growth, hydraulic execution, cultivation infrastructure, and sensing—within a shared spatial and structural envelope. While these processes operate with partial independence at the functional level, their architectural entanglement limits selective access, repositioning, and user interpretation of system behavior.

This condition can be understood as a misalignment between functional separability and architectural indivisibility. The system already exhibits differentiated operational rhythms: cultivation components require routine interaction, hydraulic elements demand periodic inspection, and the biological reactor operates as a largely autonomous core. Yet these distinctions remain implicit, requiring users to interact with the system as an undifferentiated whole rather than as a set of meaningful subsystems.

User research discussed in Section 2.3 reinforces this interpretation by indicating that concerns regarding spatial fit, configuration uncertainty, and maintenance responsibility stem from the absence of externally legible subsystem boundaries. Rather than requesting additional functionality, participants expressed difficulty anticipating how the system could be positioned, adapted, or partially serviced over time.

Within this context, modularization is approached not as an additive design feature but as an architectural strategy for externalizing existing functional differentiation. By translating implicit subsystem boundaries into physically and interactively accessible modules, the system can support selective configuration, clearer maintenance responsibilities, and progressive adaptation without altering the underlying biological process.

This perspective positions modularity as a mechanism for negotiating variability in domestic environments while preserving technical coherence. The following sections develop this argument through the identification of core functional units and the analysis of their relationships, establishing the structural foundation for the modular architecture proposed in Section 4.2.

4.1.2 Identification of Core Functional Units

Section 2.2 provided a detailed analysis of the prototype's operational flows. Building on this foundation, the present section reinterprets the system from a functional perspective, focusing not on its physical composition but on the distinct operational roles embedded within its technical structure. These functional units do not yet constitute modules; rather, they represent analytical constructs through which modular boundaries can later be articulated.

Through examination of hydraulic flow, control logic, and inter-component dependencies (Section 2.2.2), a set of seven functional units can be identified. This identification does not impose a new structure onto the prototype but makes explicit the functional differentiation already present within its operation. The analysis therefore considers each unit in relation to its operational role, its relevance to user understanding and maintenance expectations, and its interdependencies with adjacent units.

Detailed component inventories are provided in Appendix.

System Boundary Unit

The system boundary unit defines the interface between the Zero Mile system and external household infrastructure. It governs the qualification and routing of incoming and outgoing flows, ensuring that wastewater intake, tap water distribution, and overflow management are handled in a coordinated manner. Wastewater originating from the dishwasher is first evaluated for suitability through conductivity sensing before being either accepted into the treatment pathway or diverted to the sewer. In parallel, municipal tap water is distributed to both the dishwasher and, under fallback conditions, the cultivation subsystem, while overflow water from the accumulation tank is safely discharged when storage capacity is exceeded.

Although this unit operates autonomously, its reliable functioning plays a critical role in establishing user trust. Users are not expected to directly interact with boundary processes, yet they must be confident that unsuitable wastewater is rejected, that tap water remains available when required, and that overflow conditions are safely managed without intervention. In this sense, the boundary unit contributes less through direct interaction and more through the invisible stabilization of system operation.

Functionally, this unit encompasses all points at which the Zero Mile system connects to external infrastructure, including the dishwasher inlet and outlet, municipal tap water supply, and sewer discharge pathways. These connections delineate the operational limits of the system while simultaneously enabling its integration within existing domestic plumbing environments.

Pre-Treatment Unit

The pre-treatment unit performs mechanical filtration to remove suspended solids before wastewater enters the biological treatment stage. Through coarse and fine filtration layers, it protects downstream components from particulate accumulation and stabilizes the hydraulic conditions required for biological processing. In this sense, the unit functions as a conditioning layer that safeguards the continuity and reliability of subsequent treatment stages.

Unlike the system boundary unit, the pre-treatment unit introduces a recurring point of user interaction through periodic maintenance. Mechanical filters must be cleaned or replaced at intervals determined by dishwasher usage patterns and water quality conditions. For users, this creates a need not only for awareness of maintenance timing but also for clear physical access to the filtration elements and understanding of the consequences of neglect. The unit therefore represents one of the earliest moments at which technical operation becomes visible as routine care.

Functionally, the pre-treatment unit defines the transition between external input qualification and internal system stabilization. It remains hydraulically local to the accumulation stage while serving as the primary barrier preventing particulate loads from propagating further into the system. This boundary situates the unit as both a protective mechanism and a maintenance touchpoint within the broader architecture.

Hydraulic Circulation Unit

The hydraulic circulation unit constitutes the execution core of the system's water management process. It governs the movement of water between storage, treatment, and distribution points through pump-driven circulation and valve-actuated routing, while also integrating in-path UV disinfection. Through this coordination of flow control and treatment enforcement, the unit maintains the operational continuity that allows otherwise distributed subsystems to function as a coherent whole.

From a user perspective, the hydraulic circulation unit is intentionally positioned beyond direct interaction. Pumps, valve arrays, and UV components are service-only elements whose accessibility is restricted to trained personnel. Nevertheless, their operational state must remain interpretable: failures such as pump malfunction or pressure drops must be communicated as conditions requiring professional intervention rather than ambiguous system faults. The unit therefore contributes to user experience primarily through status legibility rather than direct manipulability.

Functionally, the circulation unit establishes centralized routing authority across the system. Nearly all inter-unit hydraulic flows pass through this node, making it the structural mediator between otherwise discrete functional units. This concentration of routing logic reinforces its role as both an infrastructural backbone and a key boundary separating user-serviceable subsystems from service-only technical infrastructure.

Biological Treatment Unit (Biofilter)
The biological treatment unit houses the microbial consortium responsible for degrading organic contaminants. Wastewater is retained within the reactor for a controlled period, during which microbial activity drives the transformation processes that improve water quality. In the system's functional logic, this unit is the point at which treatment efficacy is produced, rather than merely routed or buffered.

For the user, this unit is distinctive because it is both visible and meaningfully interpretable. The transparency of the reactor vessel—required for light access—makes microbial activity observable and can support trust by allowing users to see that "something is alive and working." At the same time, the unit introduces a recurring maintenance commitment: maintenance is required approximately every six months. Although the task is user-serviceable, it cannot remain implicit; it must be clearly communicated in terms of timing and the actions expected.

Functionally, the biofilter defines the system's biological transformation boundary. It is hydraulically decoupled from upstream filtration and downstream storage, separating the act of biological treatment from both particulate removal and volumetric buffering. This decoupling allows the unit to be treated as a distinct functional core for monitoring, maintenance planning, and user communication.

Storage Unit
The storage unit provides volumetric buffering across two stages. The accumulation tank stores pre-treated wastewater awaiting biological treatment, while the reuse tank stores treated water that is ready for irrigation. Together, these tanks enable the system to operate across mismatched rhythms, separating when water is generated, when it is treated, and when it is consumed.

The storage unit provides volumetric buffering across two stages. The accumulation tank stores pre-treated wastewater awaiting biological treatment, while the reuse tank stores treated water that is ready for irrigation. Together, these tanks enable the system to operate across mismatched rhythms, separating when water is generated, when it is treated, and when it is consumed.

Functionally, this unit introduces a temporal buffer between water generation, treatment, and consumption. By storing water at different stages, it allows these processes to occur at different rhythms rather than requiring immediate coordination. In practice, the storage tanks absorb fluctuations in inflow and demand, helping stabilize system operation. Although users do not directly interact with the tanks, they serve as a primary source of system-state information, particularly regarding water availability and system capacity.

Cultivation Unit

The cultivation unit receives treated water and distributes it to plants through irrigation lines, while collecting excess return flow and routing it back to the accumulation tank for recirculation. In this sense, it functions as the endpoint of the hydraulic loop, where treated resources are translated into biological growth.

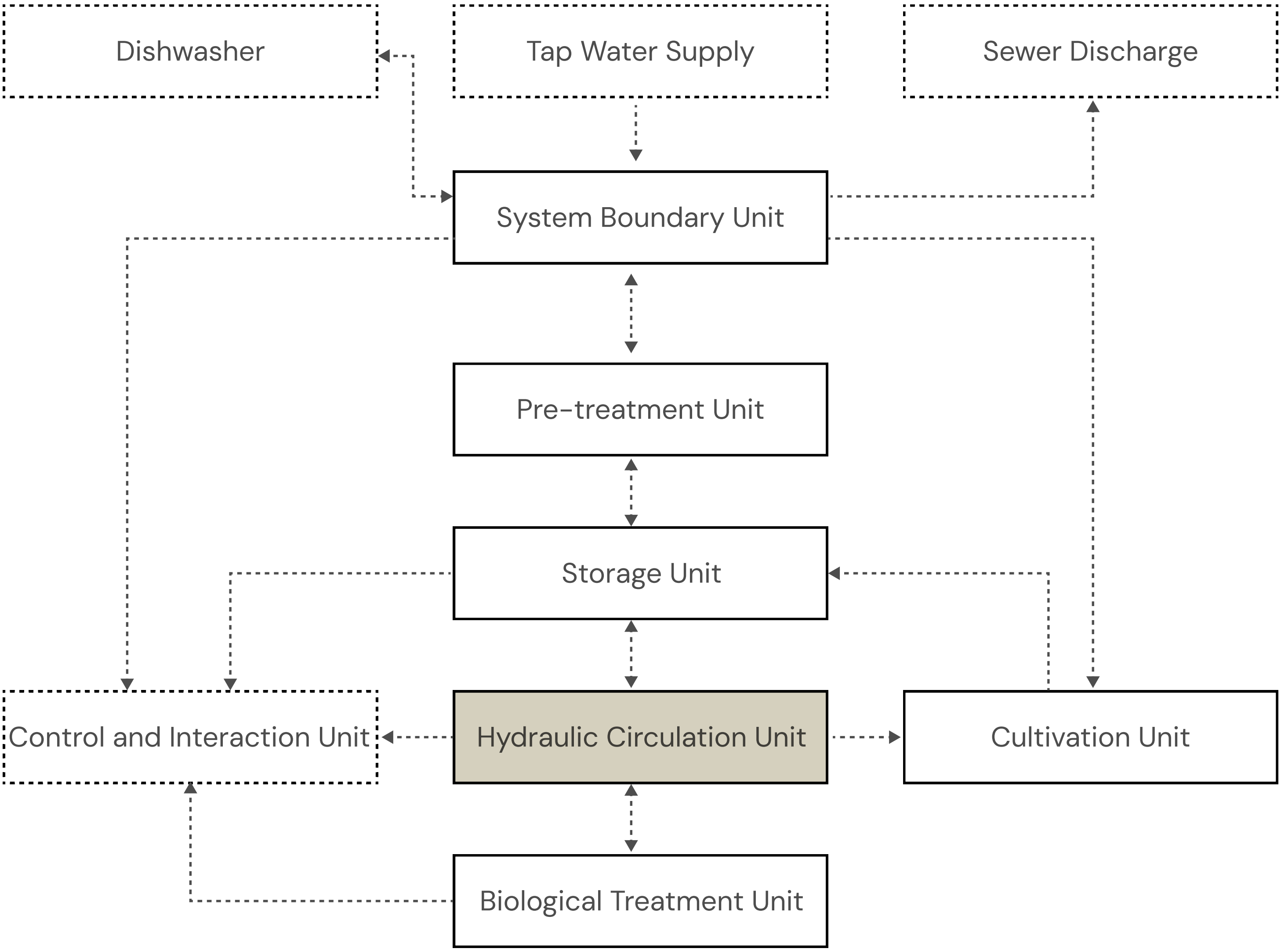
From a user perspective, this unit represents the most visible and frequently interactive part of the system. It is the location where users harvest plants, replant, observe plant health, and may occasionally adjust irrigation behavior. Beyond interaction frequency, its spatial independence is significant: the cultivation unit can be positioned on countertops, windowsills, or mounted surfaces, allowing placement separate from the treatment core.

Functionally, the unit defines the boundary between distribution and return collection while maintaining autonomy in spatial placement. It operates as both a productive interface and a spatially flexible extension of the treatment system.

Control and Interaction Unit — Note on Scope

In the current prototype, system monitoring and actuation are implemented through an Arduino-based controller integrating relay boards and sensor wiring. This infrastructure enables sequencing of pumps and valves while maintaining awareness of system conditions.

Within the modular architecture developed in Section 4.2, however, this functionality is not preserved as a standalone physical module. The unit is therefore documented here for analytical completeness. While it plays a critical role in the prototype’s operation, its architectural relevance lies primarily in informing the modular decomposition rather than defining a persistent module within the final system configuration.



Dashed connections indicate informational or control dependencies rather than physical modular coupling

Figure 18. Functional Decomposition and Inter-unit Dependencies(Source: Author's own illustration)

4.1.3 Functional Relationships and System Structure

With the functional units identified, the analysis turns to the relationships that exist between them. The aim is not to describe operational flow alone, but to understand how different forms of dependency—hydraulic, temporal, and informational—shape the system's structural flexibility. These relationships determine where physical separation is feasible and where integration must be preserved, thereby establishing the architectural conditions for modularization.

The stage analysis presented in Section 2.2.2 reveals several recurring relational patterns.

A first pattern is the presence of a tightly coupled execution core, composed primarily of the Hydraulic Circulation Unit, portions of the Pre-treatment Unit, and elements of the System Boundary Unit. The pump, valves, UV disinfection, and fine filtration operate as an interdependent network requiring continuous coordination. Their behavior cannot be meaningfully separated without redesign of the control logic and hydraulic routing. This indicates that, within a modular architecture, these elements must remain internally integrated even if their external interfaces are standardized.

In contrast, the Storage Unit represents an operationally passive structure. The accumulation and reuse tanks require only inlet and outlet connectivity together with level monitoring. Because they do not actively regulate upstream or downstream behavior, their role is primarily temporal buffering. This limited dependency suggests that storage can be modularized with relatively weak coupling, functioning as an interface-connected rather than execution-critical component.

A third pattern is the functional independence of the Biological Treatment Unit. While hydraulically connected to the execution core, the biofilter does not impose structural or control dependencies on surrounding elements. Its operational requirements—controlled residence time and light exposure—are largely internal to the unit. This independence enables spatial flexibility and supports its treatment as a discrete module whose placement may be guided by visibility, accessibility, or environmental conditions rather than by strict integration constraints.

The Cultivation Unit exhibits a different form of independence characterized by endpoint decoupling. Irrigation distribution and return collection become passive once water is delivered, and the unit may be supplied either by treated reuse water or directly by tap water. This dual sourcing and passive behavior indicate that cultivation is structurally separable from treatment, allowing spatial placement to be determined by plant growth conditions and domestic integration rather than hydraulic centrality.

Finally, the System Boundary Unit introduces a distinct form of architectural entanglement. Although intake qualification and tap water distribution are physically separable from the treatment core, their sensing and actuation logic are embedded within the shared control infrastructure of the prototype. This creates a hybrid condition in which hardware separation is feasible but control separation requires deliberate re-partitioning. The boundary therefore functions less as a module candidate and more as a structural interface zone.

Taken together, these relational patterns—tight execution coupling, passive buffering, functional independence, endpoint decoupling, and boundary entanglement—are not design decisions but intrinsic characteristics of the existing system. They establish the conditions under which modular separation can occur and provide the architectural rationale for the module boundaries proposed in the following section.

4.1.4 Implications for Modular Architecture Design

In the current prototype, the functional boundaries identified above are not reflected in the physical configuration of the system. Despite the separability of storage, biological treatment, and cultivation functions—and the internally differentiated roles within the System Boundary Unit—all elements are consolidated into a single vertically stacked assembly. Storage tanks are positioned alongside the circulation core, the biofilter is directly integrated into the hydraulic execution pathway, and the cultivation unit is permanently mounted on the base structure. Consequently, functional independence does not translate into spatial or service independence, as individual subsystems cannot be relocated, reconfigured, or maintained without affecting the integrity of the whole.

This physical consolidation stands in tension with the user needs identified in Chapter 2, particularly spatial adaptability, clarity of maintenance responsibility, and the ability to interpret the system as a set of meaningful parts rather than as a monolithic artefact. The issue is therefore not the absence of functional differentiation, but the lack of correspondence between functional organization and physical articulation.

The functional units defined in Section 4.1.2, together with the relational patterns examined in Section 4.1.3—tight execution coupling, passive buffering, functional independence, endpoint decoupling, and boundary entanglement—provide an analytical basis for reconsidering this correspondence. These patterns indicate where integration must be preserved and where separation is structurally feasible. In this sense, modularization emerges not as an imposed design strategy but as a translation of existing functional logic into an explicit architectural structure.

Accordingly, aligning physical module boundaries with functional unit boundaries becomes a means of preserving operational coherence while enabling spatial flexibility, clearer maintenance responsibilities, and improved system legibility in domestic contexts. Section 4.2 develops this translation into a concrete modular architecture, specifying the resulting modules and the interaction and maintenance touchpoints associated with each.

4.2 Modular Architecture Design

Section 4.1 examined the current Zero Mile prototype through functional decomposition, identifying seven functional units and analysing their interdependencies. This analysis revealed that while several system functions are operationally independent, they remain physically fused within a vertically integrated assembly. As discussed in Section 4.1.4, this tight physical coupling limits spatial adaptability, obscures maintenance boundaries, and prevents users from understanding the system as a set of meaningful parts.

To address these issues, the design translates functional units into physically separable modules while preserving the system's operational logic. This translation is guided by three principles derived from user concerns (Section 2.3) and the coupling patterns identified in Section 4.1.3:

- Spatial adaptability — modules should be positionable independently, allowing the system to accommodate diverse domestic layouts.
- Maintenance clarity — module boundaries should reflect clear distinctions between user-serviceable and service-only components.
- Core integrity — tightly coupled hydraulic and control functions must remain integrated to ensure reliable operation

Applying these principles results in a modular architecture composed of eight modules. The following subsection explains how the functional units are translated into this module set and clarifies the architectural rationale for merging, separating, or preserving specific subsystems. Subsequent subsections then define each module in terms of functional role, interaction characteristics, maintenance responsibility, and informational contribution to the digital interface.

4.2.1 Module Set and Architectural Translation

The transition from functional units to modules is not a direct one-to-one mapping but a systematic reorganization guided by specific Modularization Criteria. While functional units define the operational roles within the system's internal logic, modules represent physically separable product elements designed to support spatial configuration, maintenance legibility, and interaction clarity in a domestic setting.

As illustrated in Figure 18, this translation is informed by three strategic architectural decisions designed to shift the system from the Scientific Domain toward Domestic Intelligibility:

- Differentiation of Infrastructural Functions (Spatial Adaptability): To satisfy the criterion of Spatial adaptability, the "System Boundary Unit" is decomposed into distinct physical entities. Specifically, the Tap Water Distribution Module and the Intake Qualification Module are separated to reflect their different infrastructural roles. This allows the system to adapt to various domestic plumbing layouts, enabling flexible positioning based on the physical location of water sources.

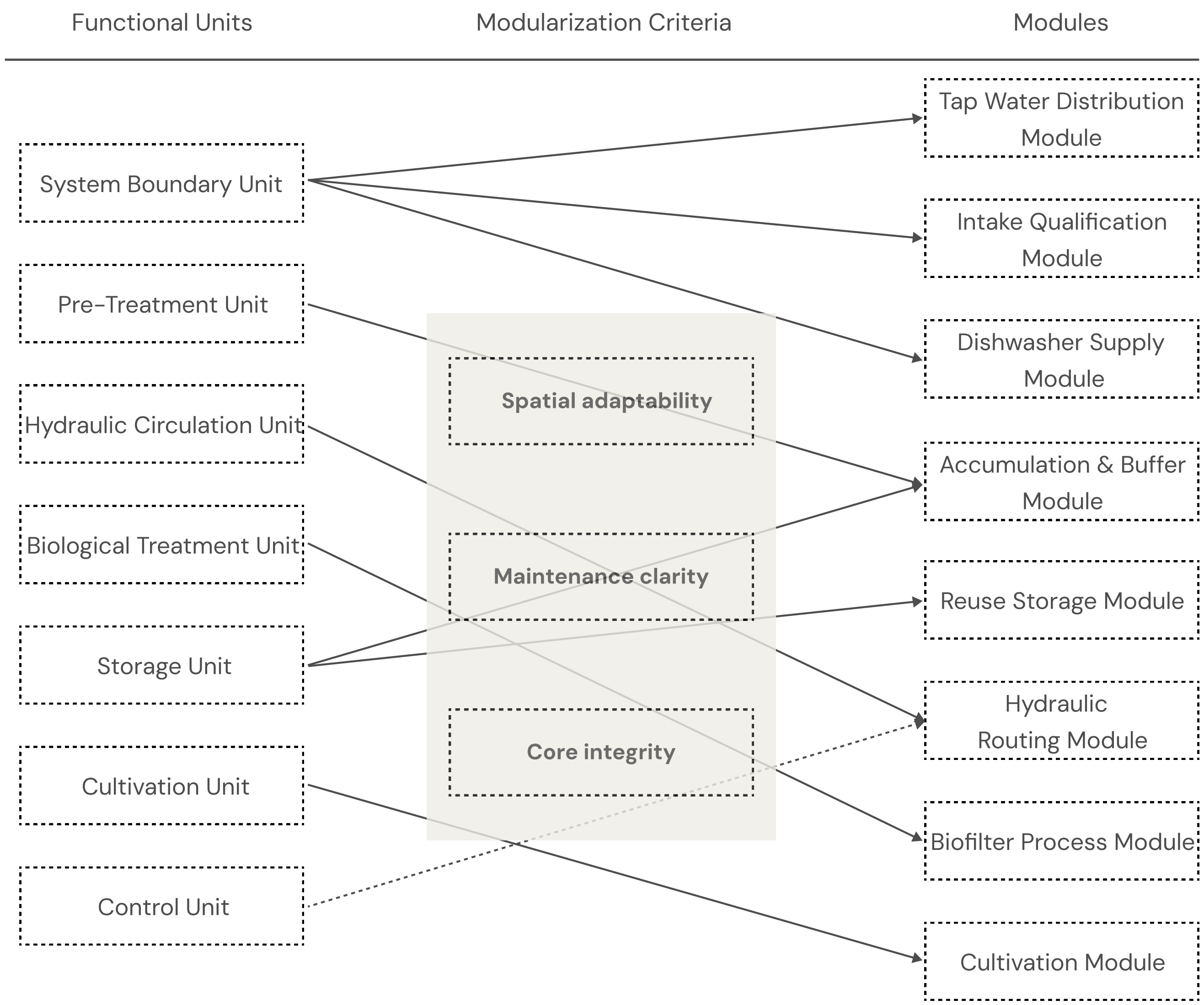


Figure 19. Architectural Translation from Functional Units to Modules(Source: Author's own illustration)

- Independent Modularization of Passive Functions (Maintenance Clarity): Guided by the need for Maintenance clarity, operationally passive functions such as the "Storage Unit" are maintained as independent modules. This results in the Accumulation & Buffer Module and the Reuse Storage Module. By keeping these low-coupling units separate, the system enhances user awareness of resource levels, directly supporting the goals of Legibility and Maintenance Intelligibility within the translation funnel.

- Consolidation of Tightly Coupled Operations (Core Integrity): To preserve Core integrity, responsibilities from the "Control Unit," "Hydraulic Circulation Unit," and "Pre-Treatment Unit" are consolidated into integrated modules. A key example is the Hydraulic Execution & Routing Module, which manages complex fluid dynamics and actuation behind a single interface. This consolidation ensures operational reliability while shielding the user from unnecessary technical complexity, thereby simplifying the domesticated product architecture.

Consequently, the resulting module set represents a strategic reorganization of the system's operational structure. By transforming abstract functional units into physically separable elements—ranging from the Dishwasher Supply Merge & Safety Module to the final Cultivation Module—the system achieves a domesticated form that balances technical necessity with user-facing clarity. The following subsection shifts from this architectural translation to a detailed definition of individual modules and their specific implications for the user experience.

4.2.2 Module Definition

Intake Qualification Module

The Intake Qualification Module regulates the entry of dishwasher wastewater into the reuse system and therefore operates as a critical boundary mediator between domestic infrastructure and the internal treatment process. Incoming water is assessed for suitability and either directed toward the Accumulation & Buffer Module or diverted to the sewer when quality thresholds are not met. The same routing pathway also supports the discharge of overflow water originating from upstream storage, ensuring safe operation under variable load conditions.

From the user's perspective, the module remains largely invisible. It does not invite direct interaction but instead contributes to system intelligibility through indirect informational exposure. When repeated rejection events occur, system notifications may inform users of potential detergent misuse or abnormal water conditions, supporting awareness without requiring intervention.

Maintenance responsibilities are similarly abstracted from everyday use. The sensing and routing mechanisms embedded within the module are not intended for user access, positioning the unit as service-only infrastructure whose reliability underpins the perceived stability of the overall system.

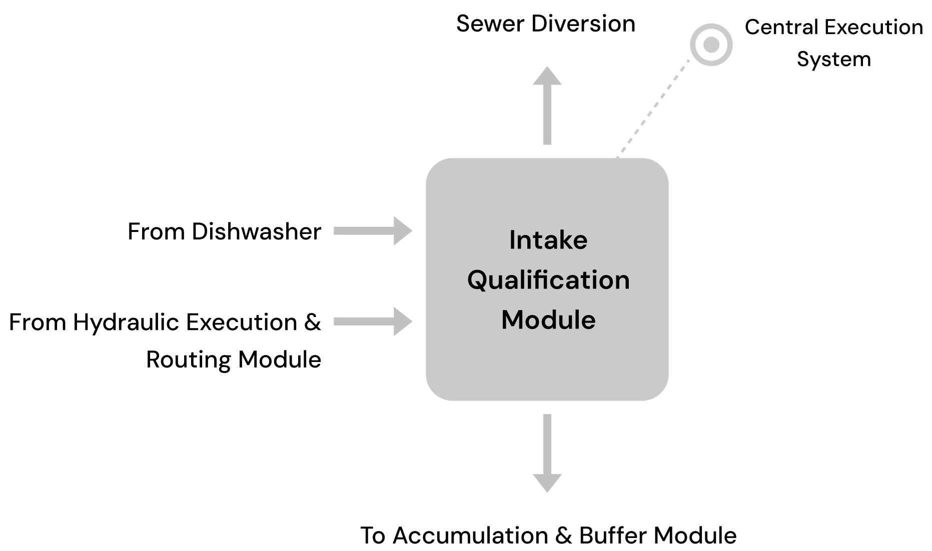


Figure 20. Conceptual representation of the Intake Qualification Module(Source: Author's own illustration)

Tap Water Distribution Module

The Tap Water Distribution Module mediates the entry of municipal tap water into the system and allocates it across operational destinations. Under normal conditions, tap water is supplied directly to the dishwasher to ensure hygienic and appliance-compatible operation. In fallback scenarios—such as insufficient treated water availability—the module may also support auxiliary irrigation by routing tap water to the Cultivation Module.

Although the module operates autonomously at the hydraulic level, its status remains informationally relevant to users. The interface may communicate when fallback irrigation is activated or when tap water supplementation occurs, allowing users to understand deviations from reuse-based operation without requiring direct manipulation of valves or routing mechanisms. Consequently, the module contributes primarily to system transparency rather than direct interaction.

From a maintenance perspective, the module contains flow control components and sensing infrastructure that remain service-only. Users are not expected to access or manipulate these elements physically; instead, system feedback is communicated through higher-level monitoring interfaces when anomalies or prolonged fallback conditions arise.

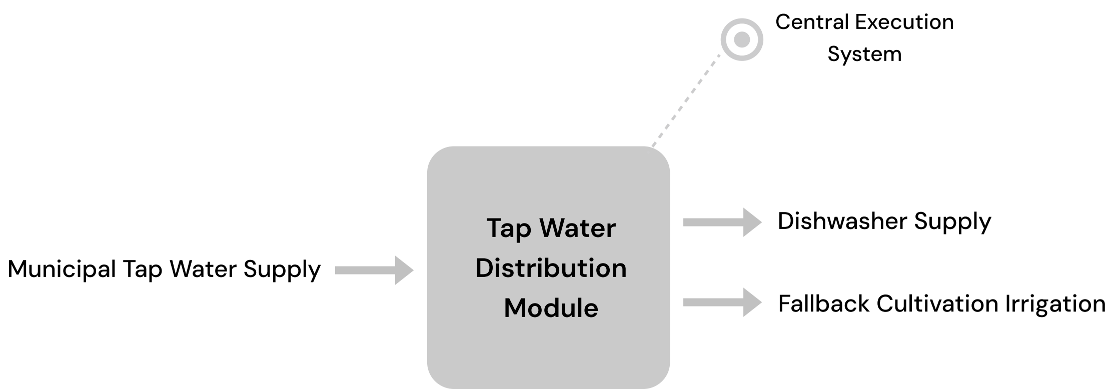


Figure 21. Conceptual representation of the Tap Water Distribution Module(Source: Author's own illustration)

Dishwasher Merge & Supply Module

The Dishwasher Merge & Supply Module governs the final water provisioning stage before delivery to the dishwasher, ensuring stable appliance operation while enabling controlled integration of alternative water sources. Municipal tap water constitutes the primary supply pathway, reflecting hygiene expectations, appliance compatibility, and user trust requirements. Treated reuse water is therefore positioned as a conditional supplementary source, activated only under predefined operating modes and excluded from intensive or hygiene-critical washing cycles.

Beyond routing, the module performs a safety validation function by monitoring supply pressure and verifying that delivered water satisfies operational constraints. This safety gating prevents unstable or unsuitable supply conditions from reaching the appliance, maintaining reliability without requiring user intervention.

Although physically inaccessible, the module contributes to system intelligibility by enabling the interface to communicate which supply pathway is currently active and when fallback or supplementary conditions occur. This informational transparency supports user awareness while preserving clear maintenance boundaries, as sensing and actuation components remain service-only.

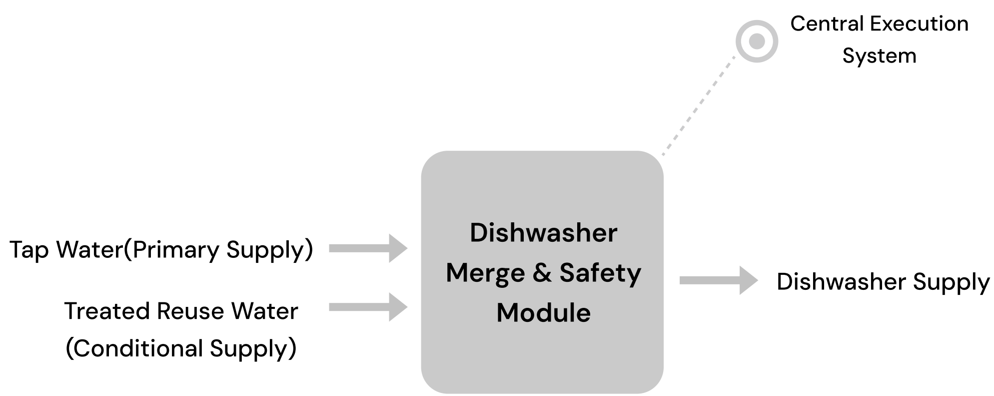


Figure 22. Conceptual representation of the Dishwasher Supply Module(Source: Author's own illustration)

Accumulation & Buffer Module

The Accumulation & Buffer Module provides intermediate storage for pre-filtered wastewater awaiting biological treatment, stabilizing inflow variability and ensuring continuity of downstream processing. Water enters the module from multiple upstream sources, including the Intake Qualification Module, the Cultivation Module return flow, and pumped overflow from the Reuse Storage Module. A 50 μm mechanical filter positioned at the inlet protects subsequent treatment stages, while integrated level and temperature sensing enable monitoring of storage conditions and process stability. As a modular product component, the storage capacity is treated as a configurable design parameter, allowing different tank sizes to accommodate variations in household demand and reuse patterns.

Although the module collects operational data, its status is not intended to be a primary user-facing metric. In particular, water availability communicated to users is anchored to the Reuse Storage Module, where treated and disinfected water can be safely interpreted as usable output. By contrast, the Accumulation & Buffer Module functions as an upstream buffer within the treatment loop; its sensed variables mainly serve control logic and stability management rather than everyday interpretation.

Maintenance responsibilities are therefore defined through a narrow, controlled physical boundary. The 50 μm filter is designed as a user-serviceable component and may be replaced or cleaned when prompted, whereas the tank body, sensors, and hydraulic connections remain service-only. This distribution preserves maintenance clarity while keeping the buffering function robust and largely invisible in routine use.

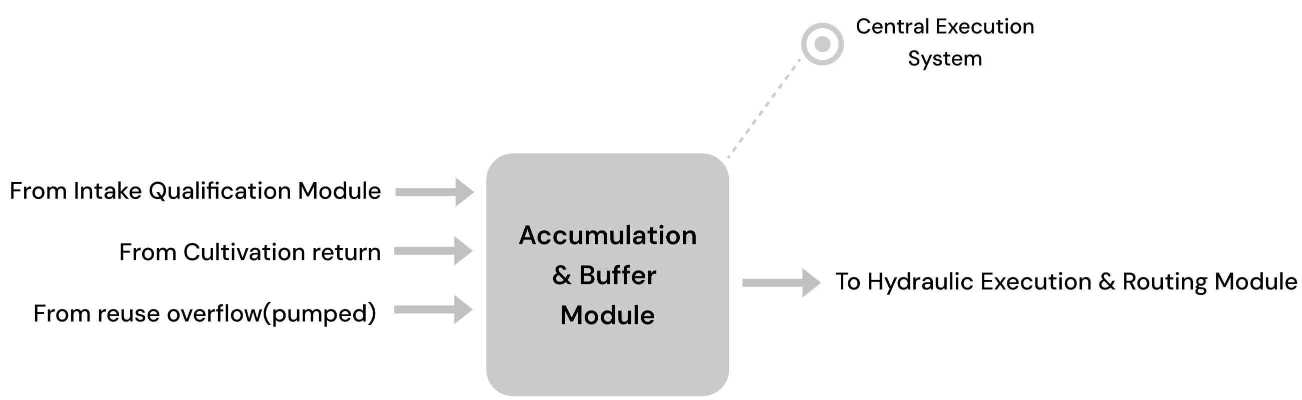


Figure 23. Conceptual representation of the Accumulation & Buffer Module(Source: Author's own illustration)

Reuse Storage Module
The Reuse Storage Module serves as the terminal reservoir for biologically treated and disinfected water awaiting reuse. Positioned downstream of the treatment chain, it represents the system's primary availability buffer for irrigation and low-risk reuse activities. Water is supplied from the Hydraulic Execution & Routing Module, which retains full authority over pumping and diversion decisions, while this module provides passive capacity and temporal decoupling between treatment output and reuse demand.

Although operationally passive, the module plays a critical role in user intelligibility. The perceived availability of reuse water is primarily associated with this storage state rather than upstream buffering, supporting user awareness of system performance without exposing routing complexity. Any information communicated through the interface therefore reflects aggregated treated-water availability rather than raw storage dynamics.

Maintenance access remains intentionally restricted. Sensing components are not user-serviceable, reinforcing the module's role as sealed storage infrastructure whose reliability supports safe reuse availability without exposing execution or treatment mechanisms.

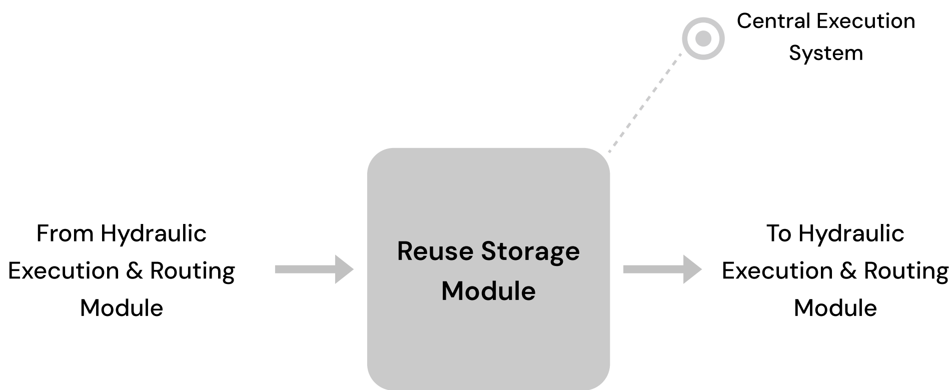


Figure 24. Conceptual representation of the Reuse Storage Module(Source: Author's own illustration)

Hydraulic Execution & Routing Module

The Hydraulic Execution & Routing Module constitutes the operational core of the system, integrating pumping, valve-based routing, fine filtration, and UV disinfection within a execution authority. Rather than serving as a storage or endpoint element, this module governs all actively driven water movements and mediates transitions between passive storage, biological treatment, and downstream utilization.

Water extracted from the Accumulation & Buffer Module is routed toward biological treatment, after which treated water is transferred to the Reuse Storage Module for availability. The same execution layer also enables irrigation delivery, safety diversion pathways, and inter-tank balancing operations when required. By centralizing these transitions, the module preserves operational coherence while preventing the propagation of unsafe or unstable hydraulic states across the system.

From a user perspective, the module remains physically inaccessible and does not support direct manipulation. Its presence is instead communicated through system-level feedback mechanisms, including ambient status indicators and application-based monitoring, which convey overall operational state without exposing execution complexity. This abstraction reinforces the separation between system decision-making and user interaction.

Maintenance access is restricted to professional servicing. Pumping components, routing valves, UV treatment elements, and fine filtration remain enclosed within the execution core, ensuring reliability while maintaining clear boundaries between user-serviceable storage modules and service-only operational infrastructure.

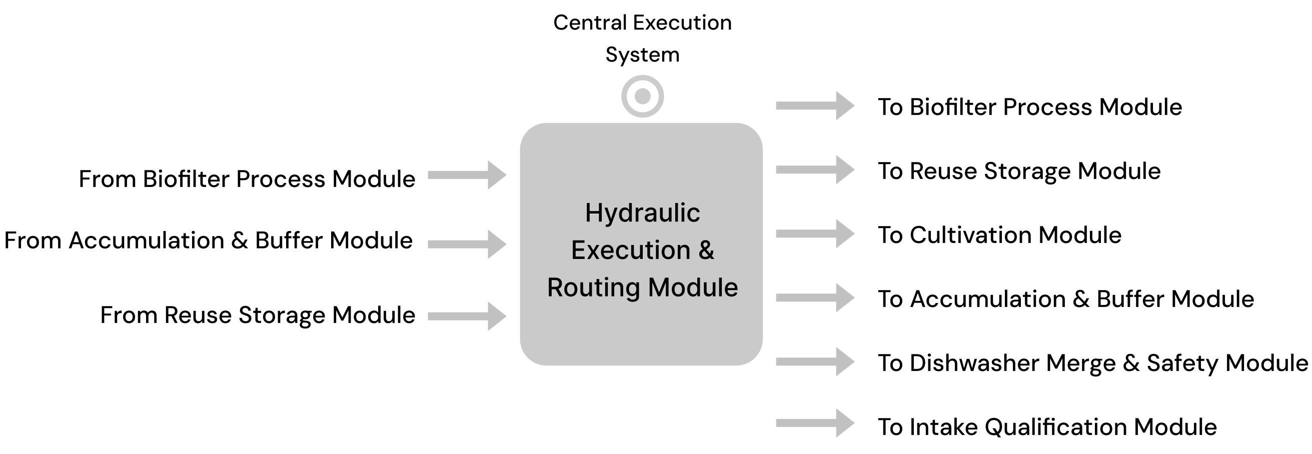


Figure 25. Conceptual representation of the Hydraulic Execution & Routing Module(Source: Author's own illustration)

Biofilter Process Module

The Biofilter Process Module constitutes the biological transformation stage of the system, enabling microbial degradation of organic contaminants prior to reuse. Unlike routing or storage modules, its primary role is process-oriented, introducing temporal buffering through extended retention while remaining operationally dependent on the execution core for hydraulic movement.

To support system interpretability without compromising modular separation, the module may incorporate minimal sensing capabilities that confirm reactor occupancy and the presence of inflow. These observations do not determine treatment completion but instead provide temporal anchoring for the system to estimate retention progression. Release timing and subsequent hydraulic actuation therefore remain governed by the Hydraulic Execution & Routing Module, preserving centralized execution authority while allowing the biological process to remain operationally autonomous.

The module exhibits a unique form of perceptual accessibility. Its transparency supports visual observation of microbial activity, contributing to user trust and process intelligibility without requiring active control. Interaction is therefore observational rather than manipulative, reinforcing the distinction between biological processing and execution authority.

Maintenance occurs at extended intervals and is limited to periodic cleaning and inspection. While reminders may be communicated through the system interface, the module primarily supports physical maintenance access rather than digital interaction. This positioning reflects its hybrid character as both a functional process unit and a perceptually meaningful element within the domestic environment.

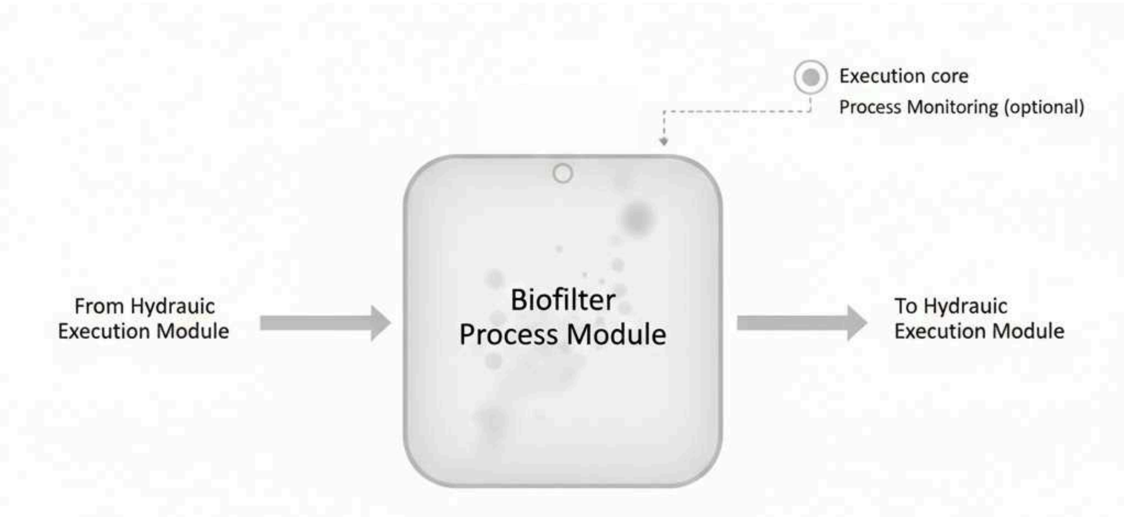


Figure 26. Conceptual representation of the Biofilter Process Module(Source: Author's own illustration)

Cultivation Module

The Cultivation Module represents the primary endpoint of reuse within the system, where treated water is transformed into visible domestic value through plant growth. Unlike upstream modules focused on qualification, storage, or routing, this unit introduces spatial independence and user-driven interpretation, allowing placement across diverse domestic locations without constraining the operation of the treatment core.

Interaction within this module is predominantly experiential and practice-based. Users engage through planting, observation, harvesting, and everyday care activities, relying on personal judgement rather than automated sensing to assess plant health and environmental suitability. Digital support remains optional and interpretive, offering reminders or reflective records without replacing embodied interaction.

Maintenance responsibilities are distributed accordingly. Plant care and cultivation practices remain fully user-managed, while embedded irrigation infrastructure operates as background service components. This separation reinforces the module's role as a domestication interface, where technical reuse processes become meaningful through everyday engagement rather than system visibility.

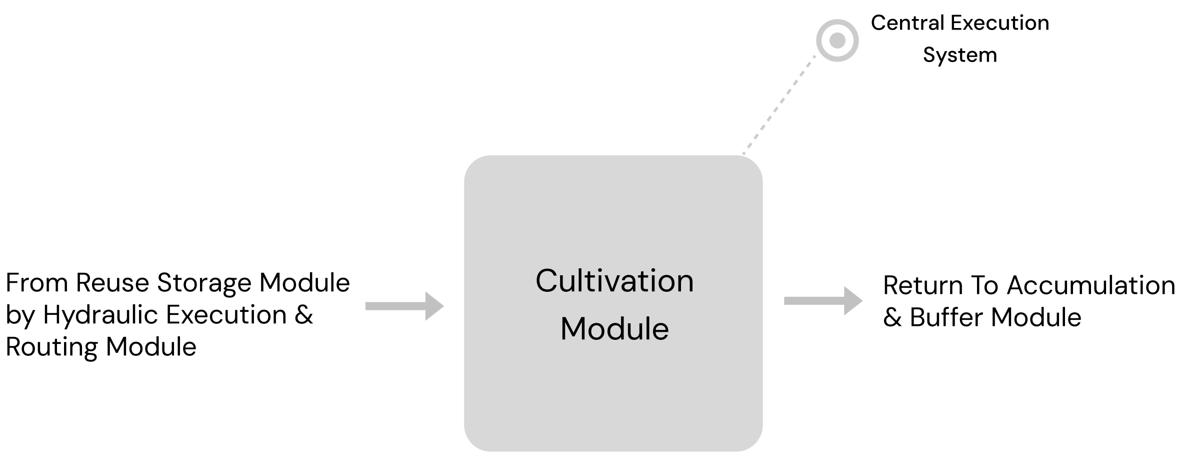


Figure 27. Conceptual representation of the Cultivation Module(Source: Author's own illustration)

4.2.3 System Observability and Information Sources

The modular dishwasher wastewater reuse system operates primarily as a background domestic infrastructure in which hydraulic, biological, and storage processes remain physically unobtrusive. While modular decomposition clarifies functional responsibilities across qualification, buffering, execution, treatment, storage, and cultivation, it does not inherently determine which aspects of infrastructural activity become perceptible or available for interpretation.

Observability therefore requires an additional informational layer that selectively connects infrastructural processes to detectable conditions. Rather than assuming comprehensive monitoring, the system adopts a distributed observability perspective in which individual modules contribute partial informational traces that together form a heterogeneous awareness substrate.

At the informational level, observability begins with detectability. Certain infrastructural conditions—such as water presence, storage level, temperature variation, routing activation, and component operation—become perceptible through embedded sensing mechanisms that render otherwise hidden processes informationally accessible.

Module	Sensing mechanisms enabling detectability	Measured variables
Tap Water Distribution Module	Flow sensor; Valve state detection	Tap-water flow presence; Pathway activation
Dishwasher Supply Merge & Safety Module	Pressure sensor; Flow validation	Supply pressure stability; Active supply pathway
Intake Qualification Module	Conductivity sensor; Presence detection	Wastewater acceptance threshold; Diversion detection
Accumulation & Buffer Module	Level sensor; Temperature sensor	Stored volume; Thermal stability
Hydraulic Execution & Routing Module	Flow sensor; Pump state detection; Valve activation	Circulation activity; Routing transitions; Overflow occurrence
Biofilter Process Module	Presence detection; Retention-time monitoring	Treatment duration; process continuation
Reuse Storage Module	Level sensor	Available treated-water volume
Cultivation Module	Irrigation delivery detection; Configuration awareness	Water delivery occurrence; Planting context

Table 4. Sensing basis of infrastructural observability across modules(Source: Author’s own table)

The sensing mapping above establishes the evidential grounding of observability by outlining representative mechanisms through which infrastructural conditions become detectable across modules. The table is illustrative rather than exhaustive and clarifies detectability without specifying hardware implementation details or diagnostic thresholds.

While sensing mechanisms enable detectability, observability also depends on how these detectable conditions are distributed across the system and combined into a coherent informational structure. Figure 28 therefore illustrates how localized signals emerge across modules and collectively contribute to system-level awareness without forming a centralized monitoring architecture.

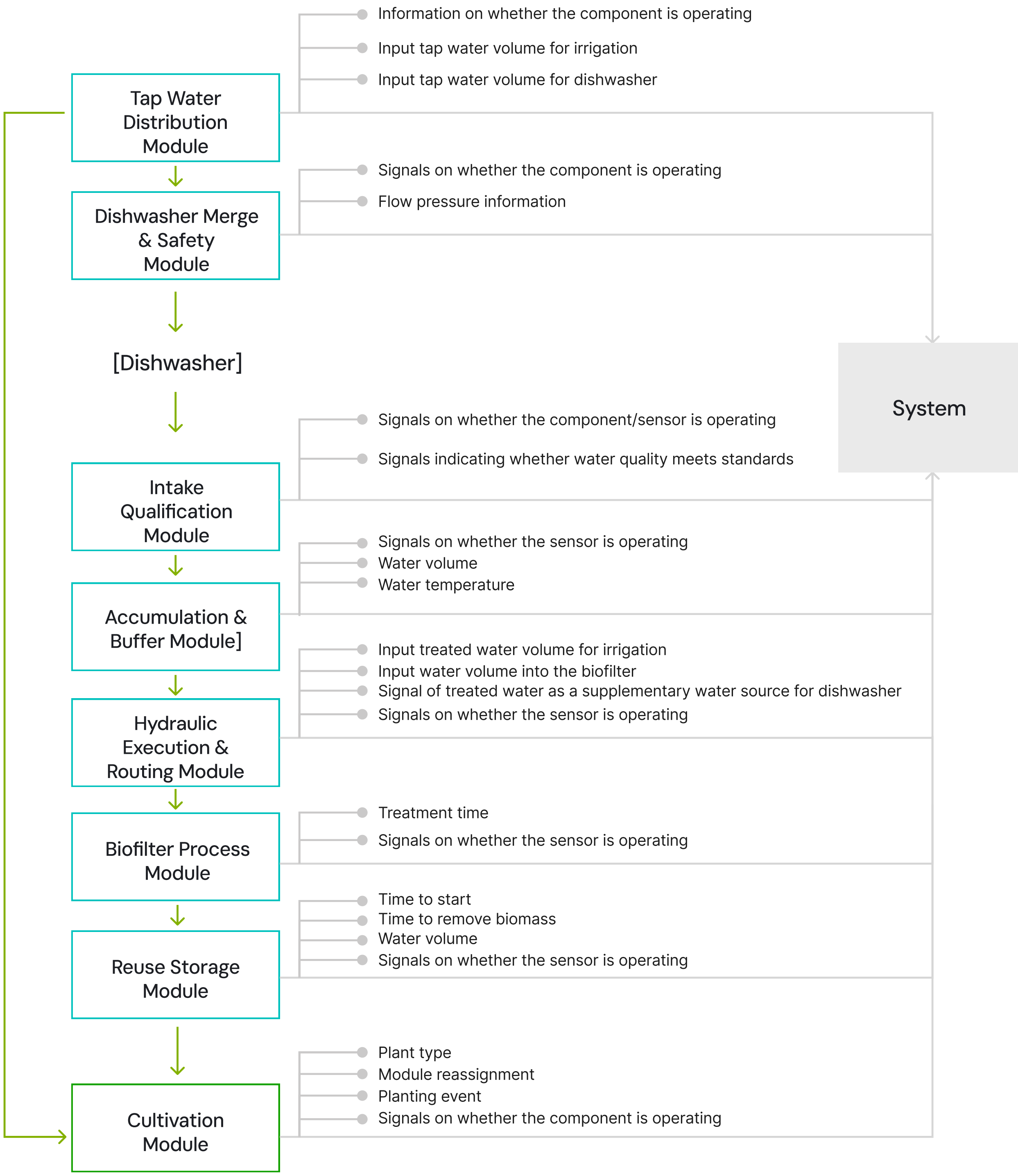


Figure 28. System Observability Diagram(Source: Author's own illustration)

The diagram emphasizes the partial and heterogeneous character of informational visibility, showing how modules provide localized signals that collectively support awareness of routing continuity, treatment progression, and resource availability.

Beyond sensing, observability further incorporates signals derived from configuration, execution logic, and temporal transitions. These include routing confirmations, acceptance or rejection events, buffering continuity, and treatment phase progression inferred from process timing. Such signals complement direct sensing by enabling awareness of infrastructural behavior without exposing raw technical parameters.

Module	Sensed observability (objective infrastructural signals)	Declarative / inferred observability (configuration or execution-derived signals)	Notes for awareness construction
Tap Water Distribution Module	Component operational status; flow validation	Tap water fallback activation; irrigation supplementation state	Supports appliance safety reassurance and supply intelligibility
Dishwasher Supply Merge & Safety Module	Supply pressure validation; pathway activation status	Active supply pathway (tap-first vs supplementary reuse)	Supports appliance safety reassurance and supply intelligibility
Intake Qualification Module	Sensor operational status; wastewater quality threshold validation	Acceptance/rejection events; sewer diversion occurrences	Enables safety gating awareness without exposing raw quality metrics
Accumulation & Buffer Module	Water volume; temperature; sensor operational signals	Storage readiness for pumping; buffering continuity	Contributes indirect process continuity awareness rather than actionable user data
Hydraulic Execution & Routing Module	Pump activity; valve activation; information on water flow to various locations	Routing state; overflow handling; process transition events	Serves as execution-state backbone supporting system-wide coherence inference
Biofilter Process Module	Sensor operational signals (process presence)	Treatment phase progression; retention time completion	Treatment continuity is primarily temporal rather than sensor-driven
Reuse Storage Module	Water volume; storage availability signals	Irrigation readiness; reuse sufficiency state	Represents the primary actionable resource awareness for users
Cultivation Module	Component operational signals (irrigation delivery presence)	Cultivation configuration context; module identity persistence	Provides contextual grounding linking infrastructural operation with visible domestic outcomes

Table 5. Observability and Information Sources Across Modules(Source: Author's own table)

Building on the sensing basis and signal distribution illustrated above, the table summarizes the observability scope of each module by distinguishing between directly sensed infrastructural conditions and declarative or inferred signals emerging from configuration and execution logic. Whereas the sensing mapping focuses on detectability, this observability mapping addresses how detectable conditions become informationally meaningful within the broader awareness framework.

Together, these distributed signals constitute the informational substrate through which infrastructural activity becomes observable. Importantly, this observability layer defines what can be detected and differentiated across modules but does not yet prescribe how such signals are interpreted as higher-level system conditions. The following section therefore addresses how distributed observability is consolidated into intelligible infrastructural meaning.

4.2.4 System State Model and Health Interpretation

From Observability to Interpretability

While Section 4.2.3 established the evidential and informational basis of observability—what can be detected and how signals are differentiated—these informational fragments do not by themselves constitute meaningful system conditions. Interpretability therefore requires an additional abstraction layer that consolidates heterogeneous signals into coherent infrastructural meanings.

Rather than exposing raw measurements, the system state model organizes distributed observability into qualitative operational conditions that can be understood without engineering expertise. This transition from detectability to interpretability enables infrastructural processes to become experientially intelligible while preserving the system's background character and domestic usability.

Categories of Interpretable System States

The system organizes infrastructural activity into a small set of complementary interpretive dimensions that together describe operational readiness without revealing technical complexity. These dimensions function as an interpretive vocabulary through which distributed signals become experientially meaningful.

Operational continuity reflects the coherence and stability of hydraulic routing and execution. Treatment progression captures the temporal evolution of biological processing within the biofilter. Resource availability represents the sufficiency and usability of treated water within storage. Lifecycle proximity and maintenance emergence describe gradual accumulation of care requirements. Contextual cultivation states connect infrastructural performance with visible domestic outcomes such as irrigation readiness and planting continuity.

Primary interpretive dimension	Interpretive condition	Indicative signal constellation	Interpretive implication
Operational continuity	Stable routing coherence	Consistent pump activity; uninterrupted circulation	Supports reassurance of infrastructural continuity
Treatment progression	Processing stability	Retention time progression; Continuous biofilter activity	Indicates ongoing treatment readiness
Resource availability	Reuse sufficiency	Adequate storage level; absence of fallback activation	Signals irrigation readiness and reuse reliability
Lifecycle proximity	Routine care emergence	Biomass accumulation timing; extended treatment cycles	Suggests approaching maintenance without malfunction
Operational continuity + treatment progression	Degraded continuity	Routing inconsistencies; treatment interruption	Indicates emerging instability requiring attention
Resource availability	Resource insufficiency	Declining storage level; repeated fallback reliance	Suggests reduced reuse readiness
Cross-dimensional	Operational anomaly	Pressure instability; persistent diversion; prolonged inactivity	Signals deviation from expected infrastructural behaviour

Table 6. Illustrative aggregation of infrastructural signals supporting the interpretation of system health(Source: Author's own table)

The table above provides representative examples illustrating how distributed signals may be qualitatively aggregated across these interpretive dimensions to support health-related understanding. The mapping is illustrative rather than exhaustive and aims to clarify interpretive reasoning rather than define diagnostic thresholds.

Health as an Emergent Infrastructural Condition

Within this framework, system health is not a directly measurable parameter but an emergent interpretive synthesis arising from the stable interaction of operational continuity, treatment progression, resource availability, and safety validation. Health therefore reflects perceived infrastructural coherence rather than the absence of maintenance activity.

Routine care activities may coexist with healthy operation, representing stewardship rather than degradation. Conversely, prolonged routing inconsistencies, persistent acceptance failures, or interrupted treatment progression may indicate declining health even in the absence of explicit failures. Health is thus best understood as a qualitative interpretation grounded in distributed infrastructural stability and temporal consistency.

Care Interpretation and Responsibility Differentiation

Maintenance-related conditions introduce additional interpretive nuance because they vary not only in urgency but also in responsibility and accessibility. The system therefore distinguishes routine care emergence from anomaly-driven intervention by interpreting temporal signal patterns—such as biomass accumulation timing, extended treatment cycles, or persistent routing deviations—within the broader state dimensions.

Across these conditions, the system further differentiates between user-serviceable and service-only responsibilities, allowing care awareness to support anticipatory engagement without conflating maintenance with malfunction.

Interface Implications

This layered interpretation enables the interface to communicate infrastructural activity as meaningful qualitative summaries rather than technical diagnostics, supporting reassurance, anticipatory care awareness, and differentiated responsibility communication without overwhelming users.

Through this approach, invisible infrastructural dynamics become legible as domestic conditions of readiness, care, and continuity. The interface therefore functions not as a monitoring dashboard but as a mediator that stabilizes trust and supports ongoing infrastructural stewardship.

Summary

Together, the observability framework and the system state model establish a continuous reasoning chain from infrastructural sensing to experiential system understanding, positioning health as an emergent condition grounded in distributed observability rather than isolated measurements.

4.3 Configuration Scenarios

Building upon the modular architecture and system observability model established in Section 4.2, this section examines how the Zero-Mile system can be spatially configured within diverse domestic environments. While the previous section articulated the functional independence, sensing boundaries, and execution relationships of individual modules, these characteristics also introduce a critical spatial consequence: the system does not prescribe a fixed physical topology. Instead, modules may be arranged, concealed, or distributed according to household constraints, installation contexts, and user preferences without compromising operational coherence.

Rather than treating configuration as a purely technical installation step, this section conceptualizes configuration as a situated adaptation process through which infrastructural components are domesticated within everyday living environments. The scenarios presented here therefore serve two purposes. First, they illustrate how modular independence enables multiple spatial arrangements of the same functional system. Second, they highlight how spatial configuration influences system visibility, maintenance responsibility, and experiential interpretation—factors that later inform the design of the configuration interface and the awareness mediation strategies discussed in Chapter 5.

4.3.1 Spatial Variability Enabled by Modular Architecture

The modular decomposition described in Section 4.2 not only supports functional separation and maintenance clarity, but also enables spatial rearrangeability across domestic environments. Because modules operate through clearly defined hydraulic interfaces and sensing boundaries, their physical placement can vary without altering the underlying treatment logic. This decoupling between functional dependency and spatial proximity allows the system to accommodate diverse housing layouts, ranging from compact apartments to spatially distributed dwellings.

A key enabler of this variability is the differentiation between execution-critical components and perceptually meaningful components. Modules such as the Hydraulic Execution & Routing Module and the Accumulation & Buffer Module primarily serve infrastructural roles and are therefore compatible with concealed placement in service areas, cabinetry, or utility spaces. Their operational significance remains high, yet their perceptual relevance to everyday interaction is limited. Conversely, modules such as the Biofilter Process Module and the Cultivation Module possess experiential or observational value, supporting trust, engagement, and domestication through partial visibility and proximity to lived spaces. This distinction allows the system to negotiate between technical concealment and experiential exposure without fragmenting the treatment process.

Spatial variability is further shaped by the distribution of maintenance responsibility across modules. User-serviceable components may benefit from accessible placement that supports periodic care and inspection, whereas service-only components can remain spatially distant from routine interaction. As a result, configuration becomes a mechanism for aligning physical accessibility with responsibility boundaries rather than merely optimizing hydraulic efficiency. This alignment reinforces the interpretability of maintenance tasks and prevents infrastructural complexity from becoming an everyday cognitive burden.

Importantly, spatial rearrangement does not eliminate the need for systemic coherence. Configuration decisions introduce constraints related to gravity return paths, pumping requirements, and connection lengths, which must be evaluated to preserve process continuity and safety margins. However, these constraints operate as feasibility boundaries rather than prescriptive layouts, allowing the system to remain adaptable while maintaining operational reliability.

From an interaction perspective, spatial variability also introduces a persistence of module identity independent of location. Once configured, each module retains its functional role and informational contribution within the system's awareness model, even when spatially distant from other components. This persistence is particularly relevant for cultivation modules, whose spatial independence reflects everyday practices of placement based on light availability, aesthetic preference, and accessibility rather than infrastructural convenience. Consequently, configuration becomes not only a spatial arrangement activity but also a process of establishing stable referential relationships between modules, their locations, and their associated experiential meanings.

Taken together, these characteristics position configuration as an intrinsic extension of modular architecture rather than a post-installation adjustment. The capacity for spatial variability enables the system to integrate into heterogeneous domestic contexts while preserving functional continuity, perceptual intelligibility, and maintenance clarity. The following subsection introduces a typology of configuration scenarios that illustrate how these spatial dynamics manifest across different domestic conditions.

4.3.2 Typology of Configuration Scenarios

Building upon the spatial flexibility enabled by the modular architecture, three recurring configuration typologies can be identified across domestic contexts. These typologies do not represent fixed installation templates, but rather characteristic spatial strategies through which households negotiate constraints of space availability, visibility preference, maintenance accessibility, and experiential engagement. Each typology demonstrates how identical functional modules can be arranged differently while preserving hydraulic coherence and system observability.

The typologies also reflect varying degrees of infrastructural concealment and experiential exposure. As modules transition from compact integration to spatial distribution, the system progressively shifts from a concealed technical appliance toward a dispersed domestic ecosystem. This gradient highlights the importance of configuration not only as a spatial arrangement task, but as a mechanism shaping how users encounter, interpret, and integrate the system into everyday life.

Compact integrated configuration

The compact integrated configuration concentrates most infrastructural modules within a single service zone, typically under a kitchen sink or inside a standard cabinet footprint. The Hydraulic Execution & Routing Module, storage tanks, and qualification components are positioned in close proximity to minimize connection complexity and reduce spatial intrusion. In this arrangement, perceptually meaningful modules such as the Biofilter Process Module and a limited number of Cultivation Modules remain partially visible, often placed on the countertop to support observation and everyday engagement without expanding the system's spatial footprint.

This typology is particularly suitable for small urban apartments where spatial efficiency and infrastructural concealment are prioritized. The configuration supports ease of installation, reduced maintenance dispersion, and clear ownership of routine care activities, while maintaining a minimal yet tangible experiential presence. The compact arrangement therefore positions the system primarily as a concealed domestic infrastructure with selective points of visibility that enable reassurance and engagement.

Vertically distributed configuration

The vertically distributed configuration leverages vertical surfaces and height differentials to expand system capacity without increasing floor occupation. Core infrastructural modules remain located within a base cabinet or service area, while observational and cultivation-oriented components are arranged along walls or vertical racks. The Biofilter Process Module may be positioned at eye level to enhance perceptual accessibility and trust through visible microbial activity, while multiple Cultivation Modules can be stacked or aligned vertically to support diversified planting practices.

This typology is well suited to dwellings characterized by limited horizontal space but greater vertical potential, such as narrow kitchens or compact studio apartments. Vertical distribution introduces a stronger experiential presence compared to the compact configuration, transforming the system from a largely concealed appliance into a visible domestic feature. At the same time, hydraulic coherence is preserved through parallel routing and gravity-aware return paths, allowing spatial expansion without increasing cognitive or maintenance complexity.

Spatially distributed configuration
The spatially distributed configuration separates modules across multiple domestic zones to optimize environmental conditions, accessibility, and experiential integration. Infrastructural components may remain in concealed service areas, while cultivation modules are relocated to spaces offering improved light exposure, aesthetic integration, or outdoor access, such as balconies, windowsills, or sunrooms. Connections between modules may span longer distances, introducing additional routing considerations while preserving functional continuity through the execution core.

This typology is particularly relevant for households that prioritize experiential engagement, plant diversity, or environmental optimization over spatial compactness. The system becomes less appliance-like and more ecosystem-like, with different modules embedded within distinct everyday contexts. Such distribution strengthens the perception of treated water as a living resource circulating across domestic spaces, but also introduces greater reliance on configuration guidance and infrastructural validation during installation.

Typology implications
Across these typologies, configuration operates as a mediator between infrastructural constraints and domestic practices. Compact arrangements emphasize concealment and simplicity, vertical configurations balance visibility with spatial efficiency, and spatially distributed configurations foreground experiential integration and environmental responsiveness. Importantly, these typologies are not mutually exclusive; households may transition between them over time as spatial conditions, maintenance preferences, or cultivation goals evolve.

From a system perspective, the typology reinforces the need for configuration mechanisms that preserve module identity, validate feasibility constraints, and maintain awareness continuity regardless of spatial arrangement. These requirements directly motivate the design of the configuration interface presented in Chapter 5, where spatial arrangement, module persistence, and awareness mediation are integrated into a coherent interaction framework.

4.3.3 Conceptual Spatial Illustrations

To complement the configuration typology while maintaining architectural generality, spatial arrangements are illustrated through abstract volumetric representations rather than realistic domestic layouts. Given that the modular system does not prescribe fixed installation contexts, representational abstraction becomes necessary to emphasize relational structure over material specificity. Modules are therefore depicted as simplified spatial entities, allowing comparison across configurations without anchoring interpretation to particular household environments.

This abstraction foregrounds the persistence of functional identity independent of spatial placement, reinforcing the modular independence discussed in Section 4.2. It also enables the visualization of visibility gradients, accessibility boundaries, and routing dependencies without exposing implementation-level complexity. By focusing on relative positioning and interaction potential, the illustrations frame configuration as a relational spatial composition rather than a prescriptive installation scheme.

Module	Color	Module	Color	Module	Color	Module	Color
Tap Water Distribution Module		Dishwasher Supply Merge & Safety Module		Intake Qualification Module		Accumulation & Buffer Module	
Hydraulic Execution & Routing Module		Biofilter Process Module		Reuse Storage Module		Cultivation Module	

Table 7. Module List for Conceptual Configuration Illustration(Source: Author's own table)

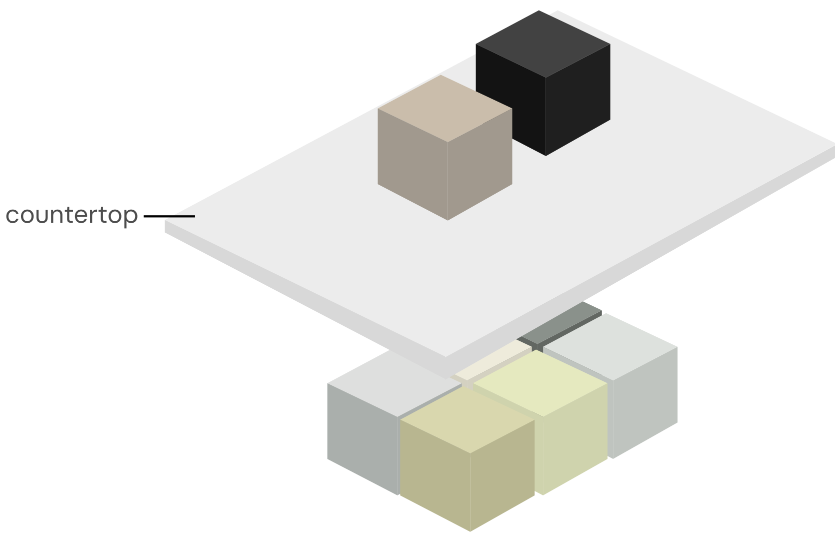


Figure 29. Conceptual Spatial illustration - Compact (Source: Author's own illustration)

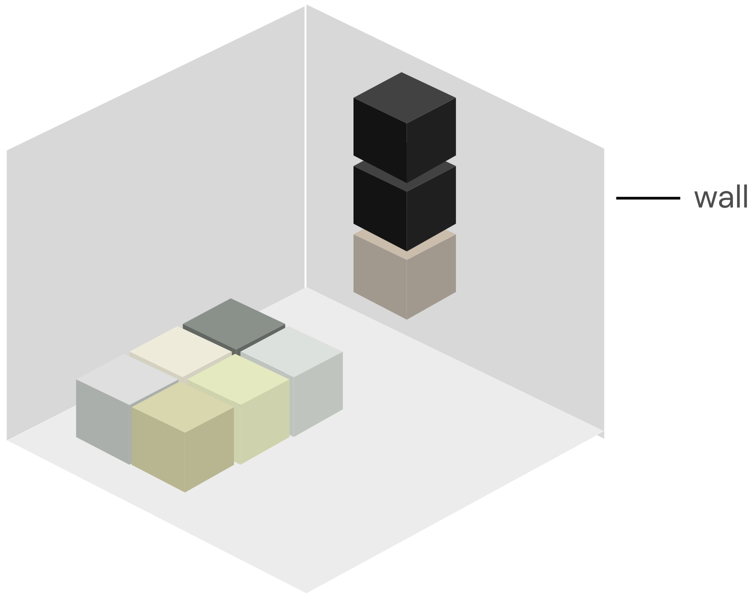


Figure 30. Conceptual spatial illustration - Vertically Distributed (Source: Author's own illustration)

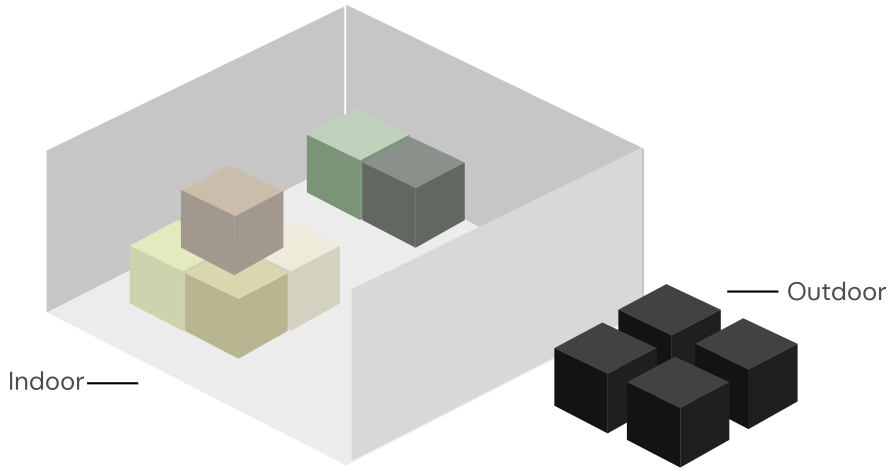
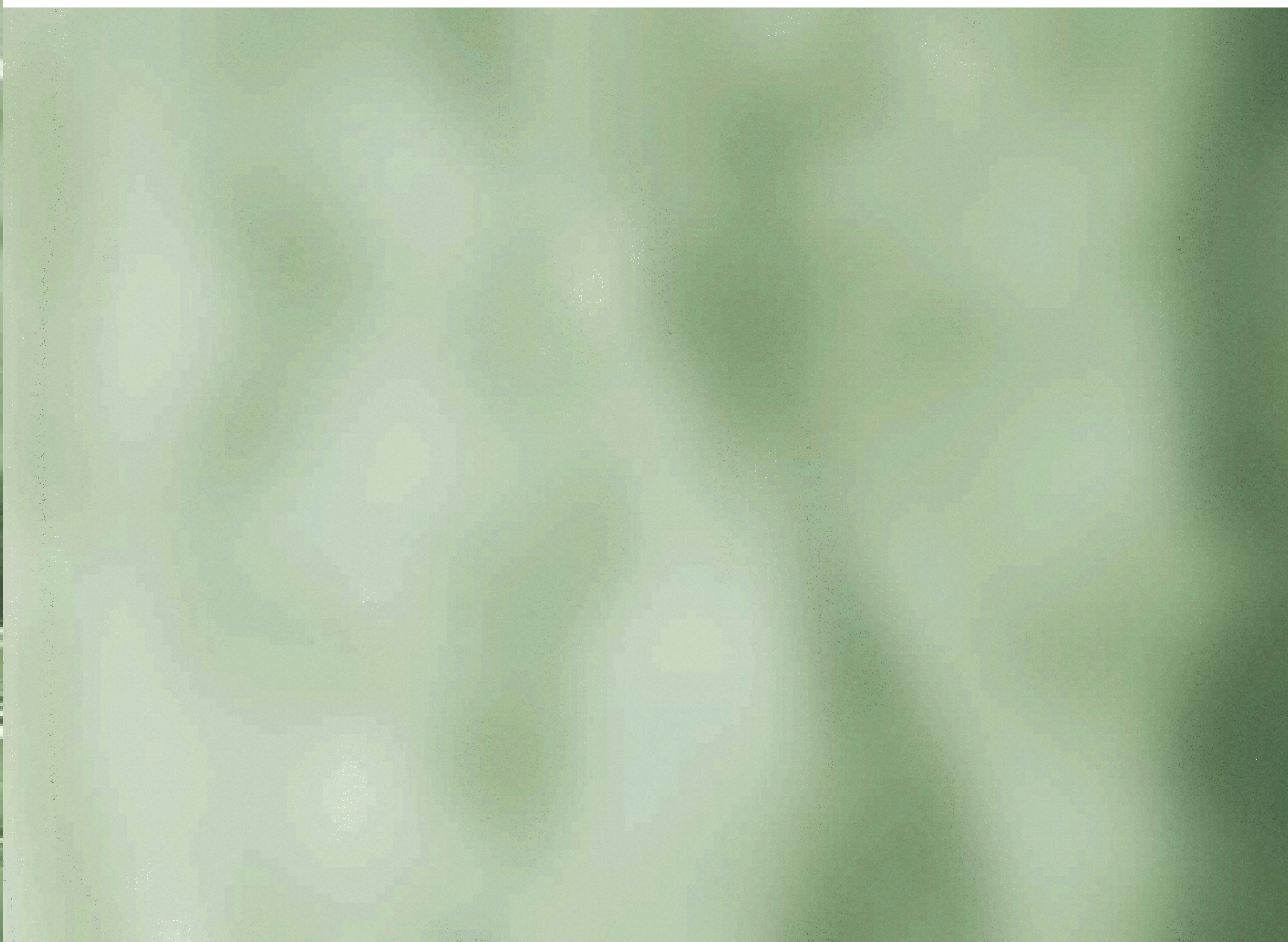


Figure 31. Conceptual Spatial illustration - Spatially Distributed (Source: Author's own illustration)

The abstract spatial illustrations emphasize that configuration operates primarily as a relational arrangement of modules rather than a fixed installation blueprint. While spatial variability enables diverse domestic adaptations, it also introduces the need for mechanisms that preserve module identity, validate feasibility constraints, and maintain awareness continuity across distributed components. Consequently, configuration cannot remain purely spatial; it must be supported by interaction structures that help users understand, construct, and sustain these relational arrangements over time. This requirement motivates the configuration interface presented in Chapter 5, where spatial composition, system feasibility, and experiential awareness are integrated into a coherent interaction framework.

Chapter 5. Interface and Interaction



5.1 From Architecture to Interface

Chapter 4 established the Zero-Mile system as a modular domestic infrastructure capable of spatial adaptation, clear maintenance segmentation, and distributed operational sensing. However, the analysis presented in Chapter 2 revealed that technical completeness alone does not ensure domestic intelligibility. Despite monitoring numerous parameters across treatment, storage, and irrigation stages, the existing prototype provides little accessible feedback to users, effectively operating as a black box whose internal states are legible only through expert inspection. This absence of ambient awareness creates uncertainty around normal operation, intervention timing, and responsibility boundaries, undermining trust and hindering integration into everyday routines.

The experiential requirements identified in Chapter 2 therefore do not call for increased system transparency in the form of raw data exposure, but for mediated intelligibility. Users need to understand when attention is required, distinguish routine care from abnormal conditions, perceive operational rhythms, and recognize which components fall within their responsibility without engaging with low-level technical representations. These requirements position the interface not as a control surface for infrastructure, but as an interpretive layer that translates system observability into meaningful domestic awareness.

Accordingly, this chapter shifts the focus from architectural decomposition to interaction mediation. Rather than mirroring internal system states, the interface selectively aggregates, contextualizes, and temporalizes information to support reassurance, maintenance readiness, and the perception of treated water as an everyday resource. In doing so, it also provides the interaction mechanisms necessary for spatial configuration, enabling users to reason about module placement and system feasibility without confronting underlying infrastructural complexity.

5.1.1 Limits of Direct System Exposure

The analysis in Chapter 2 highlights that the primary limitation of the existing prototype is not the absence of sensing or operational capability, but the absence of user-facing interpretation. Although the system monitors multiple parameters across treatment, storage, and irrigation stages, these signals remain largely inaccessible in everyday use, creating what can be understood as a black-box condition. Users are therefore unable to distinguish between normal operation, temporary inactivity, and situations requiring attention without expert intervention, leading to uncertainty and reduced trust in routine domestic contexts. This observation suggests that increasing visibility alone is insufficient; what is required is intelligibility.

Direct exposure of system observability presents several challenges. First, a semantic discontinuity exists between infrastructural signals and household decision-making. Many sensed variables—such as intermediate hydraulic transitions, pump activation sequences, or buffering continuity—are essential for internal execution yet do not correspond to stable everyday meanings. Presenting these signals directly risks transforming routine interaction into technical monitoring, placing users in the role of system supervisors rather than participants in a domesticated ecological process.

Second, unfiltered transparency can obscure rather than clarify responsibility boundaries. The modular architecture deliberately distinguishes between user-serviceable components, automated subsystems, and service-only infrastructure. If low-level operational data were uniformly exposed, users might infer agency over processes that are intentionally autonomous or professionally maintained, generating anxiety and ambiguity around intervention responsibility. Effective domestic interaction therefore requires that visibility align with ownership of action: information should become explicit where user care is meaningful, and remain abstract where operation is intentionally backgrounded.

A third limitation concerns the temporal character of biological and infrastructural processes. Many relevant states are not best understood through instantaneous measurements but through phases, rhythms, and anticipated transitions. Biological treatment cycles, buffering delays, and periodic maintenance events unfold over extended time horizons, making raw telemetry an inadequate representation of system progression. Interfaces that privilege instantaneous data risk masking the experiential continuity of the system, whereas temporally framed cues—such as readiness windows, upcoming tasks, and interpretable progression cues—better support anticipation and planning without inducing urgency.

Finally, comprehensive exposure conflicts with the system's intended positioning as a background domestic infrastructure. As discussed in Chapter 2, household technologies typically communicate operational status through low-effort, peripheral cues rather than continuous inspection. Over-exposure of internal variability may inadvertently foreground complexity that is operationally normal, thereby undermining the calm and dependable presence expected of domestic appliances. Trust, in this context, emerges not from exhaustive transparency but from appropriately scoped interpretive visibility.

For these reasons, the interface must treat system observability as a material for interpretation rather than direct representation. The challenge is not to reveal all signals, but to transform them into forms that support reassurance, maintenance readiness, and everyday understanding without demanding technical literacy. The following section introduces domestic awareness as an interpretive layer through which system states are selectively aggregated and contextualized, establishing the basis for the information architecture and interaction flows developed in the remainder of this chapter.

5.1.2 Domestic Awareness as an Interpretive Layer

If direct exposure of infrastructural observability is insufficient for domestic intelligibility, the interface must instead support forms of awareness aligned with everyday practices. The experiential requirements identified in Chapter 2 suggest that users do not seek continuous monitoring of system internals, but rather an ability to remain peripherally informed about system wellbeing, anticipate moments of required care, and understand the role of treated water within routine household activities. These expectations position interaction not as control of infrastructure but as the cultivation of domestic awareness.

Domestic awareness refers to the interpretive layer through which complex infrastructural processes are rendered legible without demanding sustained attention or technical expertise. Unlike monitoring dashboards that foreground measurement and control, awareness-oriented interfaces emphasize reassurance, temporal anticipation, and meaningful points of engagement. The goal is not to provide exhaustive visibility, but to establish a stable sense of system presence that allows users to recognize normal operation, notice emerging needs, and integrate the system into habitual practices without cognitive overload.

Within the Zero-Mile context, several distinct awareness orientations emerge. A first orientation concerns reassurance of ongoing operation. Users need low-effort cues indicating that treatment and routing processes are progressing normally, even when no interaction is required. Such reassurance addresses the uncertainty identified in Chapter 2 by providing a persistent yet unobtrusive sense of system continuity. Importantly, reassurance is not equivalent to detailed feedback; it relies on aggregated and semantically stable indicators that can be interpreted at a glance.

A second orientation relates to maintenance readiness and responsibility clarity. Domestic interaction requires users to understand when intervention is appropriate and what form it should take, while preserving clear boundaries between routine care and professional service. Awareness therefore operates as a mechanism for translating infrastructural states into actionable anticipation rather than urgent alerts. By framing maintenance in terms of upcoming tasks, expected intervals, and responsibility ownership, the interface supports confidence in routine engagement while preventing the perception of constant vigilance.

A third orientation involves resource intelligibility—the perception of treated water as an available, evolving household resource rather than an invisible technical output. Because the treatment process introduces temporal buffering and variability, users benefit from understanding availability in terms of readiness, sufficiency, and fallback conditions instead of quantitative telemetry. This awareness supports practical decision-making around irrigation and reinforces the experiential connection between wastewater reuse and cultivation outcomes.

A fourth orientation concerns experiential domestication through cultivation. Unlike infrastructural modules that operate in the background, cultivation elements provide tangible encounters with the system's ecological purpose. Awareness in this context is less about system state and more about cultivation engagement and care interaction that embed the treatment process within everyday spatial and sensory experiences. This orientation allows biological processes to be perceived as part of household life rather than distant technical operations.

Finally, configuration introduces a form of structural awareness related to how modules are arranged, related, and sustained over time. As demonstrated in Section 4.3, spatial variability enables diverse domestic placements while preserving functional continuity. Users therefore require an understanding of module identity, relational placement, and feasibility constraints that persists beyond installation. Structural awareness does not entail knowledge of hydraulic implementation but rather an ability to reason about the system as a configurable composition whose spatial arrangement influences experience without compromising operation.

Together, these awareness orientations establish the interpretive foundation for the interface. They transform Chapter 2's experiential requirements—from intervention recognition and responsibility clarity to passive operational feedback and rhythm anticipation—into coherent domains of domestic understanding. The interface design that follows does not aim to expose system internals directly, but to materialize these domains through carefully scoped information structures and interaction mechanisms. The next section therefore examines how these awareness orientations inform the information architecture and core interaction flows of the Zero-Mile interface.

5.1.3 Configuration as a Mediated Interaction Space

Beyond ongoing operational awareness, the modular structure of the Zero-Mile system introduces a need for users to form a basic understanding of how the system can be arranged within their domestic environment. As discussed in Section 4.3, modules may be spatially distributed in multiple ways while preserving functional continuity. This flexibility, however, creates a challenge at the moment of installation: users must express spatial preferences, accessibility expectations, and cultivation intentions without possessing detailed knowledge of infrastructural feasibility. Configuration therefore becomes less a technical planning task and more a mediated interaction through which domestic constraints and expectations are articulated.

Within this perspective, the configuration interface does not function as a precise simulation or engineering design environment. Instead, it serves as a lightweight interaction space that helps externalize household conditions and preferences in forms that can later be interpreted by the system and installation professionals. Early interaction steps guide users to reflect on spatial visibility, placement flexibility, and maintenance comfort, eliciting situated knowledge that is otherwise difficult to communicate explicitly. The inclusion of contextual inputs, such as photographs of the domestic environment, further bridges the gap between abstract system components and lived spatial realities.

A second role of configuration interaction lies in supporting bounded exploration. Rather than requiring users to construct a system from first principles, the interface presents a limited set of configuration typologies derived from the modular architecture. This approach allows users to recognize relatable spatial patterns and select among them without confronting underlying infrastructural constraints. In this sense, configuration operates as guided expression rather than unrestricted design, balancing user agency with feasibility preservation.

The subsequent placement interaction extends this expression by allowing users to indicate relational positioning and capacity preferences, such as the number of cultivation modules or storage volume choices. Even when represented in a simplified planar form, this interaction supports the persistence of module identity and helps users develop a mental model of the system as a composition rather than a hidden appliance. At the same time, feasibility evaluation remains external to the user's responsibility. The generation of a configuration report and its handover to suppliers preserves the distinction between domestic preference articulation and professional infrastructural validation, reinforcing responsibility boundaries identified in Chapter 2.

Through this mediated process, configuration becomes an interaction that captures domestic intention rather than enforcing technical correctness. It enables users to communicate spatial expectations, visualize possible arrangements, and maintain a sense of structural awareness while avoiding exposure to infrastructural complexity. The following section builds on this understanding to describe how configuration and operational awareness are integrated within the broader information architecture and interaction flows of the interface.

5.1.4 Mapping Architecture to Human Agency: The Persona

To bridge the architectural framework with everyday interaction realities, this section introduces personas as interpretive synthesis tools rather than demographic representations. The personas were developed through the aggregation of insights from prior contextual inquiry, workshop feedback, prototype evaluation sessions, and reflective scenario exploration conducted throughout the design process. Rather than representing statistically validated user groups, they capture distinct interpretive orientations toward domestic ecological infrastructure, revealing how different users seek reassurance, transparency, or predictability when interacting with the system.

- Elena: The Emotional Co-existence and System Vitality Elena, a landscape designer and sustainable lifestyle blogger, represents users who view the domestic ecosystem as a living companion rather than a mere utility. For her, the "interpretive layer" must bridge the gap between invisible biofiltration and the emotional well-being of her plants. Her agency is driven by the desire for a closed-loop lifestyle and a "zero-waste" philosophy, yet she faces a knowledge barrier regarding complex biochemical processes. The interface for Elena prioritizes the Home and Garden modules, focusing on "system health" and psychological reassurance—translating technical data into the feeling that the system is "breathing healthily".

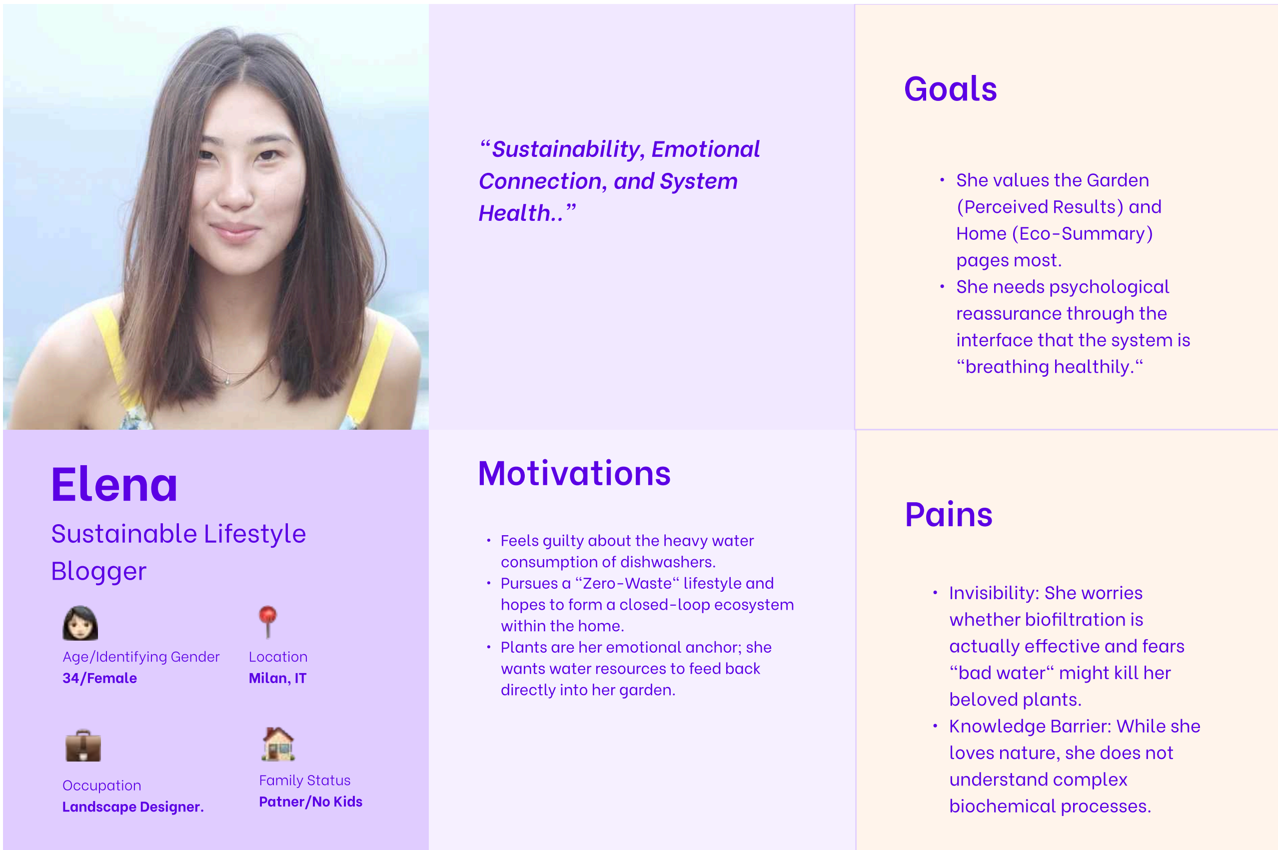


Figure 32. User Persona: Sustainable Lifestyle Blogger. (Author's own illustration)

- Amy Vaugn: Predictability and Managed Utility As a project manager and parent, Amy embodies the need for the system to be a seamless, "foolproof" part of a busy routine. Her interaction with the system architecture is defined by a desire for predictability; she views the technology as a manageable utility that should not add to her cognitive load. Amy's primary pain points are "maintenance anxiety" and fragmented time, which require the interface to provide clear boundaries between user tasks and automated professional services. Consequently, her interface experience focuses on Care and Setting modules, offering step-by-step guidance and "at-a-glance" status updates to ensure the system remains a helpful tool rather than a burden.

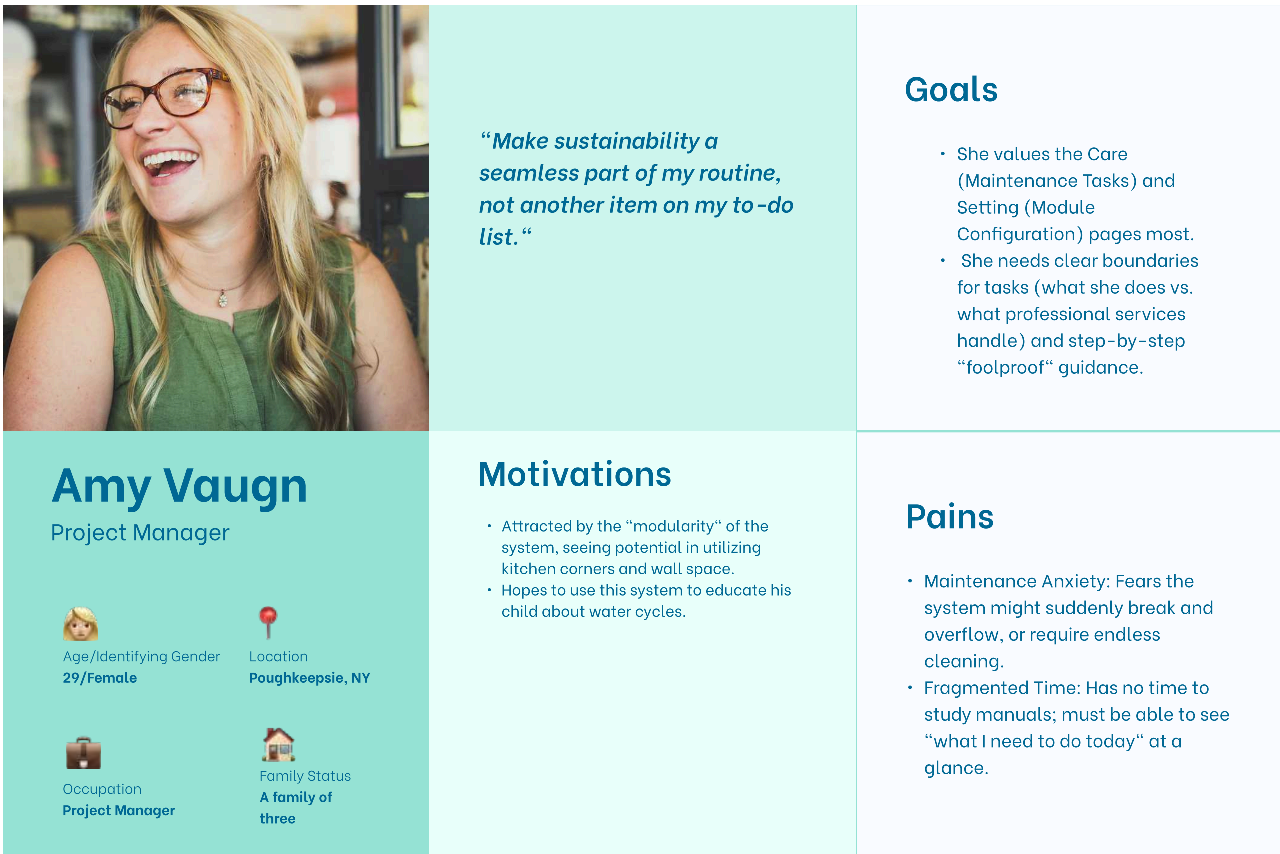


Figure 33. User Persona: Project Manager. (Author's own illustration)

- Irene Simpson: Transparency and Logical Understandability Irene, a software engineer and tech blogger, represents the expert-level user who seeks to "see the logic behind the flow". Her agency is expressed through monitoring, optimizing, and experimenting with cutting-edge infrastructure. For Irene, the interface must dissolve the "invisibility" of the system by providing logical evidence and real-time processing data. She lacks patience for slow, opaque processes and requires a clear sense of rhythm through progress bars and data streams. Her interface focus centers on the Water and Home modules, where the architecture is translated into a transparent, "living machine" that she can analyze and trust through data-driven transparency.

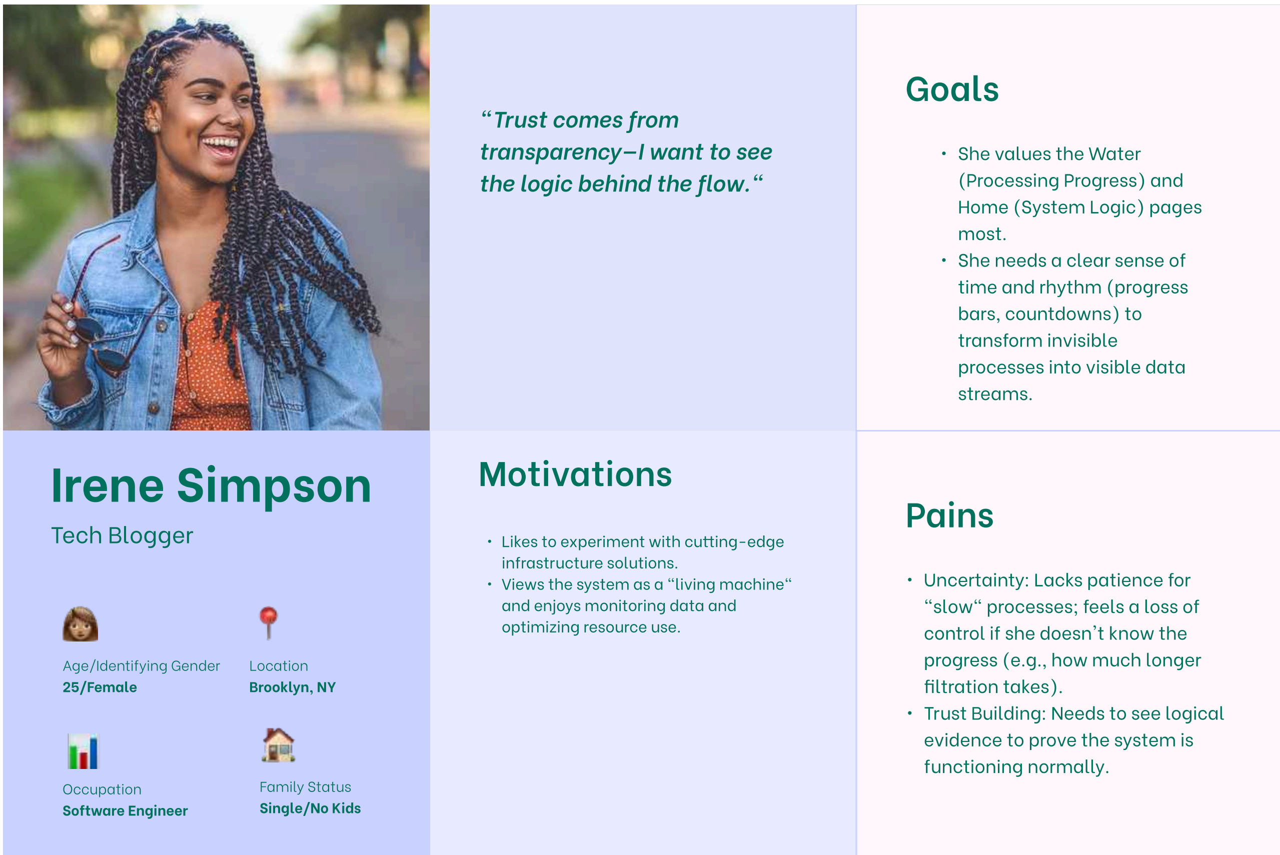


Figure 34. User Persona: Tech-Savvy Early Adopter. (Author’s own illustration)

The diverse profiles of Elena, Amy, and Irene demonstrate that "human agency" in a domestic bio-system is not monolithic; rather, it fluctuates based on the user's emotional involvement, technical literacy, and lifestyle constraints. By synthesizing their motivations and pain points, we can establish a clear mapping between user values and the prioritized interface modules.

Persona	Core Value Validated	Interface Focus
Elena	Co-existence: The system as a living companion.	Home / Garden
Amy Vaugn	Predictability: The system as a manageable utility.	Care / Setting
Irene Simpson	Understandability: The system as a transparent process.	Water / Home

Table 8. Mapping User Core Values to Interface Focus.(Author’s own table)

Comparative Analysis of User Needs

- Emotional vs. Functional Reliability: For Elena, reliability is perceived through the "vitality" of her plants and the emotional satisfaction of a closed-loop lifestyle. In contrast, Amy defines reliability as the absence of maintenance surprises (Maintenance Anxiety). This necessitates an interface that can toggle between "biological health" narratives and "mechanical status" alerts to satisfy both psychological and functional needs.

- The Transparency Gradient: Irene demands high-resolution transparency to "see the logic behind the flow". However, for Elena, too much raw data creates a "Knowledge Barrier" that can be overwhelming. The system must therefore implement an interpretive layer that abstracts complex biochemistry into intuitive visual metaphors (like "breathing healthily") for non-experts, while allowing deep-dives for power users.

- Time and Interaction Frequency: Amy’s "Fragmented Time" dictates a "pushed" interaction model—where the system only asks for attention when necessary. Conversely, users like Irene and Elena engage in "pulled" interactions, actively seeking out data or emotional connection. This justifies the flow-based UI explanation in Section 5.3, which distinguishes between "everyday awareness" and "detail maintenance".

Concluding Remarks on Agency Mapping

The mapping from architecture to human agency reveals that the interface's primary role is to serve as a mediator of complexity. By aligning specific system modules (Home, Garden, Care, Water) with the core values of Co-existence, Predictability, and Understandability, the design ensures that the technical infrastructure remains subservient to human intent and domestic well-being. This framework provides the logical foundation for the high-fidelity interface realizations presented in the following section.

5.2 Information Architecture and Core Interaction Flows

Building on the interpretive orientation established in Section 5.1, the design of the Zero-Mile interface requires a structured translation from domestic awareness into navigable interaction forms. While the previous section articulated how infrastructural observability is transformed into reassurance, maintenance readiness, resource intelligibility, and structural awareness, these experiential domains must now be operationalized as an information architecture capable of supporting everyday engagement without foregrounding infrastructural complexity.

Rather than organizing the interface around technical subsystems or sensing variables, the information architecture is therefore derived from recurring household interaction situations. This approach ensures that navigation reflects moments of interpretation and action—such as seeking reassurance, anticipating maintenance, understanding cultivation conditions, or reasoning about module configuration—rather than mirroring the system's internal decomposition. In doing so, the interface maintains alignment with the principle of interpretive visibility, allowing users to access meaningful system understanding without engaging with low-level operational detail.

Within this framework, the architecture performs two complementary roles. First, it stabilizes awareness by providing persistent points of orientation through which users can interpret system wellbeing, resource availability, and responsibility boundaries at a glance. Second, it supports action readiness by structuring pathways that guide users from passive awareness toward appropriate intervention, whether through routine care, configuration reflection, or escalation to professional service. The resulting structure therefore balances ambient intelligibility with actionable depth, enabling transitions between peripheral awareness and focused interaction as required by domestic practice.

To articulate this structure, the following sections examine the core interaction domains that shape the interface and the flows through which users move between them. Section 5.2.1 describes the configuration flow as an anticipatory interaction supporting installation planning and spatial reasoning, while Section 5.2.2 addresses the ongoing monitoring and maintenance flow that sustains long-term engagement with the system. Together, these flows establish the informational and temporal backbone of the interface, forming the basis for the subsequent mapping between awareness domains, interface components, and modular system architecture.

5.2.1 Pre-installation Configuration Flow

In contrast to ongoing operational interaction, configuration represents a temporally distinct form of engagement that precedes system installation and focuses on the articulation of domestic conditions rather than the interpretation of system performance. While monitoring and maintenance flows respond to an already operational infrastructure, the configuration flow supports anticipatory reasoning, enabling users to reflect on how the modular system may be situated within their spatial, practical, and experiential context before technical validation occurs.

This flow therefore does not aim to provide an accurate simulation of infrastructural feasibility or hydraulic behavior. Instead, it functions as an exploratory interaction through which household preferences, spatial constraints, and cultivation intentions are externalized in forms that can later be interpreted by installation professionals. By reframing configuration as a mediated expression of domestic context rather than an engineering planning task, the interface preserves the distinction between user preference articulation and professional feasibility assessment established in the modular responsibility model.

From an awareness perspective, the configuration flow primarily supports structural awareness and anticipatory readiness. Users are guided to develop a basic understanding of module identity, relational placement, and capacity implications without engaging with infrastructural complexity. Early steps elicit contextual knowledge—such as spatial availability, visibility preferences, and maintenance accessibility—while subsequent interactions translate these reflections into simplified configuration choices derived from the typologies introduced in Section 4.3. This staged progression allows users to move from abstract preference expression toward spatial reasoning while maintaining cognitive clarity and bounded decision scope.

The configuration process culminates in a planar placement interaction that enables users to indicate module quantity and approximate arrangement within a simplified domestic layout. Although representationally reduced, this interaction supports the persistence of module identity and fosters a mental model of the system as a compositional infrastructure rather than a monolithic appliance. Importantly, the outcome of this interaction is not a finalized design but a configuration report that communicates domestic intentions, contextual constraints, and preliminary spatial decisions to suppliers for professional evaluation. This handover reinforces responsibility boundaries while ensuring that user participation meaningfully informs installation planning.

Through this anticipatory flow, configuration establishes the structural and experiential groundwork upon which subsequent operational interaction is built. It prepares users to recognize installed modules, understand placement rationale, and interpret system behavior within the context of their own spatial decisions, thereby linking installation anticipation with long-term domestic awareness.

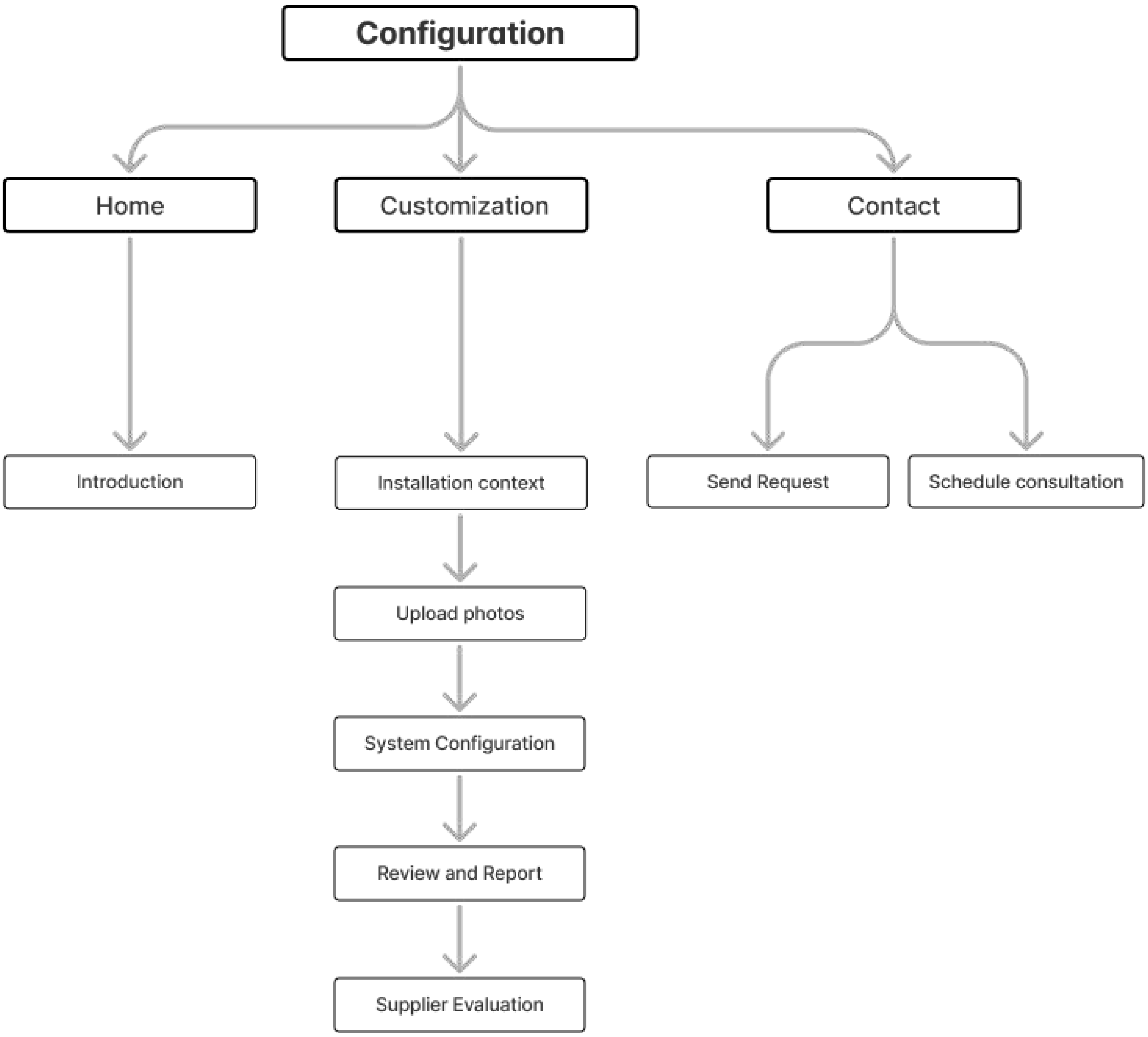


Figure 35. Pre-installation configuration - System Architecture (Author's own illustration)

5.2.2 Monitoring and Maintenance Flow

Following installation, interaction with the Zero-Mile system shifts from initial configuration toward a cycle of long-term interpretation and care. This monitoring and maintenance flow addresses an extended form of engagement, where users maintain a subtle awareness of system wellbeing and recognize necessary interventions without the burden of constant technical oversight. Rather than framing monitoring as a rigorous inspection of parameters, the system cultivates a sustained, low-effort awareness that provides reassurance and prompts timely action only when essential.

To achieve this, monitoring operates through aggregated and semantically stable indicators that communicate the health of both the overall system and individual modules at a glance. By prioritizing interpretive clarity over raw data precision, the interface allows users to easily distinguish between standard operation, emerging needs, and conditions requiring escalation. This approach significantly reduces the cognitive load on the user while reinforcing trust in the system's autonomous functioning.

Maintenance interactions emerge naturally from this layer of awareness, progressing from passive reassurance to focused engagement only when required. When a task arises, the interface provides contextualized information regarding the nature of the work, its urgency, and clear boundaries of responsibility. Routine, user-serviceable tasks are presented as predictable, scheduled activities, while more complex technical interventions remain backgrounded and linked directly to supplier support pathways. This structure ensures that users feel empowered in their agency without feeling overwhelmed by the necessity of safe operation.

A defining characteristic of this flow is its temporal orientation. Because biological treatment, buffering, and resource circulation unfold through natural rhythms rather than instantaneous states, the interface emphasizes anticipatory cues and readiness indicators over real-time telemetry. This temporal framing transforms maintenance from stressful, reactive troubleshooting into a predictable part of domestic care, allowing interaction to be integrated into existing daily habits.

Finally, the flow sustains a structural understanding of the installed system by providing easy access to module identities, installation contexts, and supplier relationships. This ensures that the infrastructure remains legible even when direct interaction is infrequent. By combining ambient reassurance, anticipatory guidance, and persistent structural context, the monitoring and maintenance flow establishes a lightweight yet reliable mode of long-term engagement, completing the experiential foundation for the system's information architecture.

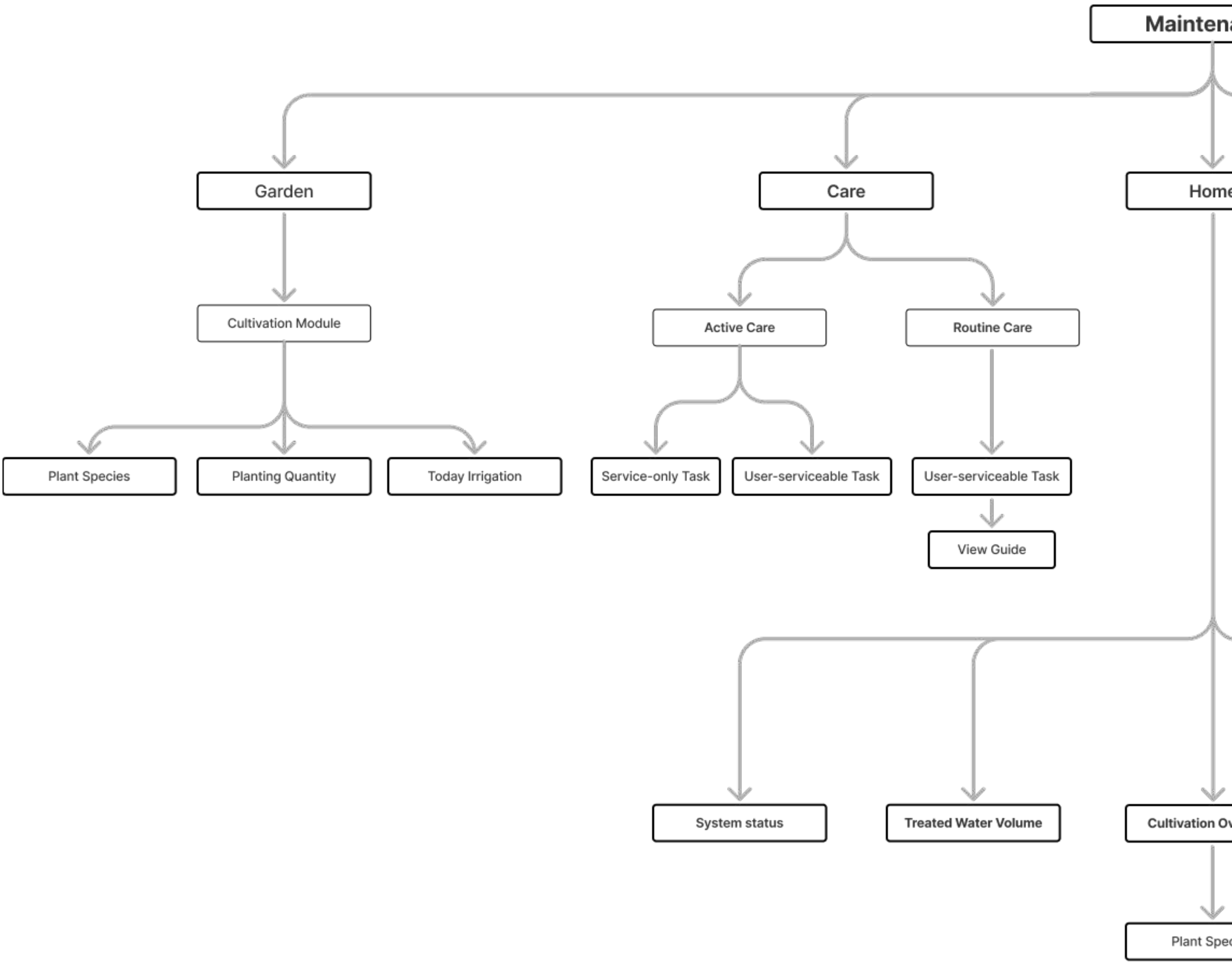
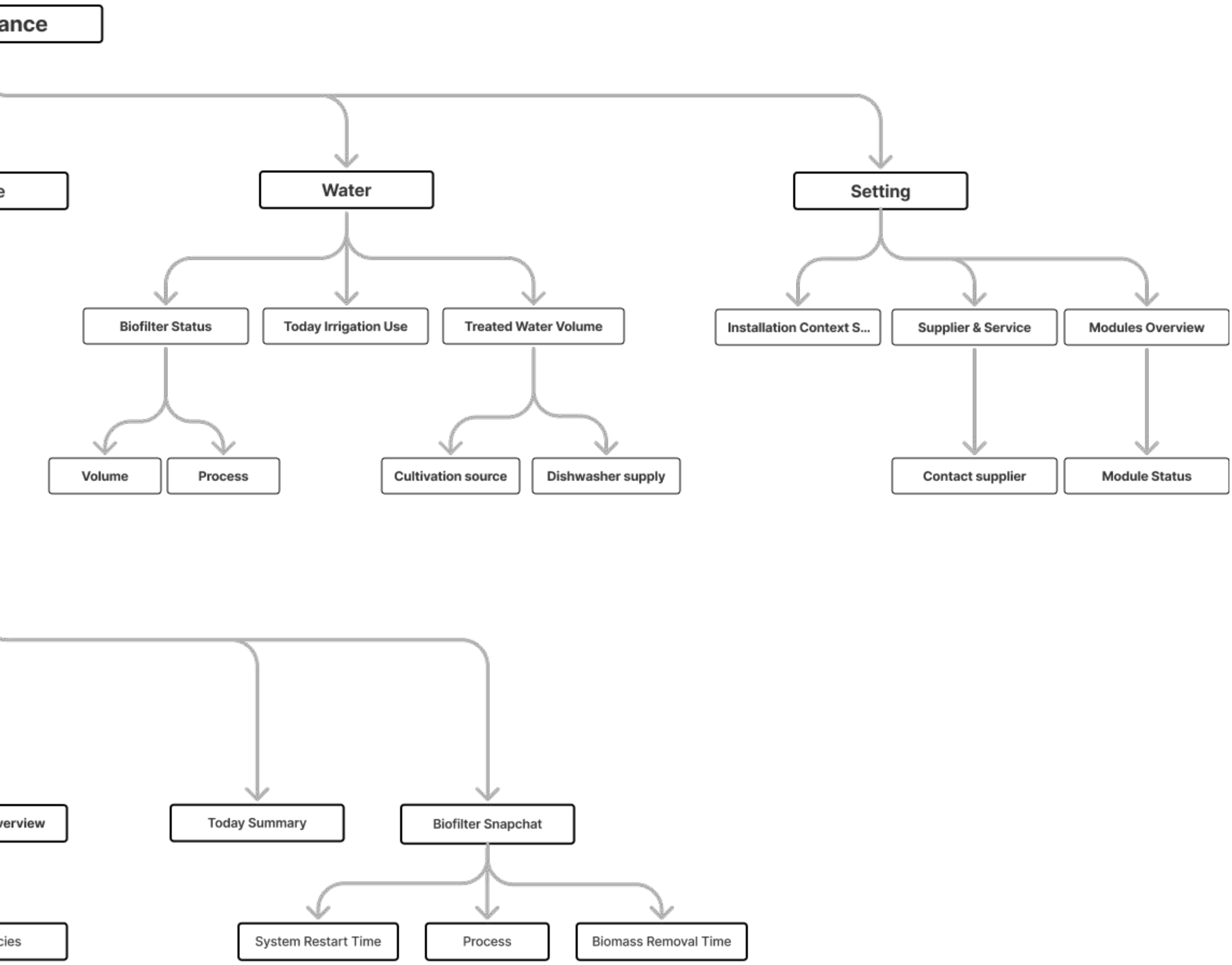


Figure 36. Monitoring and maintenance System Architecture (Author's own illustration)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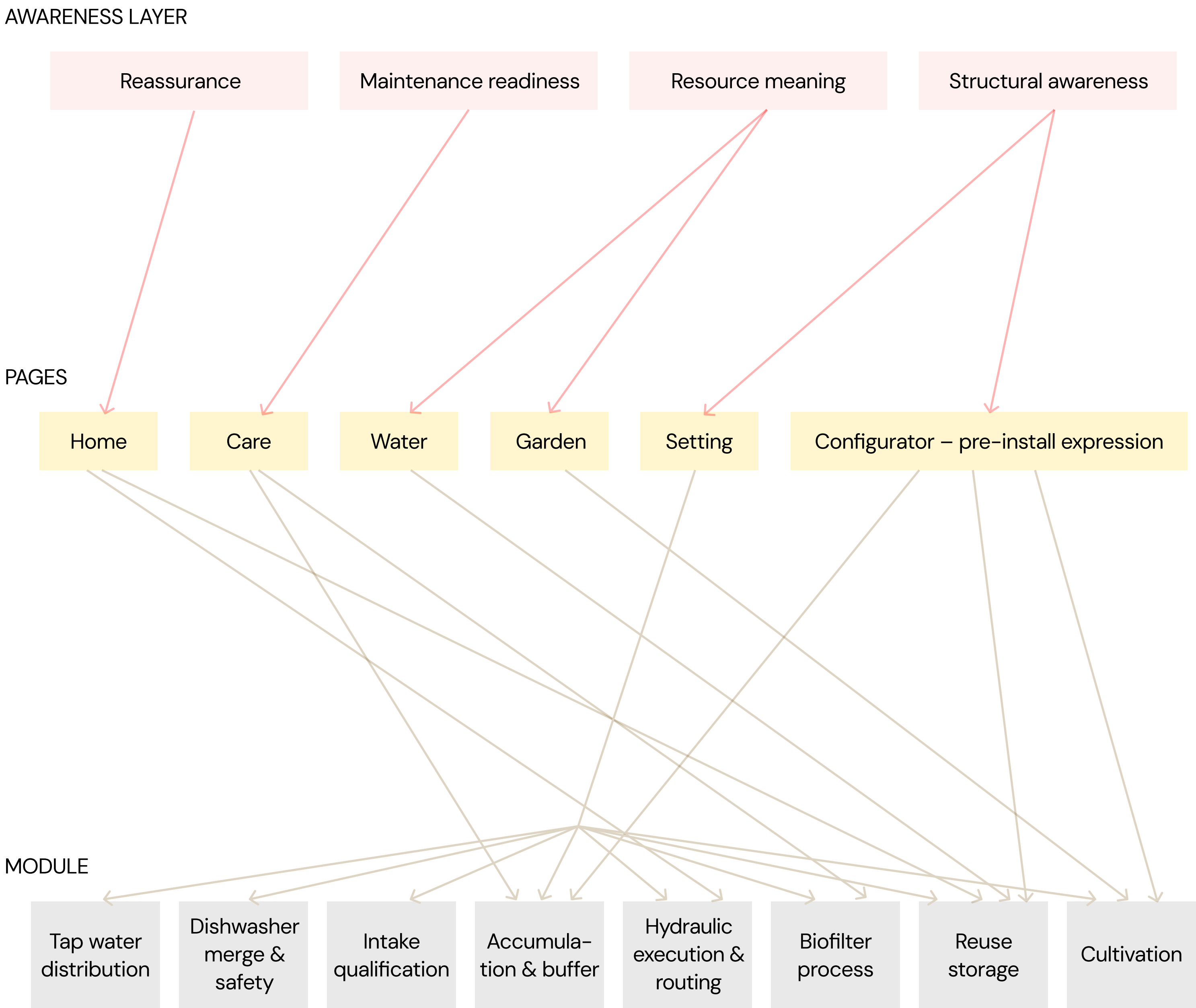

Figure 37. Mapping of domestic awareness orientations to interface domains and module(Author's own illustration)

The mapping illustrated in Figure 37 demonstrates how domestic awareness orientations are selectively materialized through interface domains and their relationship to the modular infrastructure of the Zero-Mile system. Rather than providing direct exposure to all system components, the interface operates as an interpretive filter that mediates between infrastructural complexity and everyday intelligibility. Each awareness domain is therefore expressed through a limited set of interface entry points that reveal only the module relationships necessary for meaningful interpretation and action.

Although the awareness–page–module mapping primarily serves as an analytical framework for articulating the relationship between infrastructural processes and interface domains, it also functions as an implicit orientation scaffold for users. Rather than exposing the mapping as an explicit system taxonomy, the interface operationalizes it through differentiated page semantics, selective module visibility, and clearly bounded action spaces. User orientation is further supported by stable page roles, persistent system status cues, and clearly separated task domains across the Home, Care, Water, and Garden pages, which act as cognitive landmarks within everyday interaction. Each interface domain foregrounds a distinct mode of system understanding — reassurance, resource comprehension, maintenance responsibility, or experiential outcome — allowing users to infer their position within the broader water–treatment ecosystem without requiring direct knowledge of underlying modules. In this sense, orientation emerges not from structural transparency alone but from interpretive consistency across navigation, feedback phrasing, and actionable affordances, enabling users to maintain a stable cognitive sense of “where they are” within a complex domestic infrastructure.

5.3 Configuration Interface

The web-based interactive system developed in this study serves as the primary architectural nexus connecting end-users with the underlying design logic. Its core objective is to utilize digital mediation to transform complex, often ambiguous spatial requirements into actionable and quantifiable system configuration schemes. Within the initial phase of the design specification, the web-based workflow assumes the critical roles of "environmental sensing" and "requirement deconstruction." Rather than a rudimentary linear input sequence, the process is engineered as a dynamic, feedback-driven interaction chain designed to resolve the inherent tension between automated efficiency and bespoke user customization.

From a macro-interactive structural perspective, the workflow establishes a closed-loop system that progresses from subjective preference capture to objective physical environment mapping, culminating in virtual simulation and validation. The journey begins with the "Multi-Dimensional Assessment Module," where a structured interface guides users to self-define critical parameters such as installation context, maintenance commitment, and spatial flexibility. This ensures the system captures the "human" element of the design before technical constraints are applied. Subsequently, through the "Environmental Data Acquisition Module," user-uploaded site photography provides the indispensable physical boundary conditions. This integration allows the configuration logic to be deeply rooted within the authentic framework of the indoor environment, accounting for architectural nuances that purely textual data might overlook.

During the data integration phase, the system employs an "Online Simulator" to facilitate the logical arrangement of modular components. This interface not only provides users with immediate visual feedback but also serves as a computational engine to verify the technical feasibility and structural integrity of the proposed layout. To maximize the inclusivity and reliability of the design output, the workflow adopts a "Dual-Track Delivery Mode" at its conclusion. The system automatically generates a comprehensive report—comprising detailed configuration specifications and spatial placement recommendations—to serve as the definitive blueprint for subsequent installation.

Recognizing the inherent limitations of user decision-making in highly complex or idiosyncratic environments, the workflow embeds a Direct Contact Mechanism at its terminus. This allows users to diverge from the automated trajectory to seek professional human intervention. This "digital-led, human-augmented" design philosophy ensures the system can rapidly respond to standard demands through automated pathways while maintaining a flexible interface to address intricate spatial puzzles. Ultimately, this robust workflow provides the necessary logical scaffolding and data integrity required for the stable operation of the entire system.

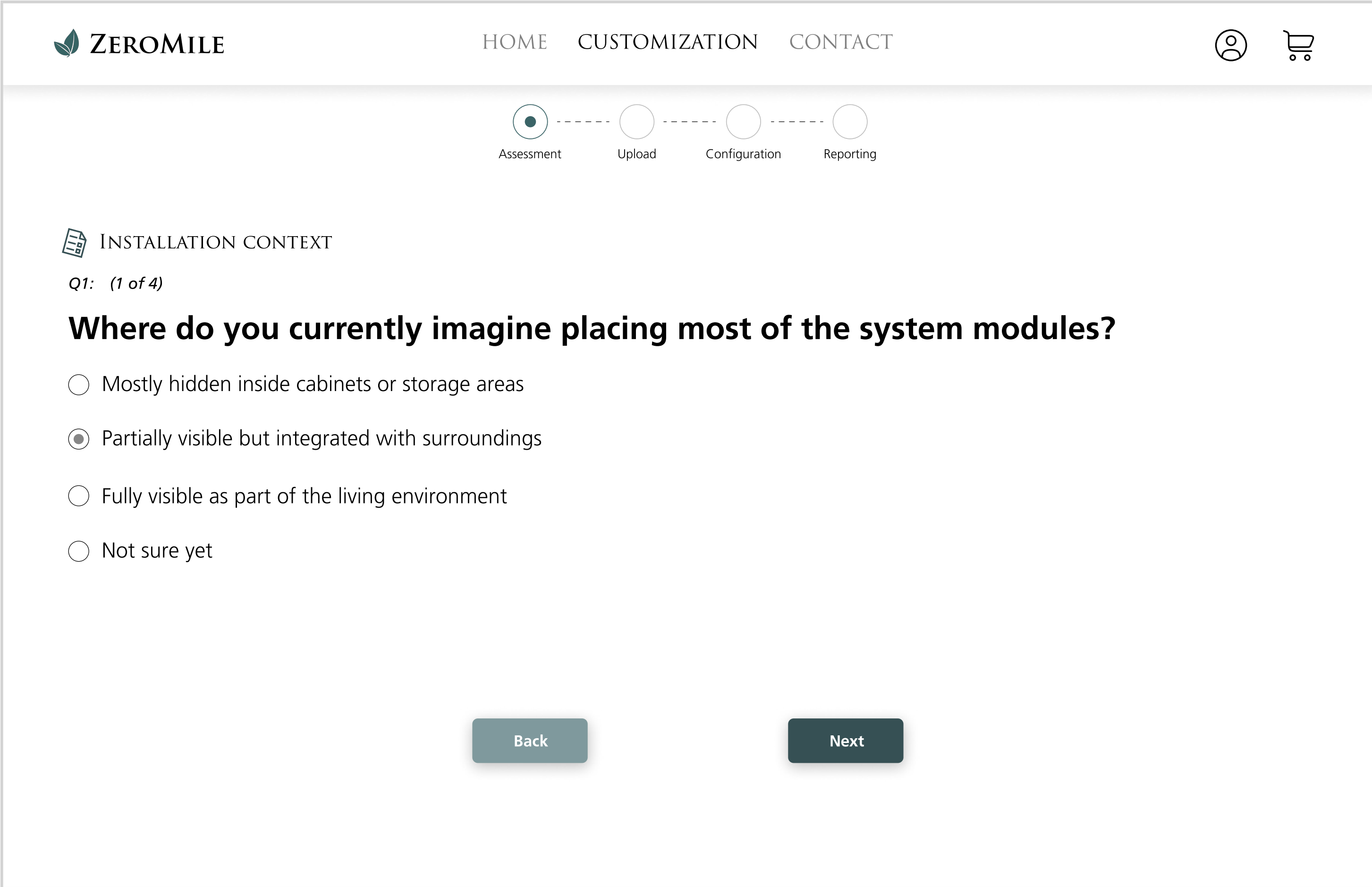

Figure 38. Configuration Interface: Assessment of Installation Location (Q1). (Author's own illustration)

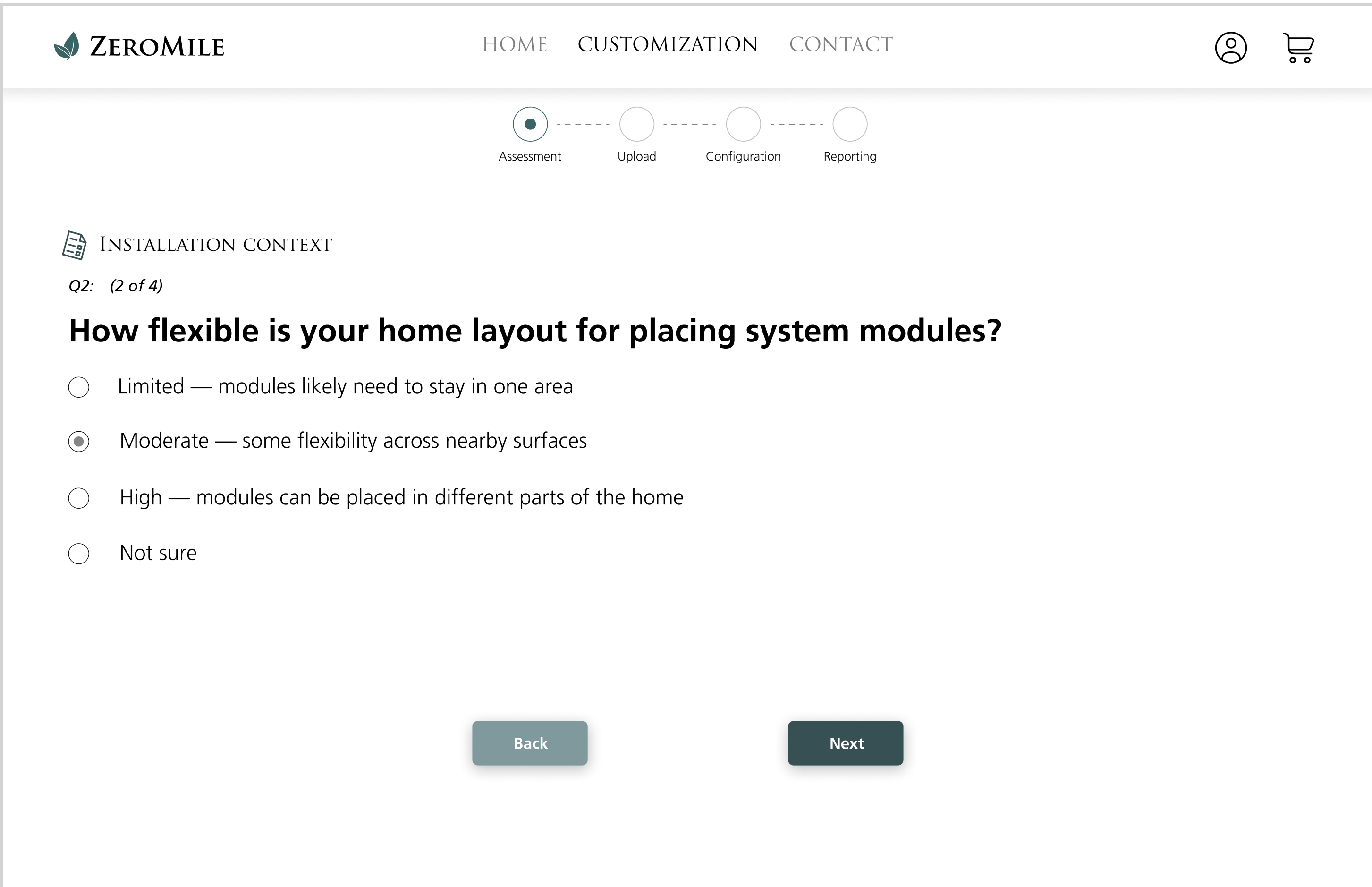

Figure 39. Configuration Interface: Assessment of Layout Flexibility (Q2). (Author's own illustration)

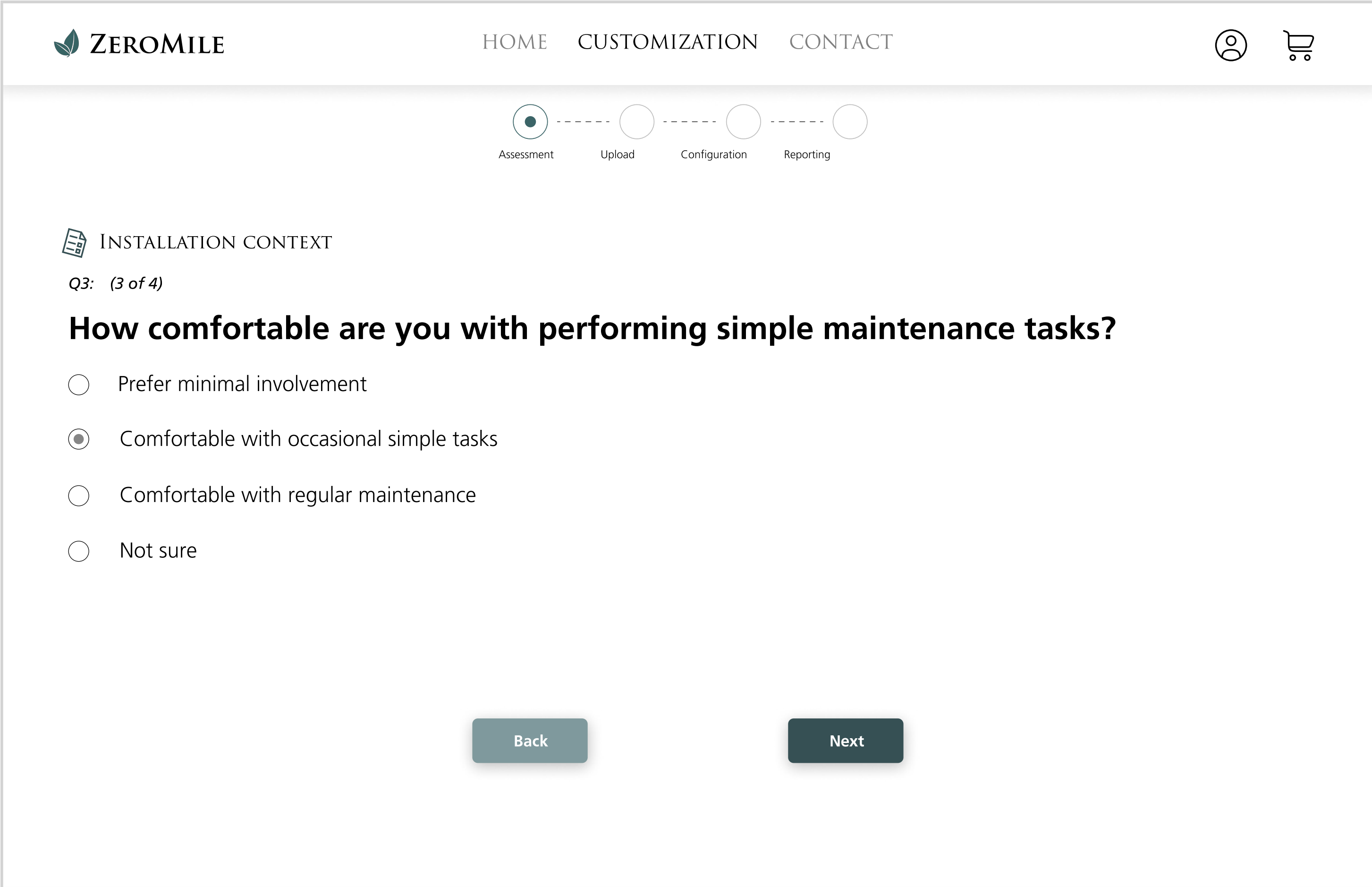

Figure 40. Configuration Interface: Assessment of Maintenance Commitment (Q3). (Author's own illustration)

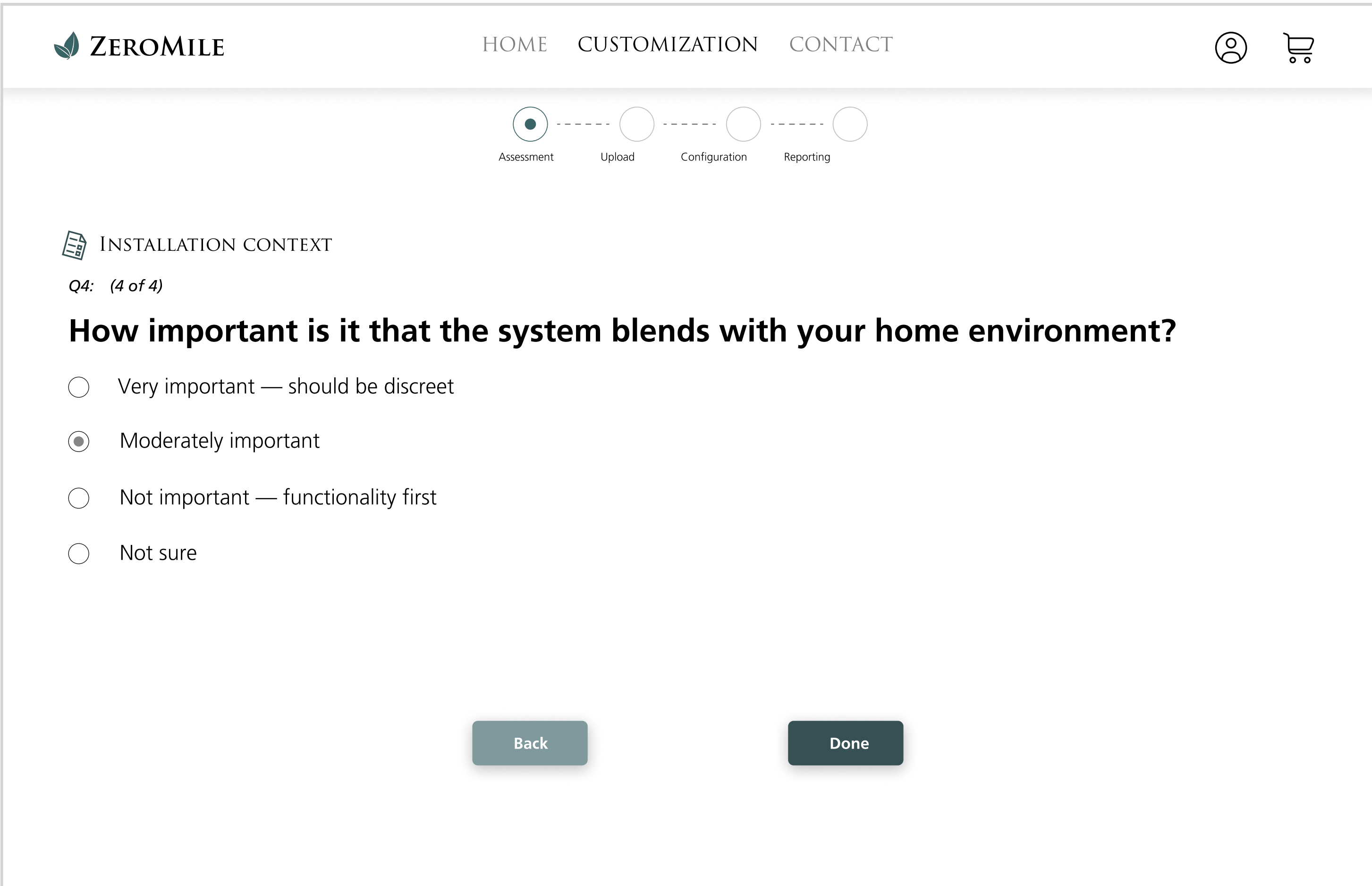

Figure 41. Configuration Interface: Assessment of Aesthetic Integration (Q4). (Author's own illustration)

Logical Framework of the Multi-Dimensional Assessment
The initial assessment phase is structured around four strategic inquiries designed to deconstruct the user's installation context and operational expectations. The logic behind these questions is to translate subjective user intent into a set of "soft constraints" that govern the modular configuration process.

1. Spatial Integration Strategy (Q1: Module Placement)
The first inquiry addresses the visual and functional presence of the system within the home. By asking whether modules should be "mostly hidden," "partially visible," or "fully integrated as part of the living environment," the system establishes the aesthetic boundary conditions. The logic here is to determine the required level of industrial design finish and the physical proximity between the core hydraulic modules (typically hidden) and the cultivation modules (typically visible).

2. Spatial Distribution and Flexibility (Q2: Layout Flexibility)
This question evaluates the architectural constraints of the user's home. The logic follows a scale of centralization versus distribution. If a user has "limited" flexibility, the system logic prioritizes a "Compact" configuration; conversely, "high" flexibility allows the algorithm to suggest "Spatially Distributed" schemes that utilize multiple areas of the home. This directly influences the length and complexity of the hydraulic routing required in the Simulator.

3. Operational Engagement (Q3: Maintenance Commitment)
The third question targets the long-term sustainability of the user-system relationship. By quantifying the user's comfort level with "simple maintenance tasks," the system adjusts the automation-to-manual-intervention ratio. Users preferring "minimal involvement" will be recommended configurations with higher-capacity buffer modules or more robust biofiltration processes to extend service intervals, whereas more engaged users can opt for more complex, high-interaction cultivation setups.

4. Aesthetic and Environmental Cohesion (Q4: Visual Blending)
The final inquiry serves as a priority filter for the final design output. By determining if the system should "blend discreetly" or prioritize "functionality first," the system assigns weights to different hardware options. This logic ensures that the generated report aligns with the user's psychological comfort within their living space, balancing the raw utility of a water-reuse system with the domestic requirements of interior design.

Detailed Functional Analysis of the Core Configuration Modules
Following the data acquisition phase, the system transitions into two technical modules that translate user inputs into a physical layout: the System Configuration Selection and the Interactive Simulator.

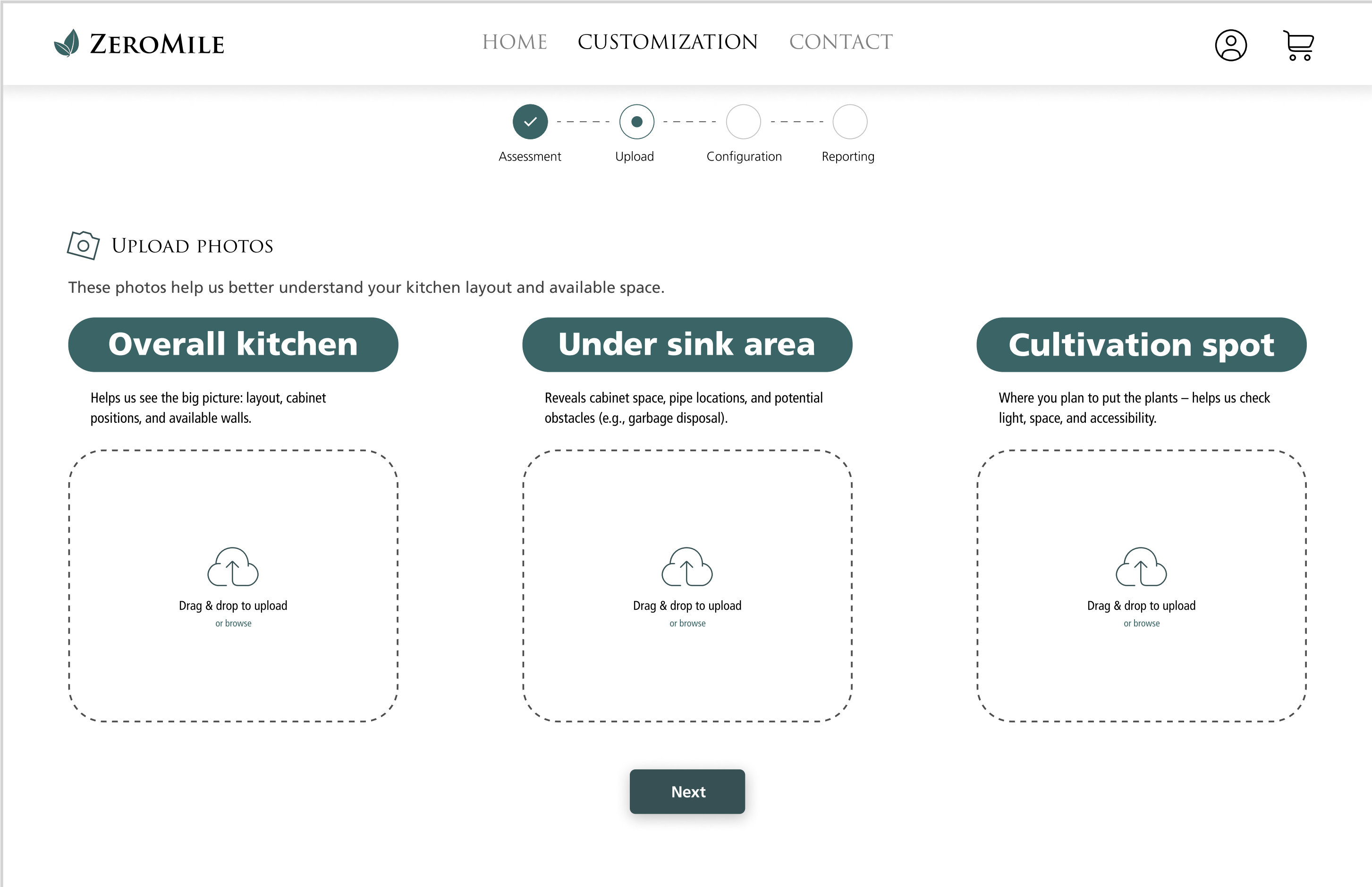

Figure 42. User environment data acquisition interface. (Author's own illustration)

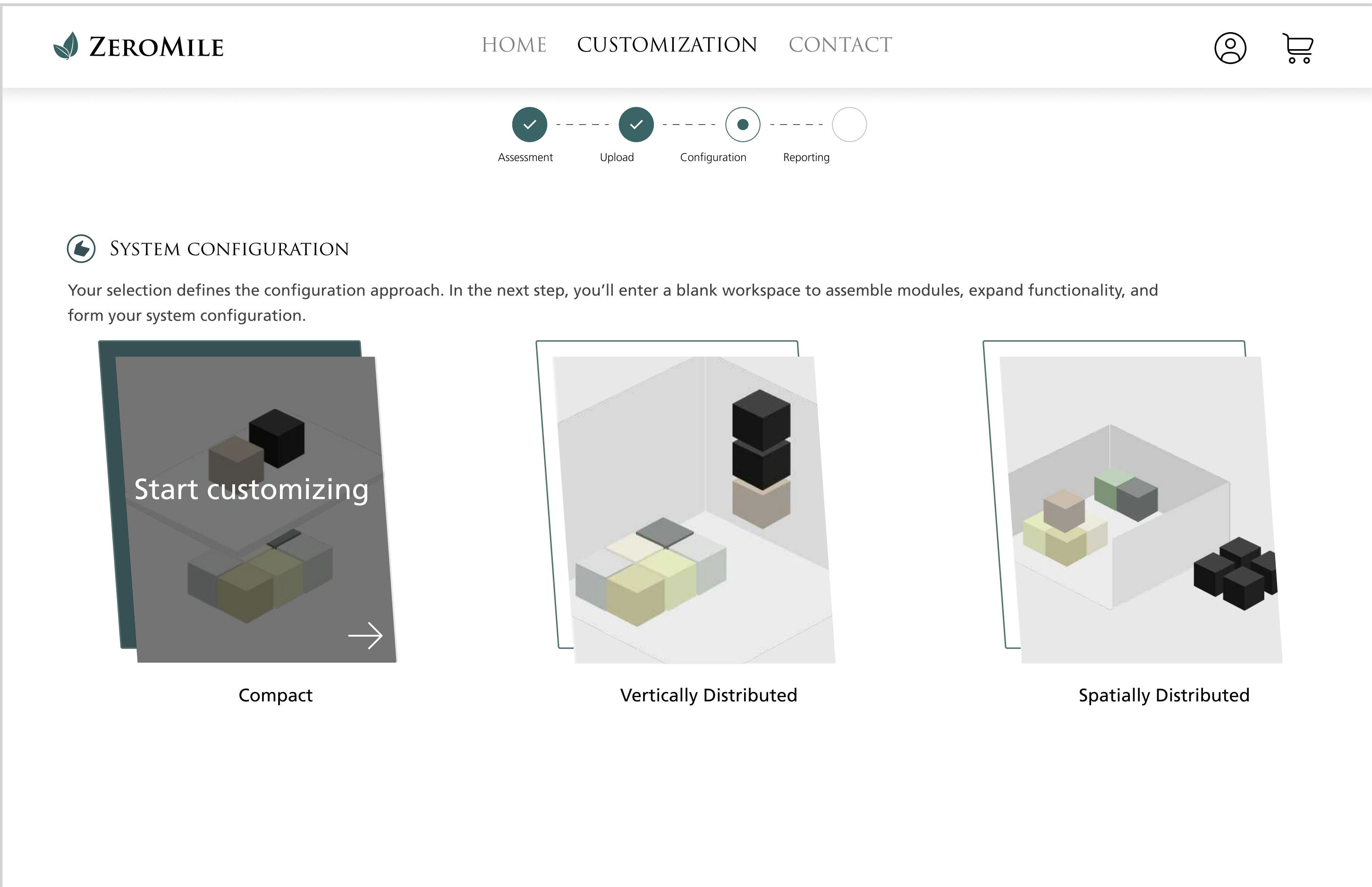

Figure 43. System configuration topology selection interface. (Author's own illustration)

The System Configuration Interface serves as a strategic filter, presenting three topological archetypes based on the user's spatial flexibility: Compact, Vertically Distributed, and Spatially Distributed. The Compact model is designed for high-density settings, clustering core hydraulic and filtration modules to minimize footprint. The Vertically Distributed approach utilizes vertical surfaces for tiered functionality, while the Spatially Distributed model allows modules to be decoupled across the home, such as separating filtration units from cultivation zones. This stage establishes the "structural DNA" of the system before the user enters the fine-grained customization phase.

The workflow culminates in the Interactive Simulator, a digital workspace composed of a Module Library and a dynamic Configuration Canvas. Users select standardized units—including Hydraulic Routing, Accumulation & Buffer, and Biofilter modules—and drag them into the canvas to construct a functional architecture. The simulator utilizes a backend logic to visualize connection paths and flow directions, ensuring technical coherence between units. Each module features a specification panel detailing its role, placement visibility (e.g., "hidden under-sink"), and interaction frequency. This environment empowers the user as a co-designer, providing a validated, site-specific blueprint that bridges the gap between digital planning and physical installation.

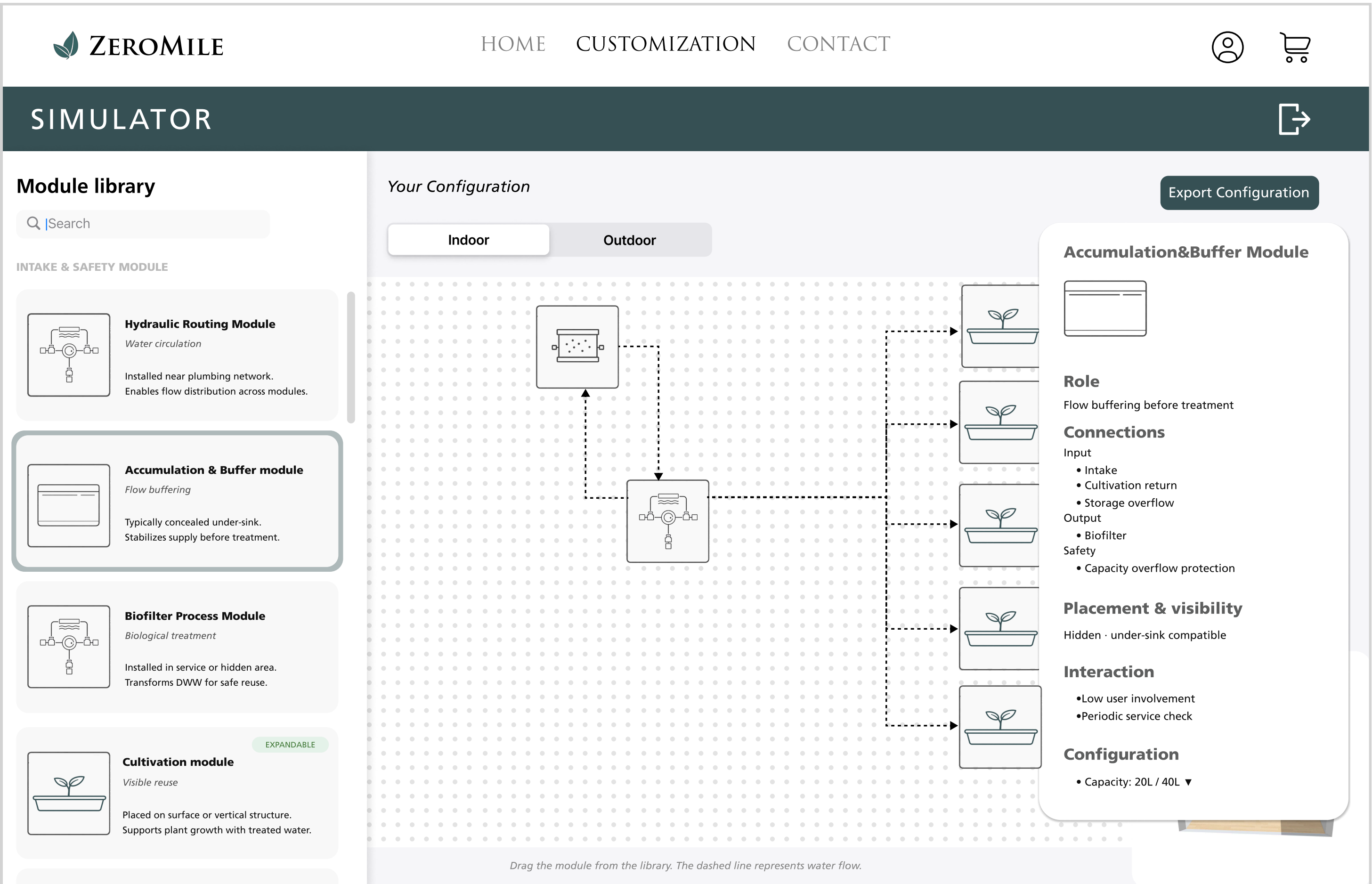

Figure 44. System logic topology and modular configuration simulation interface. (Author's own illustration)

System Logic Topology and Modular Configuration Simulation Interface
The simulation interface serves as a comprehensive design environment for mapping the functional logic and physical configuration of the water treatment and reuse system. It integrates a drag-and-drop module library with a dynamic canvas, allowing users to architect complex water-flow topologies tailored to specific spatial constraints (Indoor vs. Outdoor).

The interface is structured into three primary functional zones:

- Modular Component Library: Located on the left sidebar, this repository categorizes specialized hardware modules—such as Hydraulic Routing, Accumulation & Buffer, Biofilter Processing, and Cultivation modules. Each entry provides technical specifications regarding the module's role in water circulation and its recommended installation proximity (e.g., under-sink or plumbing network placement).

- Interactive Schematic Canvas: The central workspace utilizes a grid-based system for precise logical mapping. Users can visualize the systemic "topology" by connecting modules via dashed-line indicators that represent the directional flow of water. This allows for the simulation of the entire lifecycle of the fluid, from initial intake and buffering to biological treatment and final distribution to end-use cultivation units.

- Parameter Configuration & Technical Inspection: Upon selecting a module within the topology, a detailed contextual pane appears on the right. This feature enables "fine-tuning" of the system's operational parameters, including input/output routing, safety protocols (e.g., overflow protection), and physical capacity adjustments (e.g., 20L vs. 40L tanks).

By bridging the gap between abstract system logic and practical hardware selection, the simulator ensures that the proposed configuration is both hydraulically sound and compatible with the target environment's infrastructure.

System Summary and Configuration Reporting Interface
Following the simulation and modular selection process, the platform generates a comprehensive Review & Export interface, which serves as the final synthesis of the customized technical solution. This interface acts as a formal bridge between the user's design requirements and the physical implementation by the supplier.

The reporting interface is organized into three critical data clusters:

- Spatial and Behavioral Context: This section consolidates the environmental constraints established during the assessment phase. It highlights the intended placement (distributed across indoor/outdoor zones), the user's preference for minimal maintenance intervention, and the aesthetic priority for high visual integration. These qualitative parameters ensure the final system aligns with the user's lifestyle.

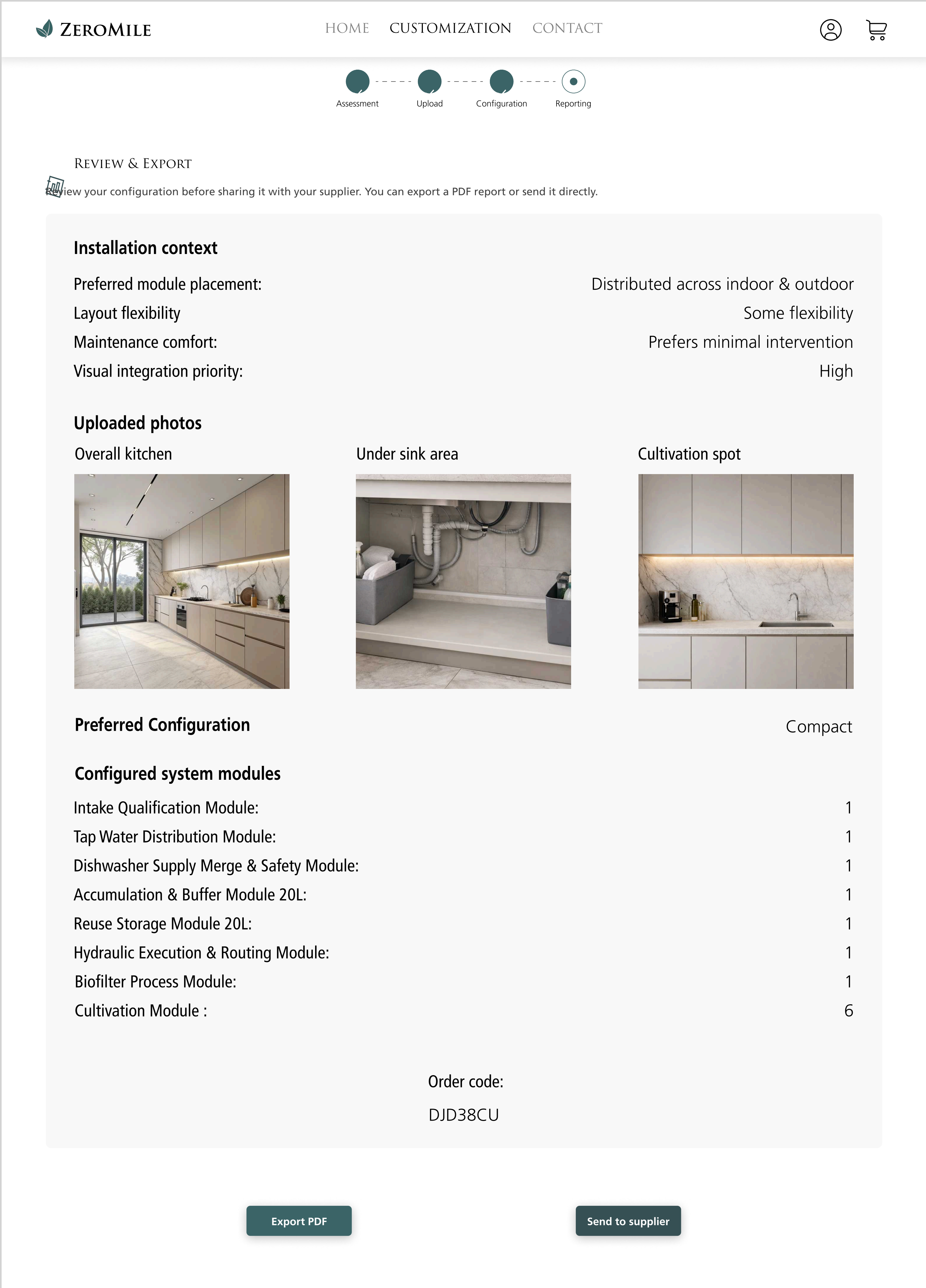

Figure 45. Customized system overview and configuration specification interface. (Author's own illustration)

- Visual Documentation and Site Verification: To facilitate accurate installation, the interface includes a verification gallery featuring uploaded site photos (e.g., overall kitchen layout, under-sink plumbing, and potential cultivation spots). This provides the supplier with the necessary spatial context to validate the feasibility of the proposed "Compact" configuration.

- Technical Bill of Quantities (BoQ) and System Serialization: The core of the report is a detailed inventory of the configured system modules. It lists the precise quantity and specification of each component—ranging from Intake Qualification and Biofilter Process modules to a specific count of Cultivation units. A unique Order Code (e.g., DJD38CU) is generated to serialize the configuration, ensuring data integrity during the export to PDF or direct transmission to the manufacturer for procurement.

Ultimately, this interface transforms a digital simulation into a standardized technical specification, facilitating a seamless transition from the conceptual modeling stage to the practical supply chain and installation phases.

Service Confirmation and Feedback Interface
Upon completion of the configuration and reporting stages, the system directs the user to the Final Confirmation Interface. This page serves as a formal acknowledgment of the successful data transmission and initiates the professional service workflow.

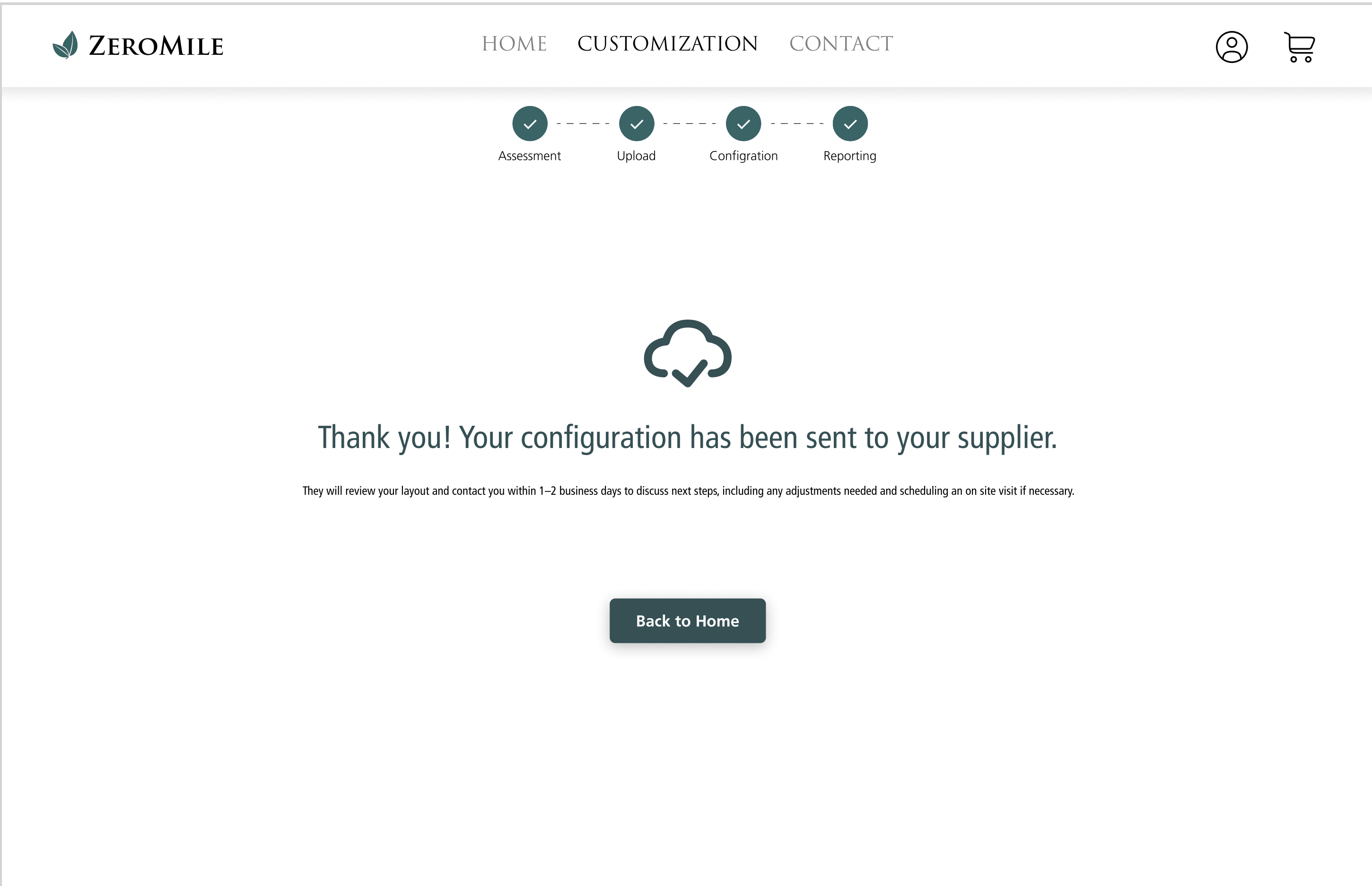

Figure 46. Service appointment confirmation and delivery feedback interface. (Author's own illustration)

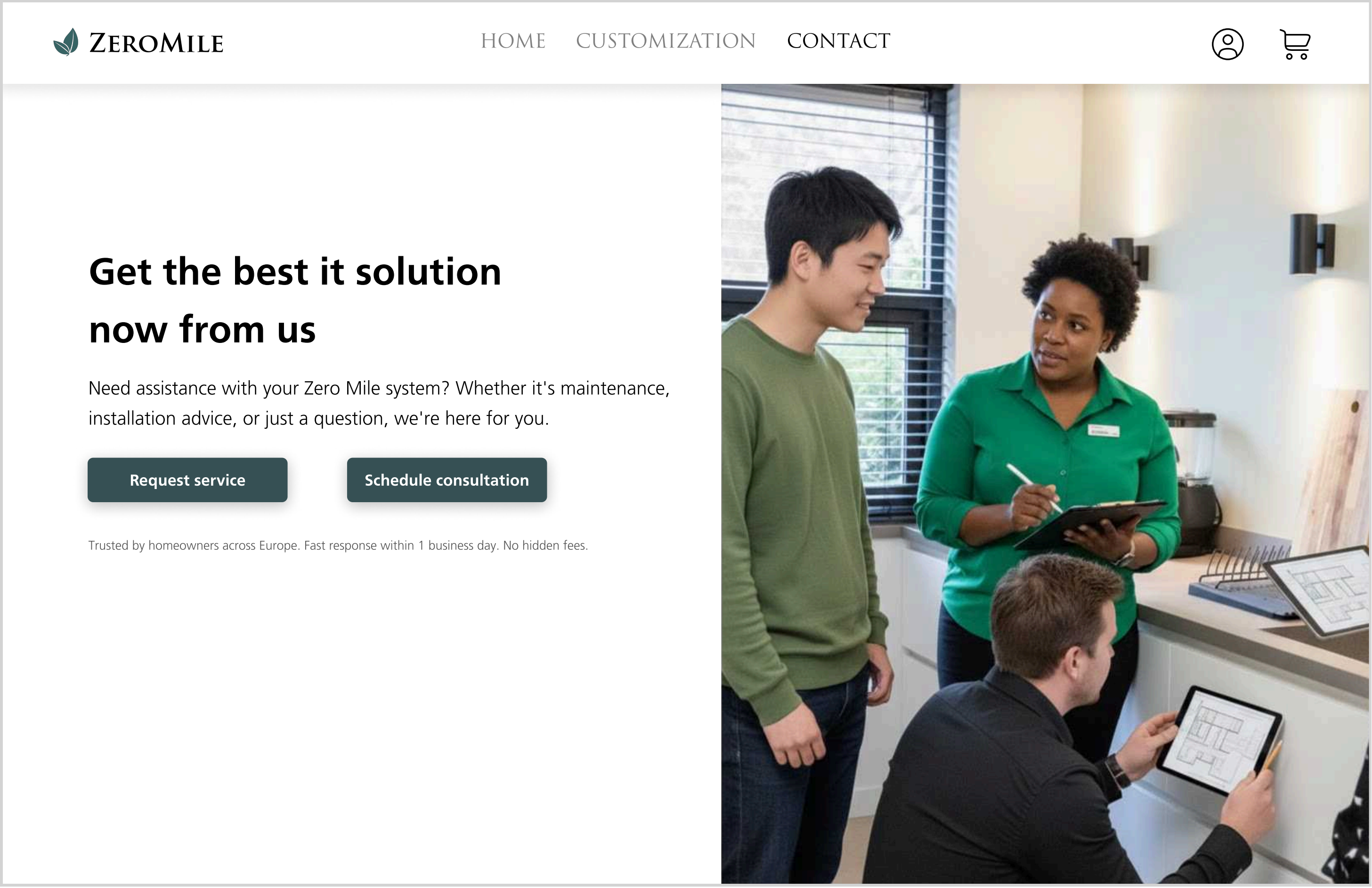

Figure 47. User support and service consultation guidance interface. (Author’s own illustration)

System service and consultation interface

The Zero Mile service portal employs a minimalist, user-centric interface designed to balance professional credibility with functional accessibility. The layout is strategically bifurcated into a textual informational zone and a contextual visual zone, ensuring that brand identity complements technical data.

A defining feature of this architecture is its Direct-Contact Configuration model. By prioritizing a "Schedule consultation" pathway over purely automated presets, the system facilitates a human-in-the-loop approach. This allows users to contact the expert team directly to initiate personalized system configurations, ensuring that maintenance and installation advice are precisely tailored to the client’s specific technical environment. This focus on bespoke IT solutions is further reinforced by integrated trust indicators, such as quantitative performance metrics and seamless navigation to "Customization" sections, which collectively validate the platform’s reliability and service depth.

Summary Conclusion for the System Overview

In summary, the web-based interactive system functions as a sophisticated digital-led, human-augmented mediator that translates subjective user intent into rigorous technical specifications.

By integrating a multi-dimensional assessment of human preferences with objective environmental data, the workflow moves beyond simple data entry to create a dynamic, feedback-driven interaction chain. The culmination of this process—supported by an online simulator for technical validation and a "Dual-Track Delivery Mode"—ensures that every design output is both computationally viable and spatially optimized. This integrated architectural nexus provides the essential logical scaffolding and data integrity necessary to sustain the stable, long-term operation of the entire system.

By integrating a multi-dimensional assessment of human preferences with objective environmental data, the workflow moves beyond simple data entry to create a dynamic, feedback-driven interaction chain. This architecture ensures that the "environmental sensing" and "requirement deconstruction" phases effectively resolve the inherent tension between automated efficiency and bespoke user customization.

5.4 Everyday Awareness Interface Design

The digital interface within this project functions as a sophisticated interpretive interaction layer. Rather than a mere control panel, its objective is to render "invisible" ecological processes into a legible human experience. By translating complex data into comprehensible system statuses, predictable maintenance rhythms, and actionable user tasks, the interface facilitates a long-term symbiotic relationship between the user and the system, prioritizing sustained coexistence over high-frequency manual intervention.

The interface logic is structured across a four-stage temporal workflow:

- Phase I: Data Integration and Initial Configuration. The journey begins with the seamless synchronization of pre-existing user data. The interface automatically imports and matches configuration parameters from the user's previous order, ensuring the digital twin accurately reflects the physical modules purchased and allowing for an efficient, data-driven onboarding process.

- Phase II: Operational Awareness and Everyday Monitoring. Once active, the system operates autonomously, recycling greywater to irrigate plant modules. During this phase, the Home page provides a low-cognitive-burden ecological summary, addressing fundamental concerns regarding system health and resource availability without requiring deep technical engagement.

- Phase III: Managed Intervention and Anxiety Reduction. When human agency is required, the Care Page partitions maintenance into "immediate" and "routine" tasks. By defining the boundaries between user actions and professional services, the interface provides step-by-step guidance that mitigates the maintenance uncertainty associated with domestic infrastructure.

- Phase IV: Perceptual Feedback and Credibility. The Garden and Water sections present the tangible outputs of the closed-loop cycle. By focusing on observable care activity and irrigation feedback rather than speculative harvest predictions, the system maintains high informational credibility and frames plants as perceptual indicators of infrastructural continuity.

This workflow is supported by a five-module architecture—Home, Care, Garden, Water, and Setting—that balances macroscopic oversight with microscopic technical control, ensuring a transparent and intuitive user experience.

Starting Page

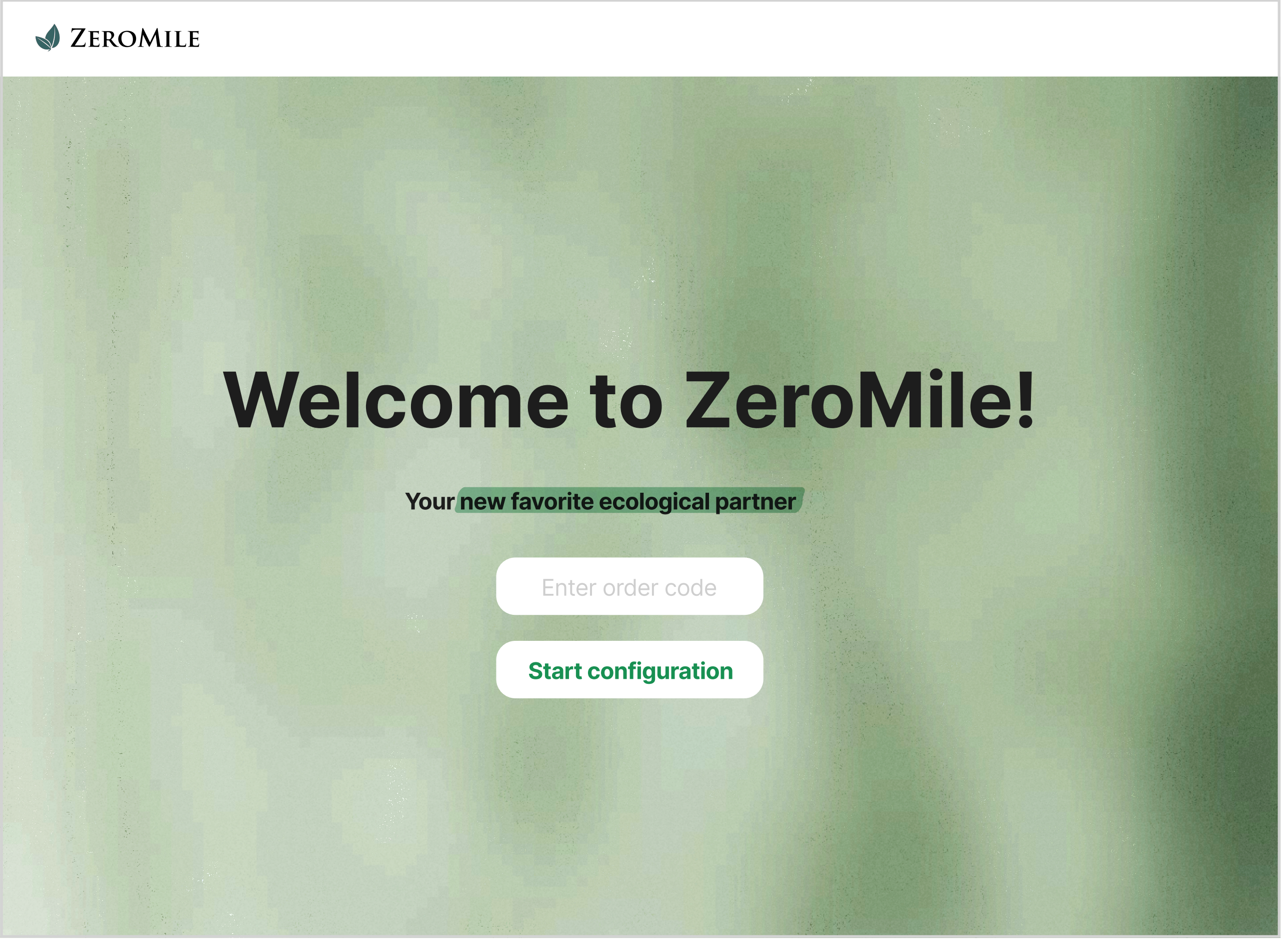

Figure 48. ZeroMile system home and configuration retrieval interface. (Author's own illustration)

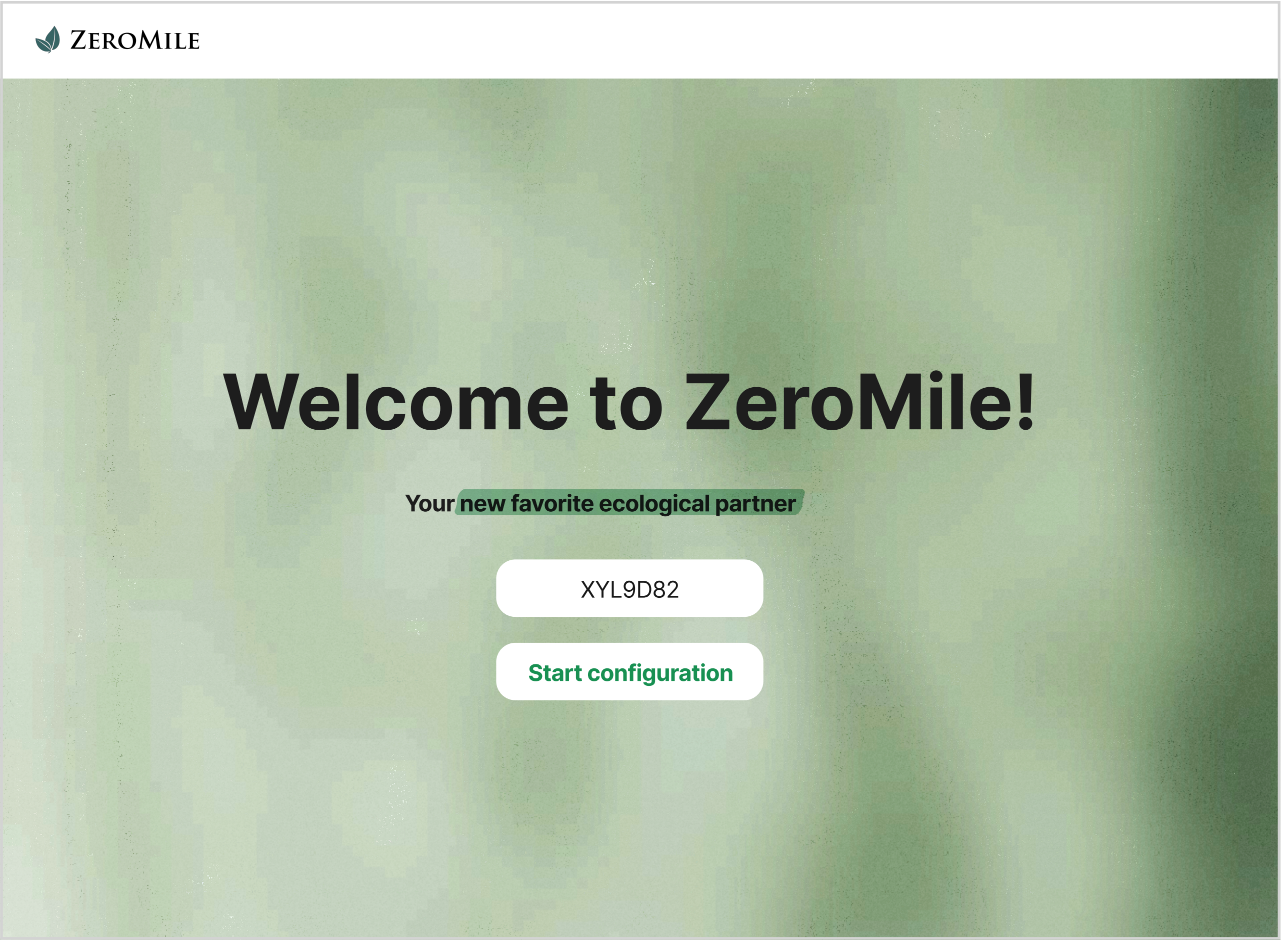

Figure 49. Automated system configuration initiation interface. (Author's own illustration)

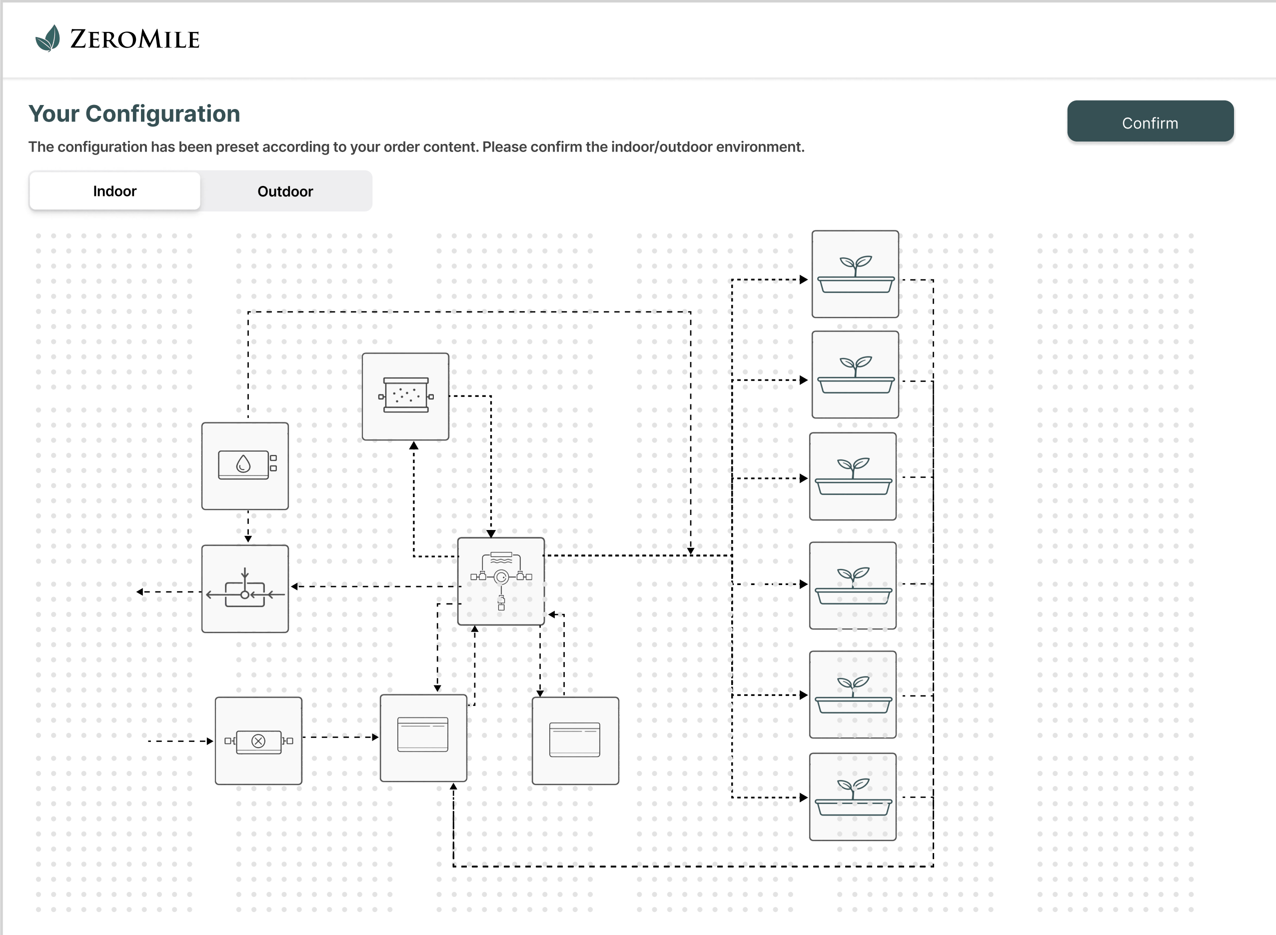

Figure 50. System configuration preset verification interface. (Author's own illustration)

The user journey within the Zero Mile digital ecosystem begins with a streamlined onboarding and data synchronization process. Upon the first login, users are directed to a minimalist "Welcome" portal designed to establish immediate brand affinity while minimizing cognitive friction. The core functional requirement at this stage is the entry of a unique Order Code, which serves as the primary key to link the physical purchase with its digital twin.

By inputting this code, the system executes an automated back-end retrieval of the user's predefined order specifications. This mechanism ensures that the digital interface is not initialized as a generic template but is instead precisely populated with the specific modular components and technical logic established during the previous customization phase.

Once the order information is successfully validated, the interface automatically transitions to the System Configuration Preset Verification page (Figure 50). At this junction, the user is presented with a schematic visualization of their modular layout, categorized by environmental context (Indoor/Outdoor). This stage is critical for maintaining data integrity; it allows the user to perform a final logical audit of the hardware arrangement before the system enters its active operational state. This transition from "order data" to "layout verification" provides the necessary logical scaffolding for a reliable and personalized system deployment.

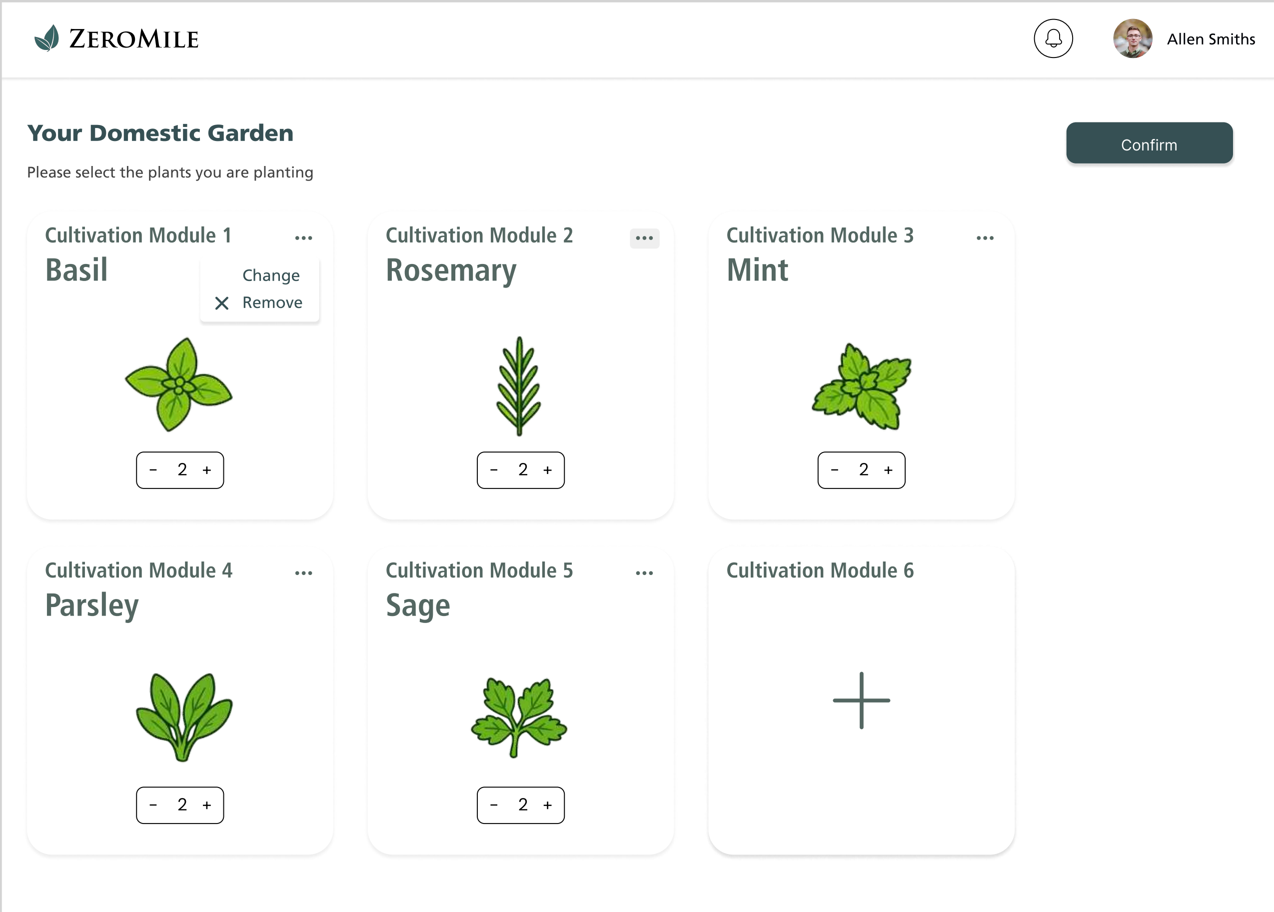

Figure 51. Overview interface of existing crop configurations. (Author's own illustration)

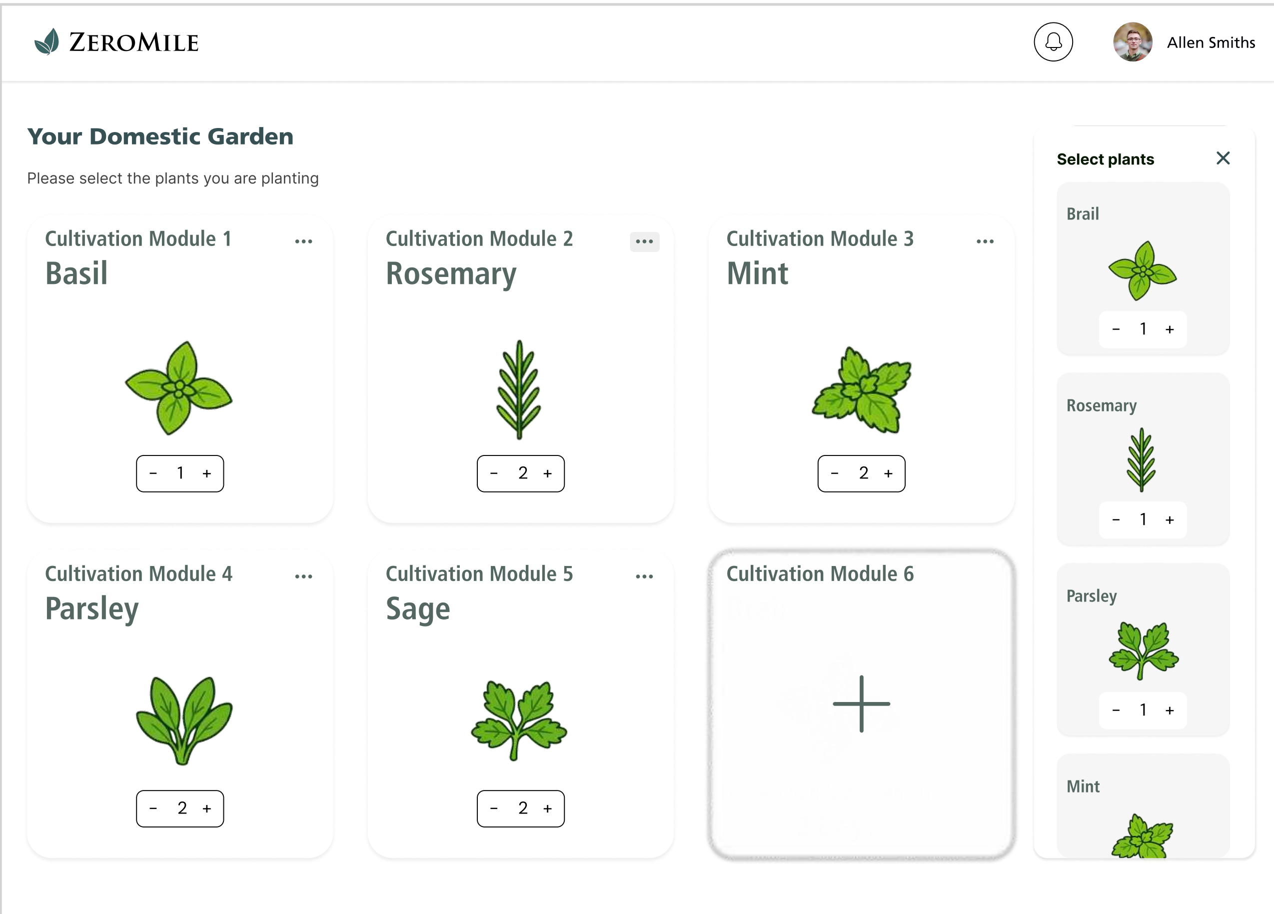

Figure 52. Interactive interface for modular crop selection and addition. (Author's own illustration)

Following the validation of the system's physical layout, the workflow transitions to the Crop Configuration and Irrigation Logic phase. This stage is designed to empower users to manually populate their "Domestic Garden" by mapping specific biological species to each previously verified cultivation module. This interactive process is crucial for calibrating the system's irrigation distribution logic, as plant selection influences allocation priorities without requiring biologically predictive modelling.

The interface provides a modular, grid-based overview where users can execute the following key actions:

Dynamic Crop Attribution: By clicking the addition icon within an empty cultivation module, users trigger a selection drawer that allows them to assign plant types such as Basil, Rosemary, or Mint —thereby establishing a visible biological identity for each hardware module.

Quantitative Irrigation Distribution: For each selected species, users can adjust the number of plants via a numerical stepper. This parameter primarily informs irrigation distribution proportionality across modules rather than prescribing plant-level watering frequency.

Flexible Modification and Optimization: To accommodate the evolving nature of home gardening, the interface supports real-time editing. Users can easily remove or modify their selections through a contextual menu, ensuring the digital plan remains agile and responsive to changing spatial constraints or personal preferences.

Upon clicking "Confirm," these user-defined parameters are integrated into the system's operational logic, completing the transition from a static modular arrangement to a functioning, bio-integrated ecosystem.

Home Page

Once crop configurations are finalized, the workflow transitions to the System Operation Monitoring and Management Dashboard. This "Home" page serves as the central hub for the interaction layer, translating real-time infrastructural signals into a legible ecological summary.

The dashboard is structured into several core functional modules:

- Hierarchical Status Indicators: A color-coded status card provides immediate feedback on aggregated system conditions. As shown in Figure 53&54, the interface uses a tiered visual language—"System Healthy" (green), "Maintenance Required" (orange), and "Service Required" (red)—to communicate the urgency of human intervention without exposing diagnostic complexity.

- Resource and Processing Progress: The "Treated Water Availability" module visualizes current recycled water levels, while the "Biofilter Snapshot" presents treatment progress and remaining cycle duration, allowing users to understand resource readiness and processing continuity.

- Biological Overview: The Cultivation Overview card presents the garden layout and plant distribution, enabling users to quickly understand module allocation and crop configuration.

- Daily Ecological Summary: A "Today Summary" list logs automated infrastructural events such as storage replenishment and filtration progression, reinforcing trust in the system's autonomous operation.

Through this synthesis, the Home interface supports informed stewardship by communicating infrastructural readiness, care rhythm, and resource circulation.

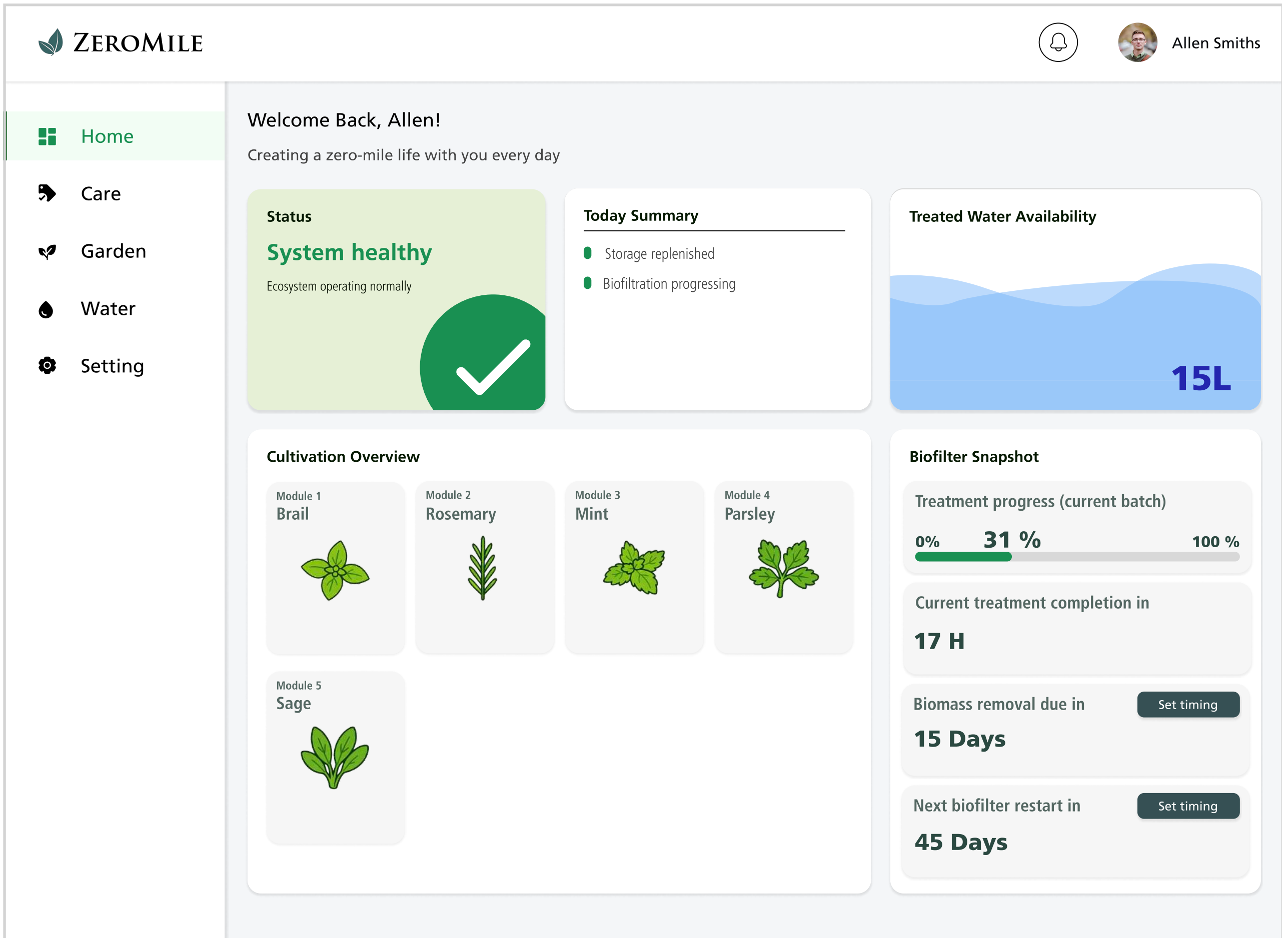

Figure 53. System operation monitoring and management dashboard. (Author's own illustration)

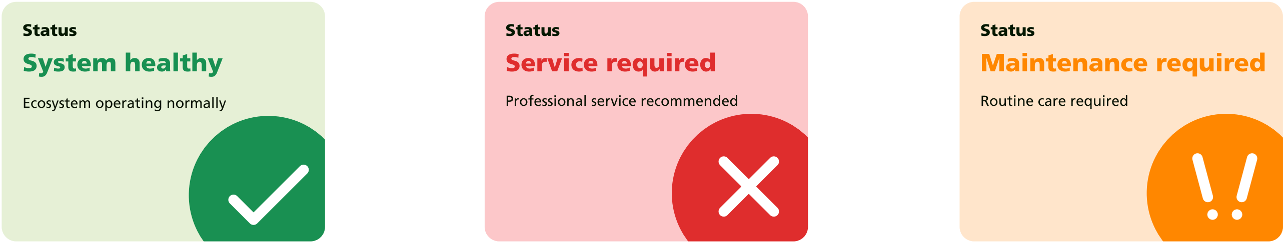

Figure 54. Hierarchical feedback interface of system operating status. (Author's own illustration)

The Treated Water Availability module (Figure 55) serves as a critical sensory interface, employing dynamic visual metaphors to communicate the real-time state of the system's water cycle. This section translates abstract resource data into intuitive spatial feedback through several design strategies:

- Fluid Visual Metaphor: The module utilizes a liquid-level illustration with a wave-like blue fill to provide a redundant representation of the numeric volume. This allows users to perceive the storage status via fill percentage, significantly reducing the cognitive effort required to interpret raw data.

- Multi-Tiered Threshold Alerts: The interface adapts its visual language based on resource scarcity. While the module maintains a calm blue tone during sufficient supply, it triggers a "Glow Effect" with red highlights when levels reach 0L. This is accompanied by explicit textual notification—"Tap water supplying irrigation"—indicating that the system has automatically switched to the municipal supply to ensure the survival of the botanical modules.

- Temporal Dimensions of Filtration: To complement the static volume data, the Biofilter Snapshot provides a temporal perspective on resource regeneration. By integrating a "Treatment Progress" bar with a quantitative countdown (e.g., "17 H"), the system transforms invisible biochemical processes into a predictable schedule for the user.

- Operational Transparency: This comprehensive monitoring approach establishes a clear causal link between "processing capacity" and "available resources". It reinforces the system's design philosophy of "low-frequency intervention" by assuring the user that the autonomous hydraulic engine is managing supply-demand fluctuations effectively.

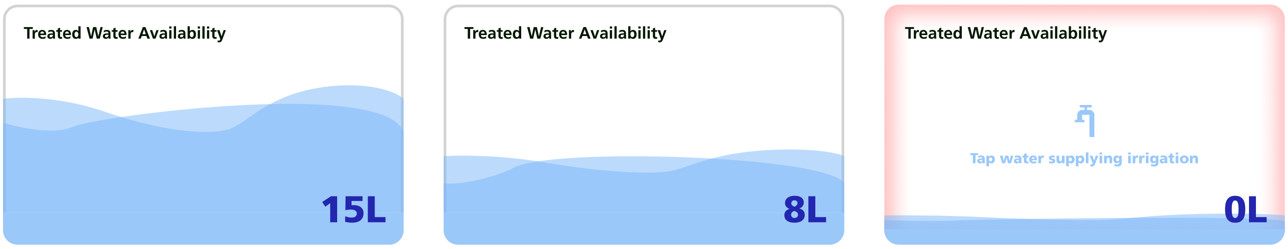

Figure 55. Monitoring interface for treated water availability (different liquid levels). (Author's own illustration)

To extend the system's accessibility beyond the desktop environment, a dedicated mobile application was developed to facilitate remote monitoring and real-time interaction (Figure 15). The mobile interface maintains strict visual and logical consistency with the web-based portal, ensuring a seamless cross-platform experience. However, the layout is optimized for vertical, one-handed operation, utilizing a modular card-based design that prioritizes "at-a-glance" information retrieval.

Key features of the mobile implementation include:

- Real-Time Push Notifications: Unlike the passive nature of the web interface, the mobile app serves as an active alert system. It delivers critical updates—such as "Maintenance Required" —directly to the user's device, ensuring timely intervention regardless of the user's physical location.

- Synchronized Data Ecosystem: All interactions performed on the mobile device, such as modifying crop quantities in the "Garden" module or acknowledging tasks in the "Care" section, are synchronized instantaneously with the central cloud database. This ensures that the system's digital twin remains accurate across all touchpoints.

Ultimately, the mobile interface functions as a portable "ecological remote," empowering users to maintain their stewardship of the greywater-to-irrigation cycle with maximum flexibility and minimal friction.

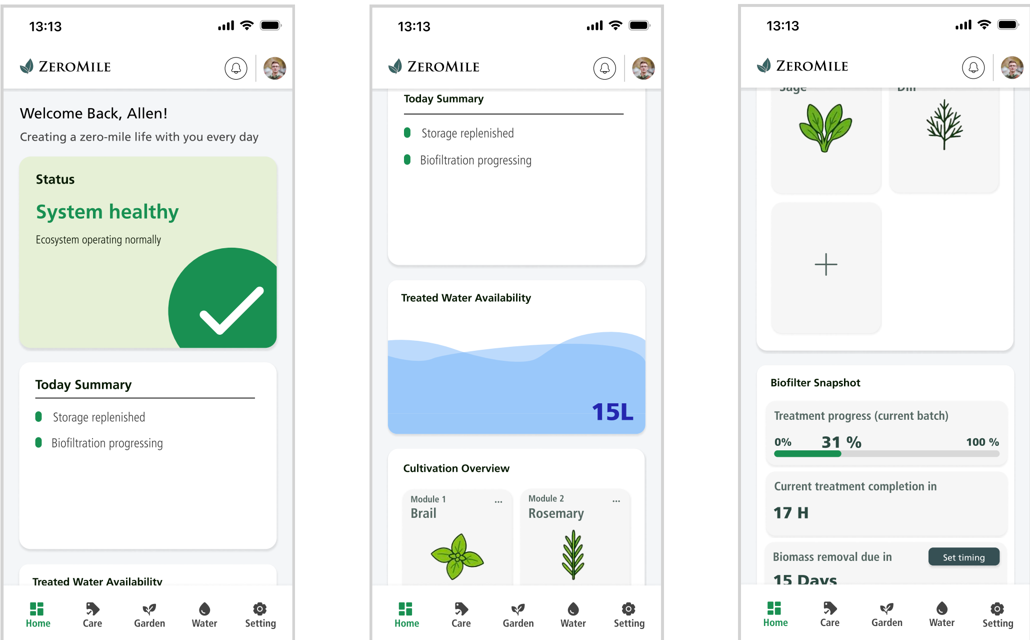

Figure 56. Mobile interface for system management and remote monitoring. (Author's own illustration)

Garden Page

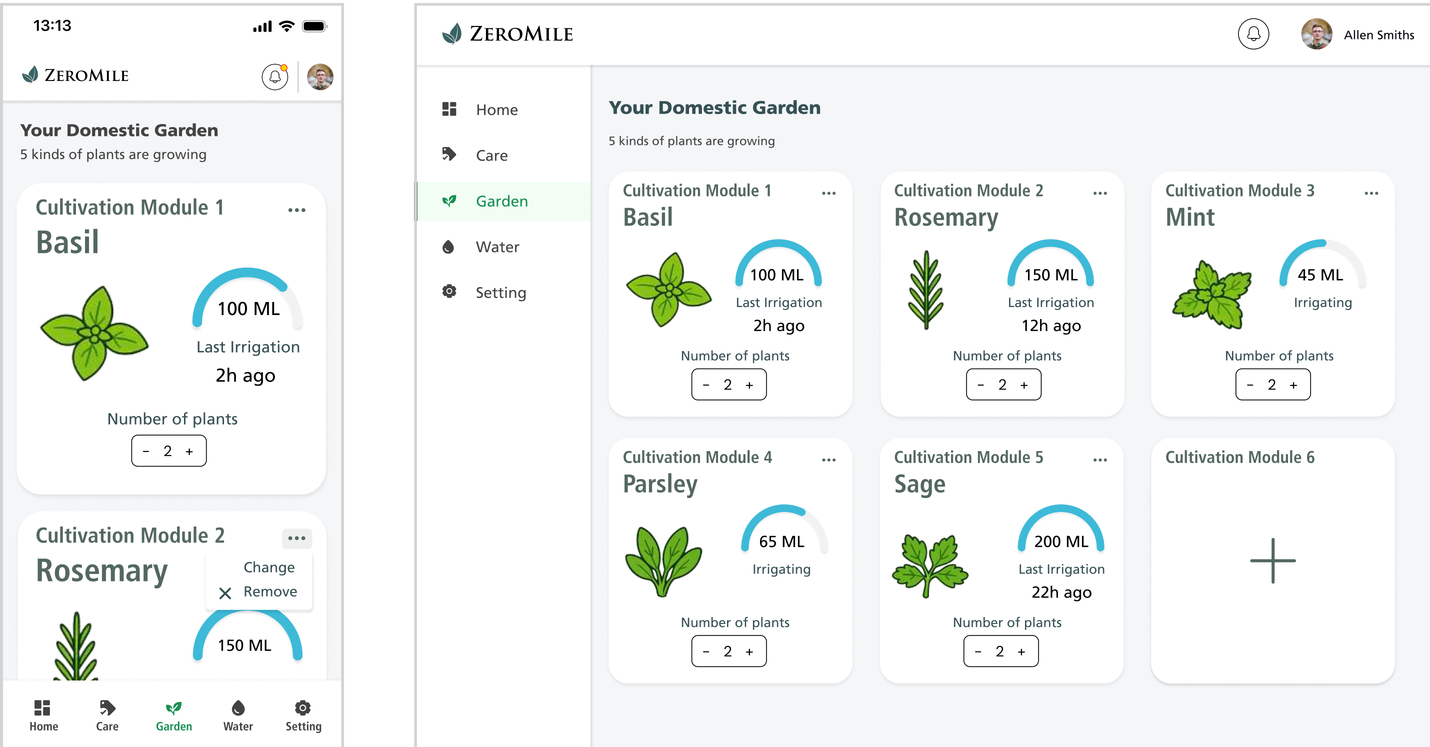

Figure 57. Multi-terminal crop growth monitoring and irrigation management interface. (Author's own illustration)

The system features a multi-terminal collaborative digital gardening management interface designed to lower the barrier to domestic farming through intuitive visualization. The interface supports responsive layouts across mobile and desktop environments, allowing users to monitor crop distribution and resource activity across various physical contexts.

The core functional architecture centers on modular cultivation monitoring cards. Each cultivation module acts as a localized information window presenting plant species, module identity, and specific irrigation data.

To enhance the transparency of the automated process, the irrigation feedback logic has been optimized through a combination of Dynamic and Historical Feedback:

- Real-time Feedback: When the system initiates an irrigation cycle based on biological demand, the interface provides immediate operational transparency. A flow animation on the semi-circular gauge, coupled with real-time incrementing volume data (e.g., "Irrigating... 85ml"), serves as direct evidence of the system's active intervention.

- Historical Reference: Once the irrigation task is complete, the interface records and displays the key metrics of the event. As suggested in the feedback, the interface now provides explicit references to time and quantity, such as "Last: 2h ago | 150ml." This ensures that non-expert users can intuitively verify the system's operational history.

In terms of interaction logic and data representation, the semi-circular gauge no longer represents a "daily goal" but functions as a Visual Status Indicator. It confirms the successful delivery of water for the most recent event, allowing users to perceive the care rhythm without the pressure of prescriptive, biologically specific watering schedules. By clarifying the details of the "Last Irrigation," the interface effectively bridges the gap between the slow metabolic cycles of the biofilter and the user's need for system assurance.

Water Page

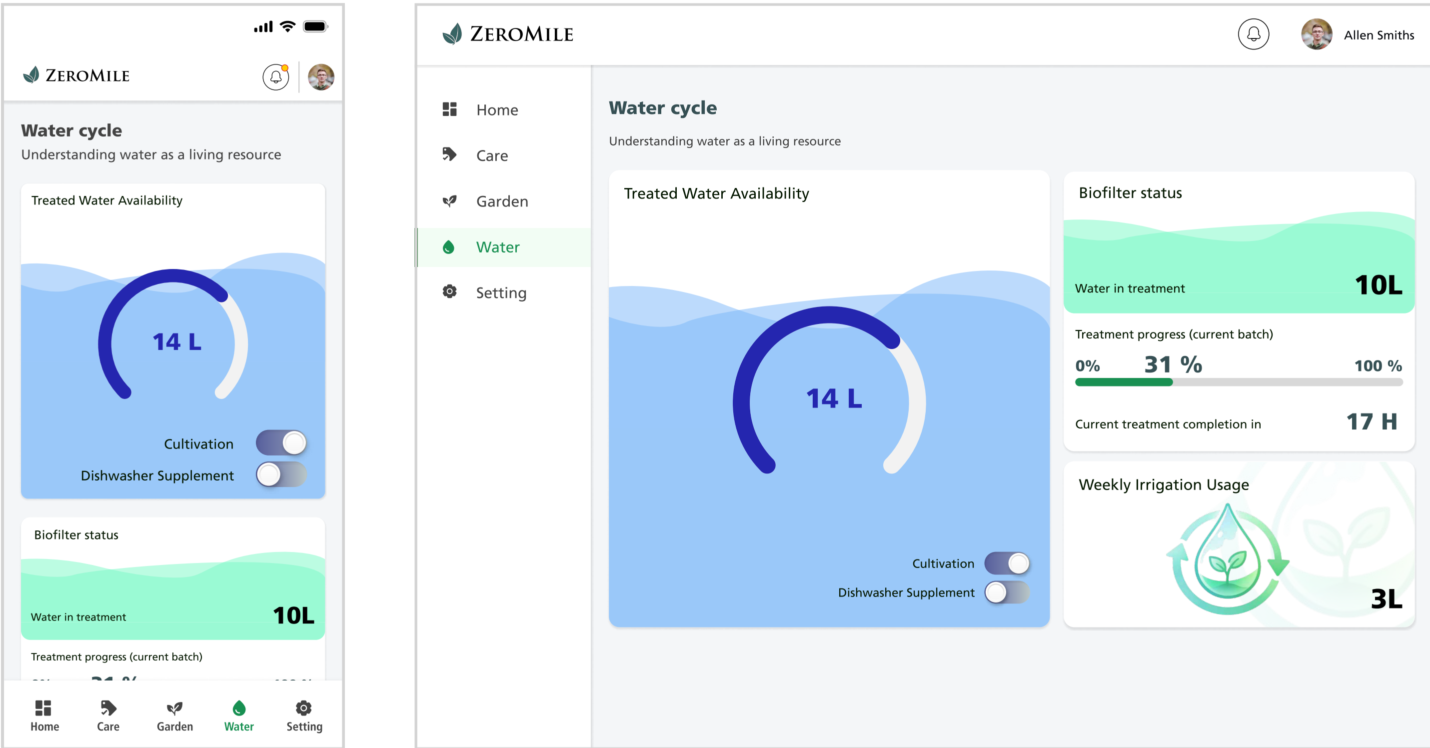

Figure 58. Multi-terminal water cycle monitoring and resource dispatch management interface. (Author's own illustration)

The ZEROMILE system implements a specialized Water Cycle Management Interface which serves as the central node for showing water reclamation and distribution. Under the design philosophy of "Understanding water as a living resource," the interface visualizes the complex transition from greywater to reusable irrigation water. This dashboard is split into distinct functional zones that allow users to track the quantitative availability of treated water while managing its dispatch to various domestic subsystems.

A primary feature of the Water Page is the Treated Water Availability card, which utilizes a dynamic wave-based visualization and a central circular gauge to indicate the current volume of ready-to-use water (e.g., 14 L). Below this indicator, the system introduces a resource dispatch toggle mechanism, enabling users to manually or automatically prioritize water allocation between "Cultivation" and "Dishwasher Supplement" modes. This high-level control ensures that reclaimed water is directed to the most critical domestic needs, promoting a circular economy within the household.

To maintain transparency in the filtration process, the interface includes a detailed Biofilter Status and Resource Usage tracking section. The "Biofilter Status" card provides real-time feedback on the current batch's treatment progress—quantified by volume (10 L), completion percentage (31%), and estimated time remaining (17 H).

Complementing this is the "Weekly Irrigation Usage" summary, which tracks the cumulative volume of reclaimed water successfully utilized over a seven-day period. This transition from a daily to a weekly temporal scale is a deliberate design choice to align the interface with the non-linear rhythms of botanical needs. By aggregating resource expenditure over a week, the system avoids the potential confusion of "zero-activity" days while providing users with a more substantial and encouraging reflection of their domestic water-saving impact. By integrating these metrics into a cohesive layout, the system empowers users to move beyond passive consumption, transforming them into active managers of a localized, sustainable water ecosystem.

5.5 Care and Setting Interface Design

The maintenance management interface encompasses a complete interaction logic ranging from desktop to mobile, aiming to provide users with an intuitive, real-time experience for system health monitoring and fault response. Through clear color coding and modular layouts, the design simplifies complex industrial or domestic water cycle maintenance tasks into easy-to-understand visual cards. Whether in a smooth-running "Healthy" state or a "Service Required" state, the interface utilizes a consistent visual language to guide users in quickly identifying the current operational focus, ensuring the long-term stable operation of the equipment.

In the desktop design, the system employs a split-pane layout where the left navigation bar provides quick access to various functions, while the core display area prioritizes tasks through two dimensions: Active Care and Routine Care. When the system is healthy, the interface uses a soft green as the primary tone, indicating that no active intervention is needed. In the event of a malfunction, the interface swiftly switches to a "Service Required" mode highlighted in alert red. At this stage, the card-based design demonstrates strong information capacity, using color-coded dot labels to distinguish fault severity and clearly marking modules as either "User-serviceable" or "Service-only." Furthermore, the routine care section on the right uses countdown timers to remind users of periodic tasks, such as biomass removal from biofilters or rinsing the reuse tank, significantly reducing the user's cognitive load.

The mobile interface design further optimizes operational efficiency for fragmented scenarios, retaining the core logic of the desktop version while adapting to a vertical orientation. Through card stacking, users can easily check the specific status of each module.

Clicking the "View Guide" button within a care task tagged with "user-serviceable" will take you to the corresponding detailed interface. The mobile interface emphasizes immediacy, with a prominent status title at the top and a red notification badge quickly attracting the user's attention. This not only enhances the system's technological feel but also builds a closed-loop service ecosystem from problem detection to resolution through detailed "View Guide" links and "Contact Supplier" buttons.

The "View Guide" of the system also utilizes a multi-terminal responsive interactive design, aimed at reducing the user’s cognitive load during complex maintenance tasks through intuitive visual guidance. The visual language remains highly consistent across mobile and web platforms, ensuring a seamless cross-device experience. At the top of the interface(Figure 62), the "Biomass Removal" task theme is prominently displayed, complemented by a progress indicator that deconstructs

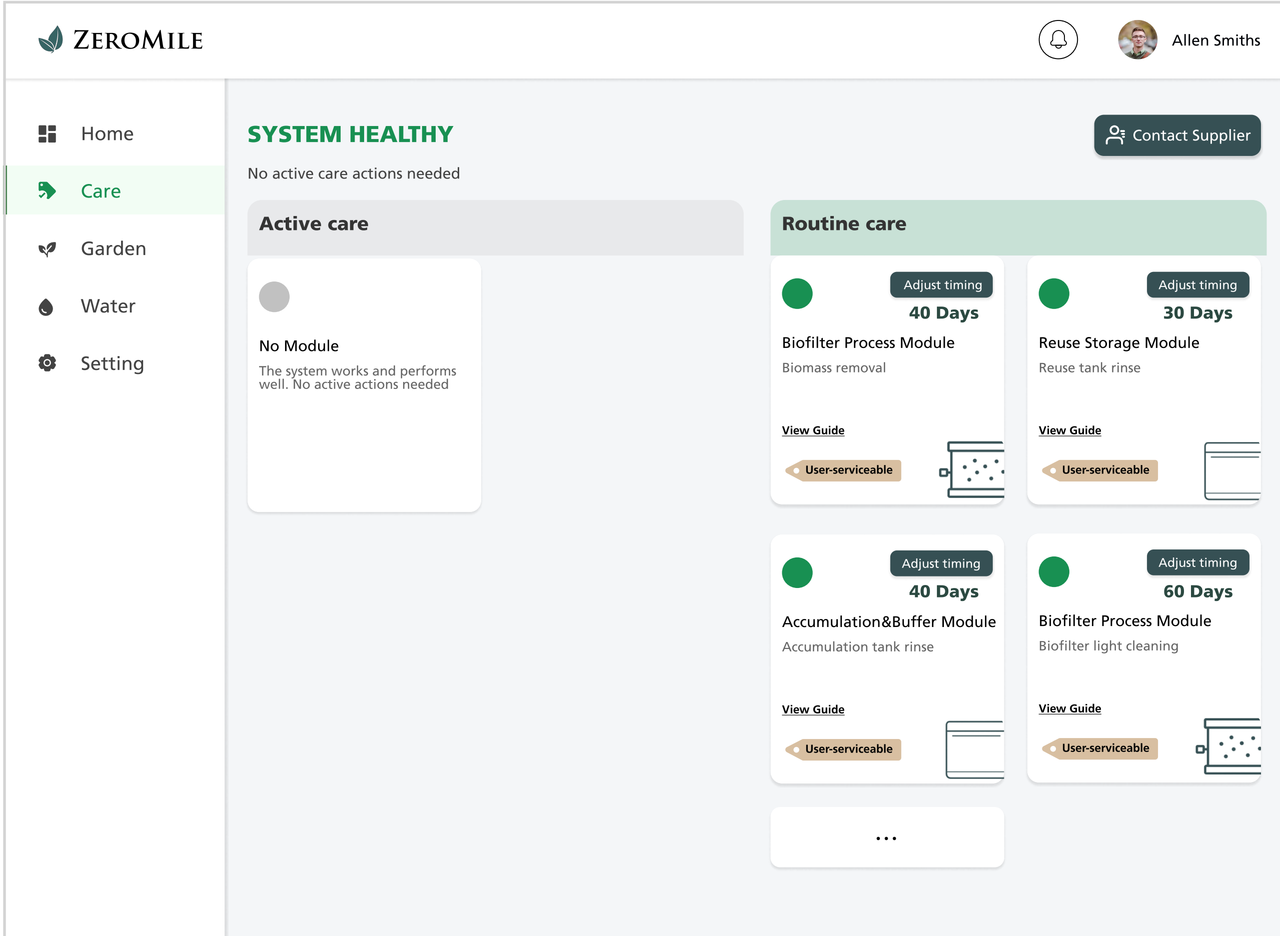

Figure 59. System maintenance management interface (Healthy status). (Author's own illustration)

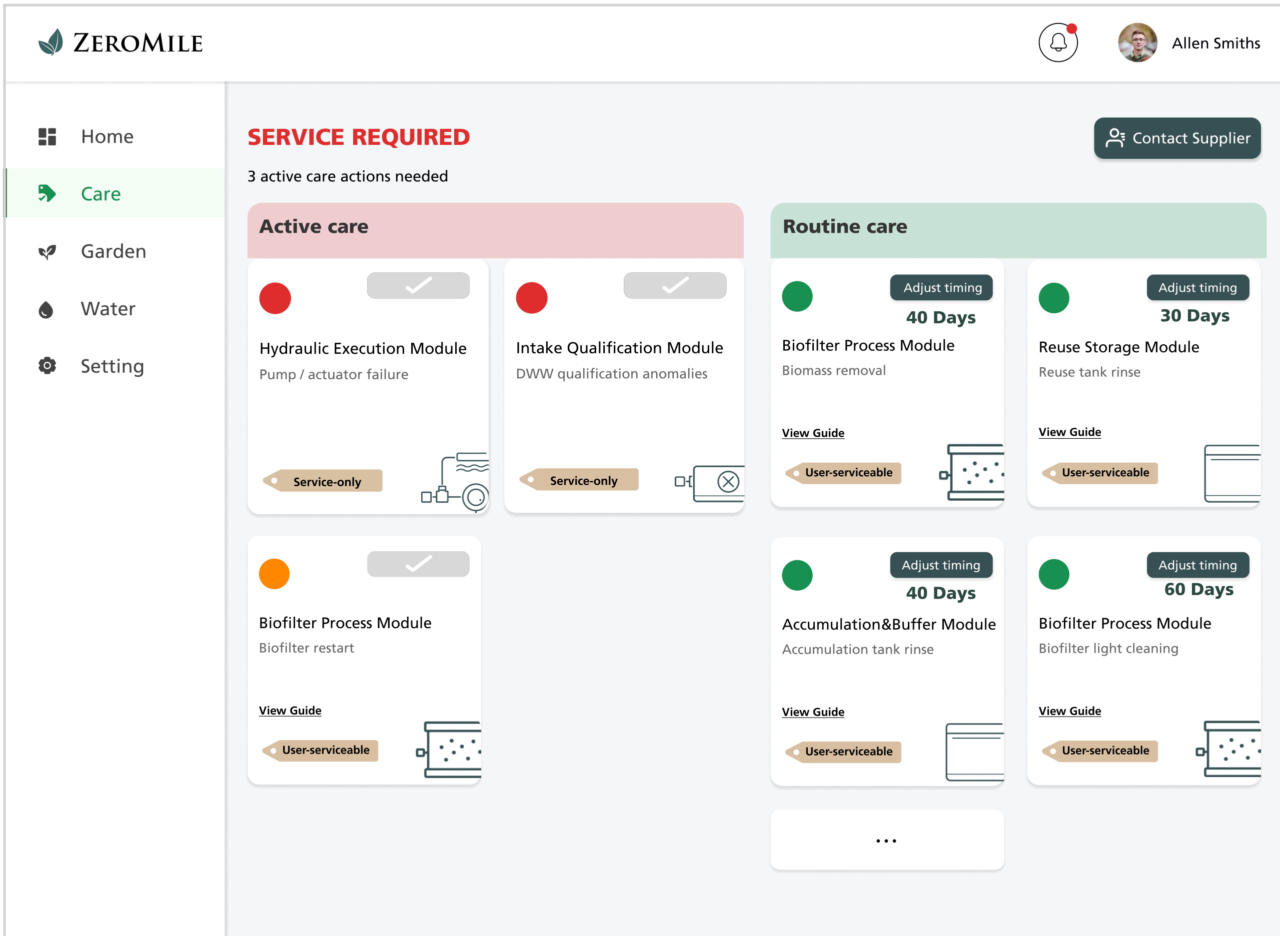

Figure 60. System maintenance management interface (Service required status). (Author's own illustration)

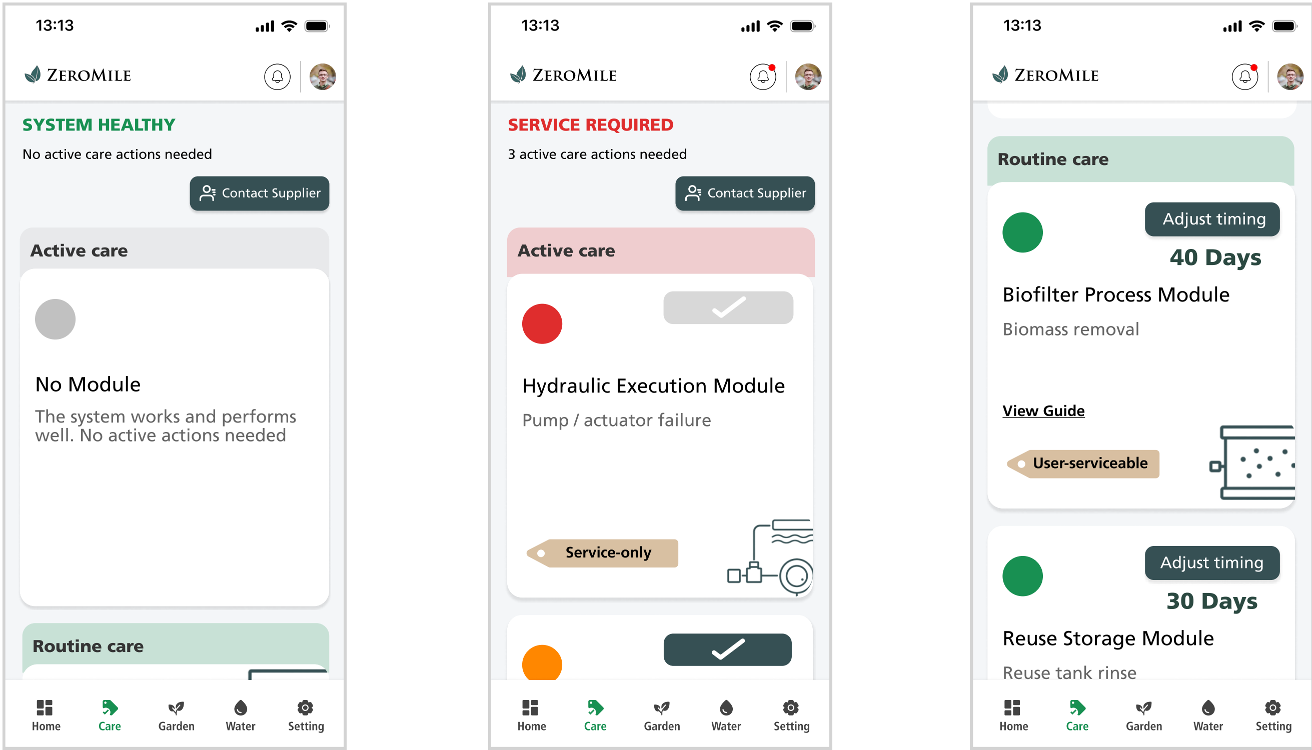

Figure 61. Mobile interface for system maintenance and real-time fault response. (Author's own illustration)

the cumbersome routine maintenance workflow into linear, manageable steps. This step-by-step guidance strategy effectively mitigates operational anxiety by providing immediate feedback and guiding the user to complete each maintenance phase systematically.

In terms of visual composition, the module prioritizes high-quality realistic imagery, transforming complex textual instructions into a "text-image complementary" pedagogical model. Taking the "Prepare a large dropper" step as an example, a large central image intuitively demonstrates the required tool and the correct way to hold it, significantly enhancing the efficiency of information transmission. The typography adopts a clear hierarchical structure, where bold action commands are paired with functional descriptions in a lighter font weight, ensuring users capture core operational points at a glance. Furthermore, the prominent "Next" button in the bottom right corner aligns with the user's natural visual scanning patterns, creating a fluid operational flow.

To strengthen the system's service support attributes, the "Care" interface integrates a conspicuous "Contact Supplier" entry point. This design considers unpredictable situations users might encounter during maintenance, establishing a fault-tolerance mechanism and a sense of security through a convenient help channel. In the web interface, the persistent left-hand navigation bar provides a global perspective, allowing users to jump quickly between modules like "Care," "Garden," and "Settings," while the operation area on the right maintains a minimalist whitespace aesthetic, keeping the user's focus entirely on the current care task.

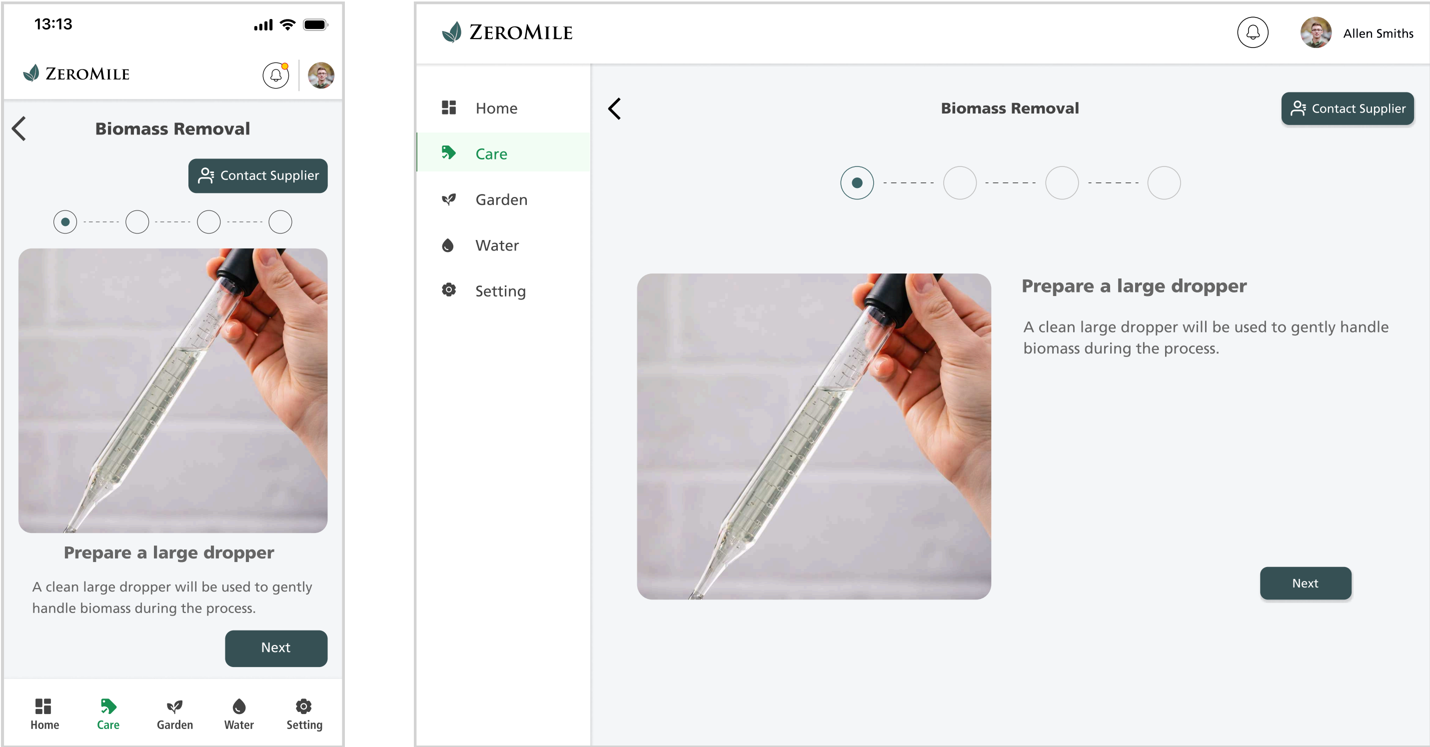

Figure 62. Multi-terminal interactive routine maintenance guidance interface. (Author's own illustration)

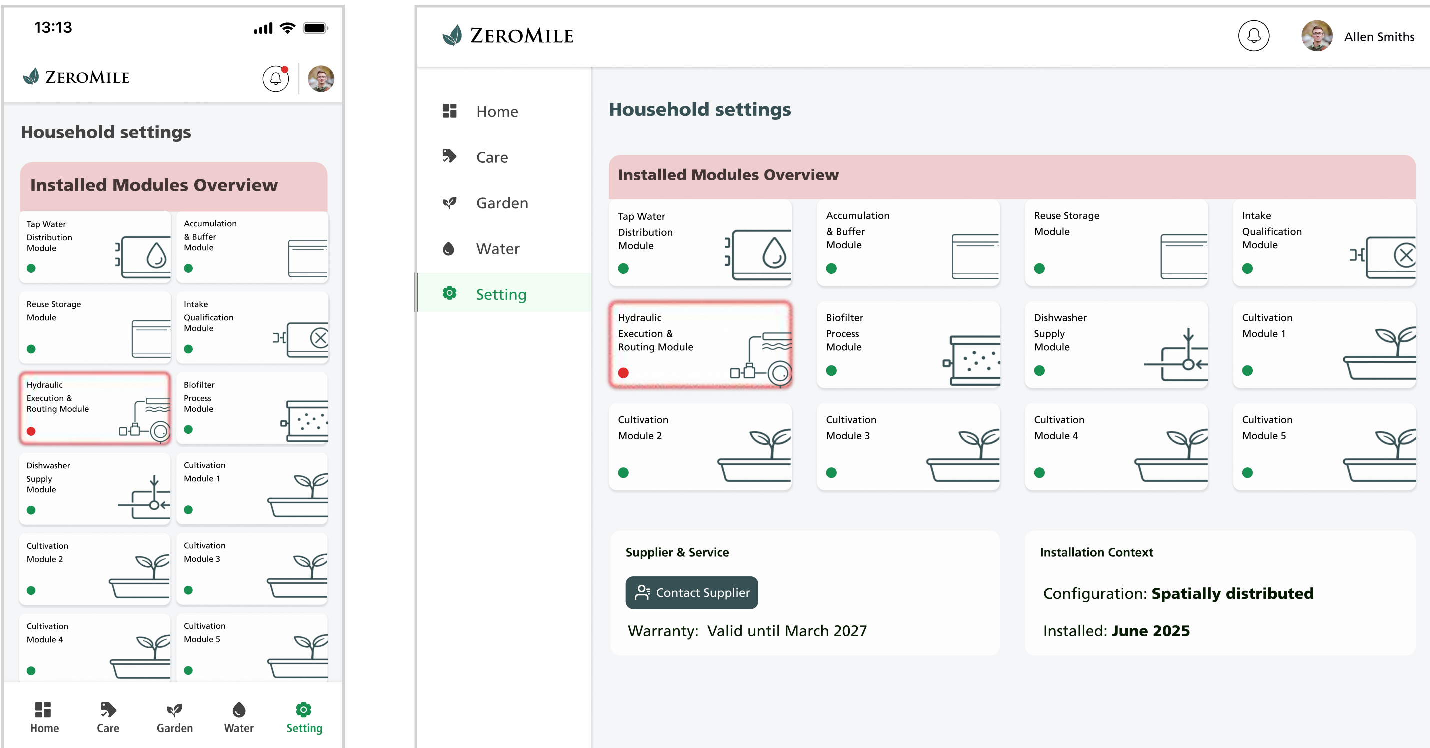

Figure 63. Multi-terminal system settings and installed modules overview interface. (Author's own illustration)

"Cultivation Modules" as discrete interactive cards. This modular visual language not only clearly defines the system's physical composition but also achieves instantaneous communication of diagnostic data through standardized status indicators. Green indicators signify normal operation, while red indicators (as seen in the "Hydraulic Execution & Routing Module") leverage visual contrast to alert users to potential anomalies, embodying an "exception-centered management" logic that significantly enhances troubleshooting efficiency.

In terms of Information Hierarchy, the interface balances macro-overviews with micro-details through multi-dimensional labeling. Beyond core module awareness, the lower section of the interface integrates "Supplier & Service" and "Installation Context," encompassing static lifecycle data such as warranty validity and installation dates. This integration of long-term maintenance records with ongoing operational context provides users with a comprehensive asset management perspective. Furthermore, the explicit labeling of the configuration mode (e.g., "Spatially distributed") helps users establish an accurate spatial mental model within a multi-device collaborative environment. Regarding multi-terminal adaptation, the system utilizes responsive scaling techniques: the mobile version adopts a compact two-column layout for vertical scanning, while the desktop version expands into a multi-column matrix, ensuring the legibility and clarity of module icons and technical schematics across all screen dimensions.

Chapter 6. Evaluation

6.1 Design and Objectives of the Questionnaire

To systematically evaluate the interfaces of the Domestic DWW Bio-filtration & Eco-System Interface, this study designed a structured questionnaire complemented by a brief semi-structured interview. The questionnaire was intended to capture both quantitative and qualitative user perceptions regarding usability, information clarity, interaction quality, and the shift in trust through visual transparency.

The questionnaire had three main objectives:

1. To identify baseline user expectations and pain points regarding wastewater recycling, maintenance burdens, and the transparency of traditional "black box" home appliances.

2. To evaluate the efficacy of the UI prototype in communicating complex biological processes, such as filtration progress, system health, and microbial-plant synergy.

3. To assess the emotional and cognitive impact of the interface, specifically whether it fosters a sense of "collaboration" with an eco-assistant rather than a mere interaction with a machine.

The questionnaire was divided into four distinct parts to track the user journey from initial intuition to post-interaction reflection:
Part I: Background & Experience

- Collected demographic data on professional backgrounds (Design, Engineering, Education, Sustainability) and prior experience with ecological design to contextualize the responses.

Part II: Pre-Test (Expectations & Pain Points)

- Focused on the user's psychological state before interacting with the UI. It measured willingness to recycle water, anxiety regarding "invisible" safety, and the perceived burden of maintaining complex eco-infrastructure.

Part III: Post-Test (UI/UX Experience Evaluation)
The core evaluative section, subdivided into three thematic clusters:

- Transparency & Trust: Assessing the "Home" and "Water" pages for clarity on purified water levels and the "temporal rhythm" of filtration.
- Predictability & Usability: Evaluating the "Care" and "Setting" pages, specifically the reduction of maintenance anxiety through task categorization and modular layouts.
- Ecological Perception & Coexistence: Testing the "Garden" page to see if the interface successfully shifted focus from "harvest prediction" to "growth status" and fostered a multi-species collaborative feeling.

Part IV: Open Feedback

- Gathered qualitative insights into specific visual elements that provided a sense of security, the distinction between this interface and traditional smart-home apps, and suggestions for improving visual hierarchy and interaction logic.

The study employed a mixed-methods approach to data collection. Quantitative measures (Q3–Q15) utilized a five-point Likert scale, ranging from “Strongly Disagree” (1) to “Strongly Agree” (5), allowing for a statistical analysis of user confidence and clarity. Qualitative measures (Q16–Q18) consisted of open-ended prompts, encouraging respondents to articulate nuanced feedback on the "eco-assistant" concept and aesthetic preferences.

To ensure comprehension and comparability among participants from diverse backgrounds, the questionnaire was provided in English and Italian. It was administered in two stages—immediately before and immediately after the digital prototype interaction—thereby capturing the "explanation layer's" impact on user trust and reliability.

User Testing: Domestic DWW Bio-filtration & Eco-System Interface

Questionnaire

Project Overview: This project introduces a Domestic DWW (Dishwasher Wastewater) Bio-filtration System that recycles wastewater for home irrigation. By using a digital interface as an "explanation layer," we aim to turn slow, invisible biological processes into clear, manageable data. Our goal is to replace the "black box" nature of traditional recycling with a transparent, trustworthy experience that fosters a seamless coexistence between users and their home ecosystem.

Panoramica del Progetto: Questo progetto presenta un sistema domestico di biofiltrazione DWW (acque grigie della lavastoviglie) che ricicla l'acqua di scarico per l'irrigazione domestica. Utilizzando un'interfaccia digitale come "livello esplicativo", miriamo a trasformare processi biologici lenti e invisibili in dati chiari e gestibili. Il nostro obiettivo è superare la natura di "scatola nera" del riciclo tradizionale, offrendo un'esperienza trasparente e affidabile che favorisca una coesistenza fluida tra l'utente e l'ecosistema domestico.

1. What is your background/profession? (Multiple choices allowed)
   Qual è il tuo ambito professionale o formativo? (Selezione multipla)

- ○ Design/Art / Design/Arte
- ○ Engineering/Tech / Ingegneria/Tecnologia
- ○ Sustainability / Sostenibilità
- ○ Education / Educazione
- ○ Other:_______ / Altro:_______

2. Do you have experience with sustainability or ecological design?
   Hai esperienza in sostenibilità o design ecologico?

- ○ Yes / Sì
- ○ No / No

II. Part One: Pre-Test (Expectations & Pain Points) II. Parte Prima: Pre-Test (Aspettative e Criticità)

Instruction: Please rate the following statements based on your intuition and daily experience before interacting with the UI prototype. Scale: 1-Strongly Disagree | 2-Disagree | 3-Neutral | 4-Agree | 5-Strongly Agree
Istruzioni: Valuta le seguenti affermazioni in base al tuo intuito e alla tua esperienza quotidiana prima di interagire con il prototipo dell'interfaccia utente (UI).
Scala: 1-Fortemente in disaccordo | 2-In disaccordo | 3-Neutrale | 4-D'accordo | 5-Fortemente d'accordo

3. I am willing to use wastewater recycling technology at home to save resources.
Sono disposto a utilizzare tecnologie di riciclo delle acque reflue in casa per risparmiare risorse.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

4. I would feel anxious about water safety if I couldn't see the filtration progress.
Mi sentirei ansioso per la sicurezza dell'acqua se non potessi vedere il progresso della filtrazione.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

5. I worry that complex eco-infrastructure would add a heavy maintenance burden.
Mi preoccupa che un'infrastruttura ecologica complessa possa comportare un pesante onere di manutenzione.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

6. I feel that current home appliances lack transparency regarding their internal states.
Sento che gli attuali elettrodomestici manchino di trasparenza riguardo ai loro stati interni.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

III. Part Two: Post-Test (UI/UX Experience Evaluation)
III. Parte Seconda: Post-Test (Valutazione dell'esperienza UI/UX)

Instruction: Please rate the following statements based on your experience after interacting with the UI prototype.
Scale: 1-Strongly Disagree | 2-Disagree | 3-Neutral | 4-Agree | 5-Strongly Agree
Istruzioni: Valuta le seguenti affermazioni in base alla tua esperienza dopo aver interagito con il prototipo dell'interfaccia utente (UI).
Scala: 1-Fortemente in disaccordo | 2-In disaccordo | 3-Neutrale | 4-D'accordo | 5-Fortemente d'accordo

1. Transparency & Trust (Home & Water Pages) 1. Trasparenza e Fiducia (Pagine Home e Acqua)

7. I can quickly identify the "available purified water" and "system health" from the Home page.
Riesco a identificare rapidamente l' "acqua depurata disponibile" e lo "stato di salute del sistema" dalla pagina Home.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

8. The visualization of "filtration progress" helps me understand the system's temporal rhythm.
La visualizzazione del "progresso di filtrazione" mi aiuta a comprendere il ritmo temporale del sistema.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

9. The information provided builds my confidence in using the recycled water for my plants.
Le informazioni fornite aumentano la mia fiducia nell'usare l'acqua riciclata per le mie piante.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

2. Predictability & Usability (Care & Setting Pages)
2. Prevedibilità e Usabilità (Pagine Manutenzione e Impostazioni)

10. Categorizing tasks into "Urgent" and "Routine" effectively reduces my maintenance anxiety.
La suddivisione dei compiti in "Urgenti" e "Di routine" riduce efficacemente la mia ansia da manutenzione.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

11. The step-by-step guidance in "View Detail" makes complex maintenance feel manageable.
La guida passo-passo nella sezione "Visualizza dettagli" rende gestibile anche la manutenzione più complessa.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

12. The modular layout (Setting) helps me understand how the system fits into my home space.
Il layout modulare (Impostazioni) mi aiuta a capire come il sistema si integra nello spazio della mia casa.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

3. Ecological Perception & Coexistence (Garden Page)
3. Percezione Ecologica e Coesistenza (Pagina Giardino)

13. Seeing the "irrigation completion" and plant status gives me a sense of accomplishment.
Vedere il "completamento dell'irrigazione" e lo stato delle piante mi dà un senso di realizzazione.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

14. Focusing on "growth status" rather than "harvest prediction" feels more authentic and reliable.
Concentrarsi sullo "stato di crescita" piuttosto che sulla "previsione del raccolto" trasmette un senso di maggiore autenticità e affidabilità.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

15. The interface makes me feel like I am collaborating with an "eco-assistant" rather than a machine.
L'interfaccia mi fa sentire come se stessi collaborando con un "assistente ecologico" piuttosto che con una macchina.

Strongly Disagree Fortemente d'accordo	○ 1	○ 2	○ 3	○ 4	○ 5	Strongly Agree Fortemente d'accordo

IV. Part Three: Open Feedback IV. Parte Terza: Feedback Aperto

16. Which specific feature or visual element helped you feel the most "in control" or "secure" about the system?
Quale funzionalità specifica o elemento visivo ti ha aiutato a sentirti maggiormente "in controllo" o "sicuro" riguardo al sistema?

17. How does this interface feel different from traditional smart home or appliance apps?
In che modo questa interfaccia ti sembra diversa dalle tradizionali app per la smart home o per gli elettrodomestici?

18. Do you have any suggestions for improving the visual hierarchy, colors, or interaction logic?
Hai dei suggerimenti per migliorare la gerarchia visiva, i colori o la logica di interazione?

6.2 User Testing and Feedback Collection

This study involved ten participants in the evaluation of the Domestic DWW Bio-filtration and Eco-System Interface. Participants represented diverse disciplinary backgrounds, including design, management, biology, and non-technical fields, enabling perspectives beyond sustainability-specialized users.

To ensure a structured assessment of the interpretive layer, the evaluation adopted a Task-based Cognitive Walkthrough procedure, moving beyond a simple demonstration to observe how users navigated the system's logic independently. The session was divided into three stages:

1. Contextual Briefing: Participants were introduced to the concept of domestic DWW recycling and the role of the interface in making invisible bio-filtration processes perceptible.

2. Scenario-based Tasks: Instead of a generic exploration, participants were asked to complete three predefined navigation paths that represent the core pillars of the "Translation Funnel":

Task ID	User Goal	Predefined Navigation Path	Evaluative Criteria
Task 1	System-wide perception and transparency monitoring: Verify the treatment progress and total resources.	Home Page → Water Page → Biofilter Card	Legibility
Task 2	Fault Response and Maintenance Guidance: Identify system anomalies and obtain specific maintenance operation instructions.	Home Page(Alert) → Care Page → View Guide	Maintenance
Task 3	Dynamic monitoring and resource confirmation: Identify the irrigation status different Cultivation modules.	Home Page → Garden Page → Plant Cards	Configurability

Table 9. User Evaluation Task Design(Author's own table).

3. Reflective Feedback: After completing these tasks, participants provided feedback through Likert-scale evaluations and open-ended discussions, focusing on where the navigation path felt intuitive or where "interpretive friction" occurred.

This structured approach allows the screenshots presented in this chapter to serve as specific evidence of user interaction points, rather than mere illustrative examples.

Following the task-based cognitive walkthroughs, participants completed a structured questionnaire to quantify their perception of the system across the three thematic clusters defined in the research objectives: Transparency & Trust, Predictability & Usability, and Ecological Perception. The resulting data, summarized in Table 10, provides a statistical baseline to verify the efficacy of the "explanation layer" in mediating complex biological processes. The following analysis examines these metrics to identify key trends in how specific interface elements contributed to user confidence and system intelligibility.

Question	Mean	Max	Min
Q3	3.7	5	2
Q4	4.7	5	4
Q5	4.3	5	3
Q6	3.5	5	2
Q7	4.8	5	4
Q8	4.8	5	4
Q9	4.2	5	3
Q10	4.3	5	3
Q11	4.6	5	4
Q12	4.1	5	3
Q13	4.4	5	3
Q14	4.2	5	4
Q15	4.2	5	3

Table 10. User Ratings across Interface Dimensions (Mean, Max, Min) (Author's own table).

Pre-test responses indicated a pronounced concern regarding water safety when filtration processes remained invisible (M = 4.7). This confirms that uncertainty surrounding recycled water quality represents a primary psychological barrier to domestic adoption. Interestingly, perceptions of general appliance opacity were comparatively moderate (M = 3.5), suggesting that anxiety is not driven by technological unfamiliarity alone but is specifically associated with water-related risk perception. This distinction reinforces the relevance of transparency as a targeted design intervention rather than a purely informational feature.

Post-test transparency measures achieved the highest mean values across the questionnaire. The ability to identify system status and available purified water (M = 4.8), combined with the visualization of filtration progress (M = 4.8), indicates that the interface effectively translated invisible biological processes into interpretable states. These findings suggest that perceived safety in ecological infrastructure is strongly mediated by process visibility and temporal feedback.

Maintenance-related expectations displayed a significant contrast. Participants initially anticipated a heavy maintenance burden (M = 4.3), reflecting the perceived complexity often associated with ecological technologies. However, post-test usability measures demonstrated that structured task categorization (M = 4.3) and step-by-step guidance (M = 4.6) significantly improved perceived manageability. This discrepancy highlights a critical experiential shift: perceived complexity can be mitigated not by reducing system functionality, but by enhancing procedural clarity and predictability.

Ecological perception measures remained consistently positive, with mean values ranging between 4.2 and 4.4. Visualization of irrigation completion and plant growth fostered feelings of accomplishment and ecological participation, while the perception of interacting with an "eco-assistant" suggests emerging relational engagement. Nevertheless, these values were slightly lower than transparency scores, indicating that emotional and ecological connections may develop more gradually than cognitive trust.

Taken together, the mean analysis demonstrates that the interface's primary impact lies in transforming uncertainty into interpretable feedback, thereby reducing perceived risk and facilitating trust. Usability and ecological engagement follow closely, though they appear influenced by prior expectations and likely require longer-term interaction to fully stabilize.

Question	Q16-Perceived Control & Safety	Q17-Experiential Positioning	Q18-Design Improvement Directions
User 1	posso sapere chiaramente controllata per cosa viene usertor l'acqua reflua	il ontenuto è più deteagrato· pensando di più alla vita reale di un famiglie	No , basta cosi , è spiegato tutto nei dettagli.
User 2	The visual data of each part. I can see how every thing is going on directly. The icons can help me recognize what each part is for.	The biggest one is that modular it is. With the visualization. I can understand what's the data for easily.	I wish the visual difference among modules could be more obvious. Like use different color theme in different part.
User 3	Transforming invisible biological processes data effectively removed the "black box" anxiety,	It feels like collaborating with a eco-assistant" rather than just operating a machine.	Implement haptic feedback when the subtle micro-interactions a "Routine" task is completed to strengthen sense of "collaboration" with eco-assistant.
User 4	The Home screen directly tells me the system status, which is intuitive and clear.	Fewer features but less verbose	In terms of interaction, I hope to have more interesting animations to showcase changes.
User 5	Tell me directly where the problem is and what I should do.	It doesn't have many extra features or information, and it's very simple and easy to understand.	It's good as long as it looks clean. From an interactive perspective, it would be better to offer more signal options instead of just these few
User 6	system status / Care page	clear/direct/simple	Visual hierarchy: No colors: No Interaction logic: add some control button to stop system.
User 7	Color change of the system status card and overview in setting page	simple but easy-understanding	Maybe have a short introduction before use the app
User 8	Progress bar/color change	Purely, but it feels like you need to have some understanding of the product.	If there is more information about the microbiology section, could you please show more content?
User 9	The Garden interface tells me how much watering I've done for my plants today.	I rarely use apps, and I hope to be able to operate them directly on the furniture instead of relying on apps.	none
User 10	Biofiter snapchat directly show the process of biofiltration System status card	slightly improve the awareness of user	Only one dominant system state is retained; other information is reduced to secondary indicators 17 Deleted the adjusting time button in Home page.

Table 11. Users' Open-ended Responses (Author's own table).

Open-ended responses complemented the quantitative findings by providing descriptive insights into users' perceptions of system transparency, interaction experience, and potential areas for refinement.

Perceived Control and Safety: Participants frequently identified system status indicators, care-related pages, and process visualizations as critical elements contributing to a sense of control and safety. During Task 1, several users emphasized that being able to directly observe filtration progress and system conditions—specifically the Biofilter Status and Weekly Usage indicators—helped them understand how recycled water was being managed. One participant noted that "transforming invisible biological processes effectively removed the 'black box' anxiety," reinforcing the interface's role as a trustworthy explanation layer.

Experiential Perception and Interface Clarity: In terms of experiential perception, many participants described the interface as clear, simple, and intuitive. Feedback from Task 3 highlighted the helpfulness of the modular structure and visual organization in the Garden Page, noting that the "Last Irrigation" data made ecological processes feel seamlessly integrated into everyday domestic life. Others found the color-coded status cards and the "View Guide" button in the Care Page effective for navigating complex maintenance rituals without prior technical knowledge.

Opportunities for Refinement: Suggestions for improvement primarily focused on further enhancing visual differentiation between modules and increasing interaction feedback, such as more dynamic animations or signals during active processes. While the Setting Page provided a helpful overview, a small number of participants expressed interest in additional introductory guidance for first-time users and more in-depth content regarding microbiological sustainability.

Overall, the qualitative responses reinforced the high levels of transparency and usability observed in the quantitative data. The feedback confirms that providing explicit references to time and quantity—as implemented in the recent design updates—successfully bridged the cognitive gap between the slow metabolic cycles of the system and the user's need for immediate operational assurance.

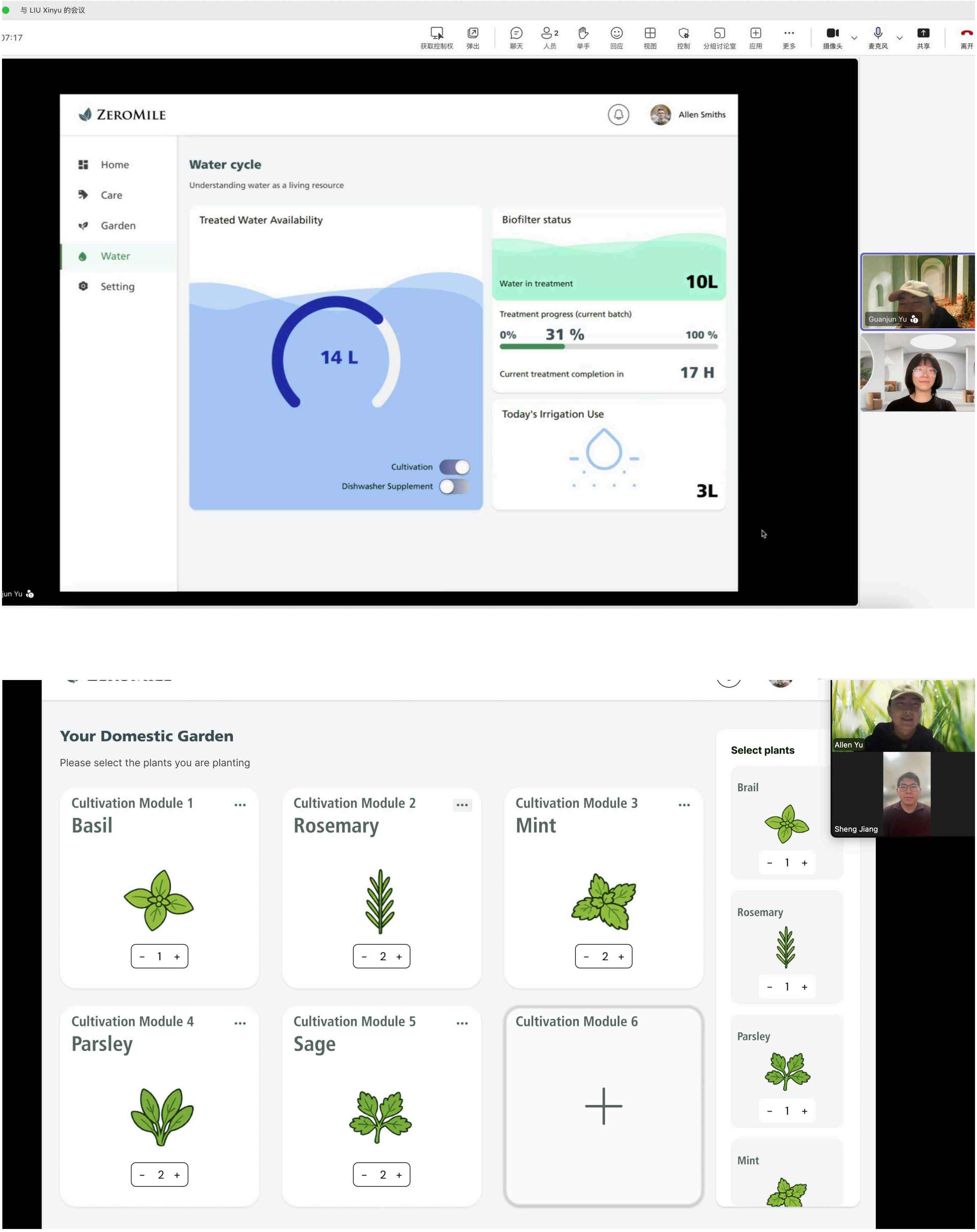

Figure 64. Online User Testing (Author's own photograph).

6.3 Design Insights and System Refinement

Based on the evaluation findings presented in Section 6.2, this study translated user perceptions into a set of design insights and corresponding system refinement directions. Rather than focusing solely on interface optimization, these insights address how interaction design can mediate trust, reduce perceived risk, and support long-term engagement with domestic DWW reuse systems.

Transparency as a Trust-Building Mechanism
A central finding of the study is that users' hesitation toward DWW reuse is primarily driven by water-related risk perception rather than technological unfamiliarity. Participants frequently described the microbiological filtration process as a “black box,” indicating that uncertainty regarding invisible biological activity undermines confidence in system safety.

The evaluation demonstrated that visualizing filtration progress, system status, and available purified water significantly improved perceived control and safety. This suggests that transparency should be understood as an interactional infrastructure for trust formation. Accordingly, system refinement focused on strengthening persistent status indicators, clarifying process transitions between wastewater treatment stages, and enhancing temporal feedback—such as the "Estimated time remaining"—to reinforce the perception of continuous biological activity.

Perceived Maintenance Complexity and Guided Manageability
Participants initially anticipated a high maintenance burden, reflecting common assumptions associated with ecological household technologies. However, usability results indicated that structured task categorization and step-by-step guidance substantially improved perceived manageability.

This discrepancy highlights that perceived complexity is experiential rather than functional. System refinement therefore prioritized guided maintainability, including clearer maintenance pathways (Active vs. Routine Care), contextual prompts like the "Service Required" alert, and improved predictability of routine interactions. These adjustments aim to transform maintenance from an anxiety-inducing responsibility into a manageable and intelligible domestic practice.

Progressive Ecological Engagement
While users responded positively to irrigation feedback, ecological attachment appeared to develop more gradually than cognitive trust. To support progressive engagement, refinements emphasized reinforcing feedback loops between filtration outcomes and visible ecological effects. By providing explicit references to time and quantity (e.g., "Last Irrigation: 2h ago | 150ml"),

the system bridged the cognitive gap between slow biological growth and the user's need for immediate operational assurance. Linking DWW purification to such tangible domestic benefits encourages users to perceive participation not merely as system operation but as an active ecological contribution.

Modular Legibility and Information Hierarchy
Given the modular structure of the biological filtration system, participants highlighted the importance of clearly distinguishing between stages of treatment. Refinement efforts therefore focused on strengthening modular legibility through clearer visual differentiation and improved symbolic representation of system states, such as the diagnostic color-coding in the "Installed Modules Overview". These changes support users in constructing a coherent mental model of DWW treatment and enhance perceived control over decentralized system behavior.

System Evolution and Context Adaptability
User feedback also suggested that different stakeholders may engage with the system at varying depths, ranging from basic operational awareness to deeper ecological curiosity. This indicates the importance of designing the system as an adaptive informational environment rather than a fixed interface.

Future refinement directions include layered information access, optional explanatory content regarding microbiological processes, and the potential for role-sensitive interaction depth. Such adaptability enables the system to function across diverse contexts while maintaining usability for everyday domestic use.

Chapter 7. Conclusion

7.1 Main Contributions and Innovations

The primary contribution of this project lies in the transition of Dishwasher Wastewater (DWW) biofiltration from a purely technical laboratory prototype to a functional, comprehensible home infrastructure. While previous research focused on the chemical and biological efficacy of greywater treatment, this project addresses the "human-system gap"—the psychological and operational barriers that prevent households from adopting slow, invisible, and complex ecological processes. By shifting the clinical focus from filtration efficiency to system legibility, the project provides a design framework that enables long-term coexistence between domestic life and circular ecological systems.

A significant innovation of this work is the Modular Spatial Adaptation Strategy. Recognizing that centralized industrial designs are incompatible with diverse kitchen layouts, this project proposes a distributed functional architecture. By decoupling the system into autonomous modules—biofiltration, storage, hydraulic execution, and cultivation—the infrastructure gains the flexibility to be integrated into various household zones. This modularity does not merely solve a spatial constraint; it redefines the system as a scalable, maintainable network, significantly lowering the threshold for domestic installation and repair.

Furthermore, the project introduces an Interpretive Interaction Layer through its digital interface design, moving beyond the traditional "control panel" paradigm. The core innovation is the transformation of invisible biological rhythms into a "readable" domestic narrative. This is achieved by providing explicit references to time and quantity—such as real-time filtration countdowns and detailed historical irrigation data (e.g., volume and time elapsed)—which successfully bridge the cognitive gap between slow metabolic cycles and the user's need for operational assurance. By categorizing maintenance through a "Care" logic and visualizing the "Garden" as the tangible output of the cycle, the design reduces cognitive load and transforms maintenance into a predictable, manageable part of daily life.

Finally, this research contributes a novel Value-Centric Design Approach for sustainable home infrastructure. It demonstrates that the success of green technology in the home depends on its perceived reliability and the user's ability to sense the "value of the cycle". By integrating growth state perception and irrigation transparency, the project fosters a sense of active participation in a micro-ecosystem. This holistic approach provides a blueprint for how complex environmental technologies can be humanized, turning a technical utility into a visible, trustworthy, and harmonious component of the modern sustainable home.

7.2 Design Significance

The design significance of this project is rooted in its ability to bridge the gap between complex environmental engineering and daily domestic life. By transforming a technical biofiltration prototype into a "legible" home infrastructure, the project moves beyond mere functional utility. Its primary significance lies in enhancing infrastructure intelligibility. Traditional greywater systems often fail in domestic settings because their biological processes are slow and invisible, leading to a "black box" effect where users feel disconnected or distrustful. This design successfully translates these abstract ecological rhythms into intuitive, low-cognitive-load information—such as real-time filtration progress and water safety status—allowing a complex biological system to become an understandable and integrated part of the household.

Furthermore, the project redefines the relationship between the user and sustainable technology through enhanced maintenance predictability. By categorizing tasks based on urgency and clearly defining the boundaries between user actions and professional services, the design alleviates the "maintenance anxiety" that often plagues home-based circular systems. As confirmed during the user evaluation, the transition from unpredictable burdens to structured, pedagogical guidance (e.g., the "View Guide" feature) significantly improved perceived manageability. This shift is crucial for the long-term viability of sustainable technologies, as it replaces friction with a sense of agency and confidence, ensuring the system is actively and correctly maintained over its lifecycle.

Finally, the project contributes to a new paradigm of long-term domestic coexistence. Rather than designing a high-interaction "appliance" that demands constant attention, this project envisions the system as a quiet, collaborative presence within the home. By utilizing plants as the "perceivable output" of the water cycle and providing a transparent digital explanation layer with explicit data on irrigation volume and timing, the design fosters a sense of ecological stewardship. The significance of this approach is that it shifts the user's role from a mere operator to a participant in a micro-ecosystem. This holistic design strategy provides a scalable model for how invisible sustainable processes can be made tangible, trustworthy, and aesthetically integrated into the modern living environment.

7.3 Future Challenges and Development

While Re-Zero demonstrates the potential of modular domestic biofiltration to support intelligible and adaptable DWW reuse, several design-oriented challenges remain for its long-term integration into everyday life.

Sustaining Trust Beyond Initial Adoption
Although transparency and modular legibility contribute to early acceptance, maintaining user trust over extended periods presents an ongoing challenge. As the system becomes familiar and interaction frequency decreases, users may gradually disengage from monitoring system states. Future work should explore how calm yet meaningful feedback—such as ambient signals or subtle haptic notifications—can sustain awareness without increasing cognitive burden.

Cognitive Fragmentation in Distributed Modules
The spatial distribution of modules improves adaptability but may also fragment users' understanding of the system as a coherent whole. Ensuring that modular decomposition supports intelligibility rather than confusion suggests the need for interaction strategies that reinforce systemic continuity across physically separated components. Strengthening the "Explanation Layer" across multi-device collaborative interfaces will be critical in maintaining a unified mental model of the water cycle.

Adaptive Information Depth for Diverse Engagement
Evaluation findings indicated that users engage with the system at varying levels of depth, from basic operational monitoring to deep ecological curiosity. A significant future challenge lies in designing an adaptive informational environment that provides layered access to content. This includes offering optional explanatory content regarding microbiological sustainability for specialized users while maintaining a minimalist, "low-cognitive-load" baseline for everyday domestic use.

Balancing Automation and Perceived Care Responsibility
A key tension identified in this study concerns the balance between automated system processes and the user's sense of responsibility for maintenance and care. Over-automation may reduce ecological engagement and awareness, while excessive responsibility may reintroduce perceived burden. Future research should investigate interaction approaches that support shared agency between users and living infrastructure, ensuring that the system remains a "collaborative eco-assistant" rather than a mere appliance.

Scaling Modular Domestic Systems Toward Collective Ecological Practices
Beyond individual households, modular DWW infrastructures raise questions regarding how decentralized systems might interconnect or contribute to broader ecological awareness. Exploring interaction models that extend from personal routines to shared environmental practices represents an important direction for future design research, potentially transforming domestic water reuse into a collective act of stewardship.

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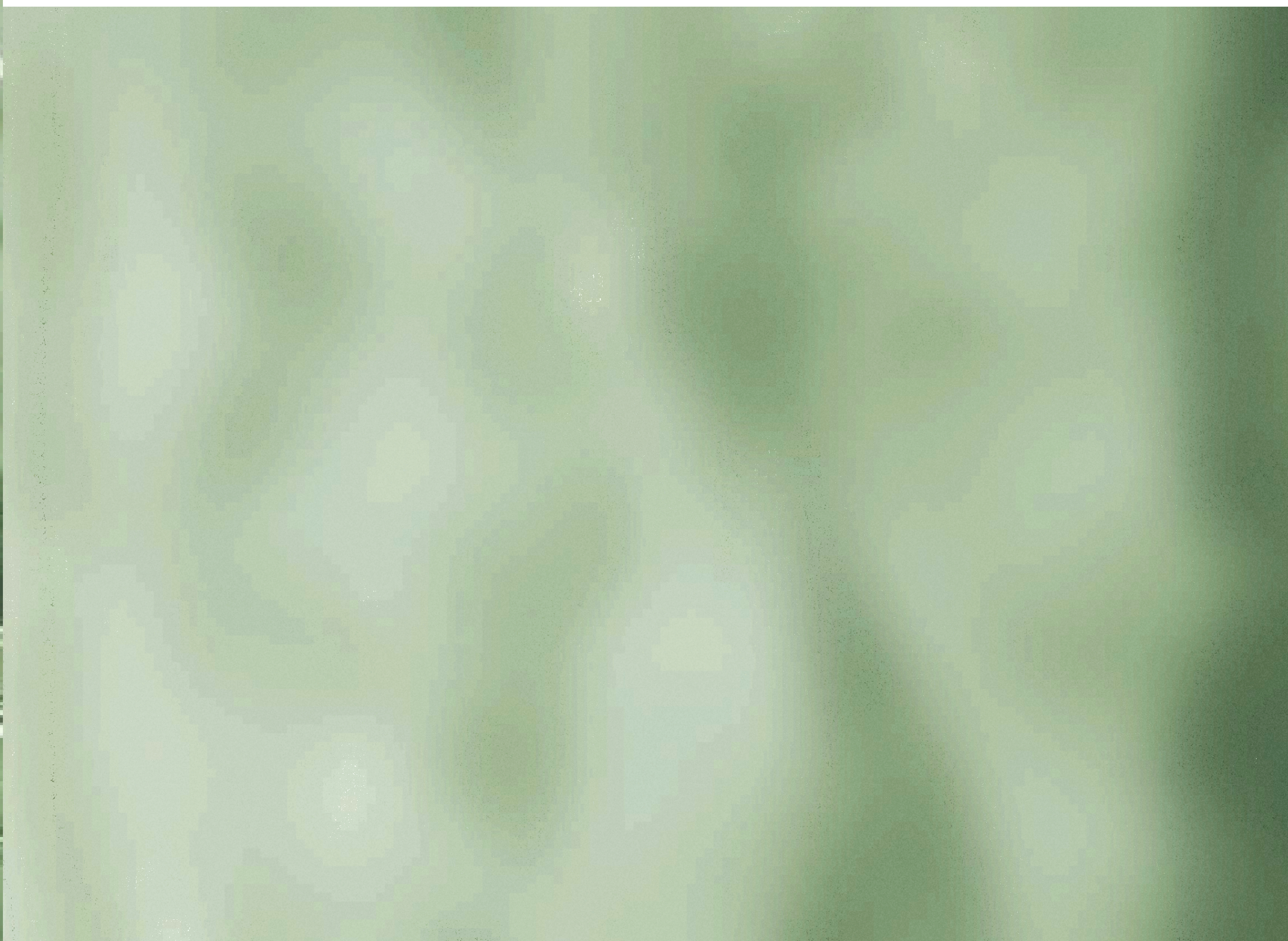

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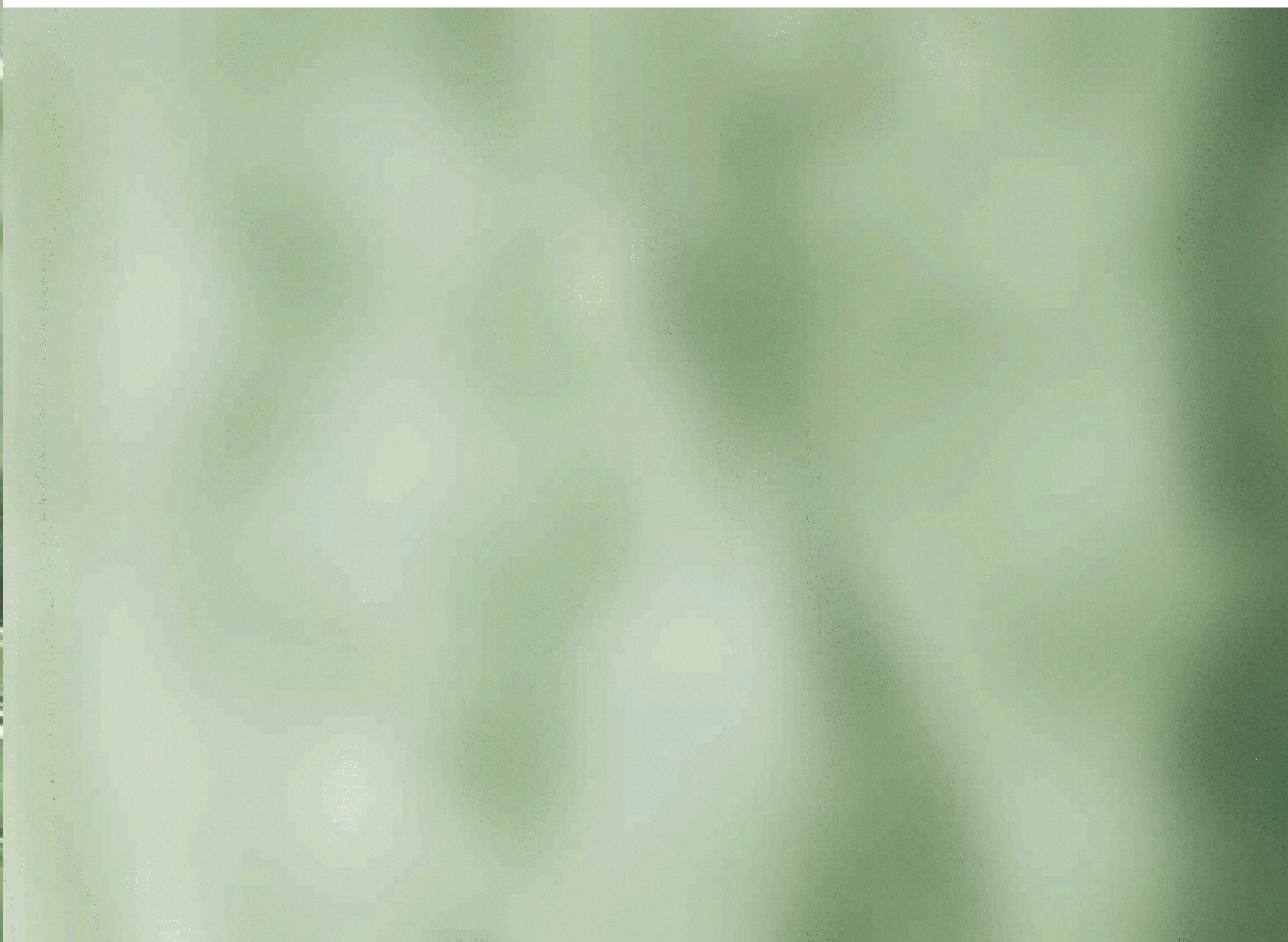
This work represents not only an academic milestone but also a personal journey of learning how design can make invisible systems more understandable, meaningful, and gently integrated into everyday life.

Guanjun Yu
Wenzhou, China
February 2026

Appendix



Component Inventory of the Zero Mile Prototype

Components	Quantity	Functional Unit	Notes
Hydraulic Components			
Membrane pump	1	Hydraulic Circulation Unit	Core routing executor
Solenoid valve	9	Supply Interface Unit/ Hydraulic Circulation Unit Cultivation Unit	EV1–EV9
Three-way valve	1	Supply Interface Unit	Wastewater intake diversion
Check valve	4	Supply Interface Unit/ Hydraulic Circulation Unit	Prevent backflow
Pressure limitation valve	1	Hydraulic Circulation Unit	Protect the pump and pipelines
Flow meter	2	Supply Interface Unit / Hydraulic Circulation Unit	Flow meter 1 & 2
Pressure switch	1	Supply Interface Unit	Monitor water supply pressure
Conductivity sensor	1	Supply Interface Unit	Dishwasher wastewater testing
50μm mechanical filter	1	Pre-Treatment Unit	Primary mechanical filtration
5μm mechanical filter	1	Pre-Treatment Unit	Secondary mechanical filtration
UV lamp	1	Hydraulic Circulation Unit	Post-treatment purification

Name	Num of component	Functional Unit	Notes
Biological Treatment Components			
Biofilter reactor container	1	Biological Treatment Unit	Temporary store DWW
Two-way valve	1	Biological Treatment Unit	Store treated water
LED grow light	/	Biological Treatment Unit	2 per tank

Components	Quantity	Functional Unit	Notes
Storage Components			
Accumulation tank	1	Storage Unit	Temporary store DWW
Reuse tank	1	Storage Unit	Store treated water
Level sensor	4	Storage Unit	2 per tank
Temperature sensor	1	Storage Unit	Located in the accumulation tank

Components	Quantity	Functional Unit	Notes
Cultivation Components			
Planter	8	Cultivation Unit	Planting Container
Irrigation drip line	8	Cultivation Unit	Distribute irrigation water
Water collection channel	1	Cultivation Unit	Collect return water
Solenoid valve	2	Cultivation Unit	EV10, EV11

Components	Quantity	Functional Unit	Notes
Control and Electrical Components			
Interaction module	1	Control and Interaction Unit	40*30*10 cm
Control wiring network	-	Control and Interaction Unit	Connecting sensors and actuators

This list is based on Sambinelli's (2023) documentation and the author's on-site observations of the prototype. The specific model numbers of some components are untraceable due to prototype iterations, but the functional classification is sufficient to support the system analysis and modular derivation in this paper.

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