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Rethinking Wastewater: Value and the Role of Sustainable Technologies in NBS Circular Transitions

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ABSTRACT

This paper critically examines the methodological boundaries of Life Cycle Assessment (LCA) within the context of sustainable design and infrastructure systems. By contrasting classical and ecological engineering logics, it reveals analytical blind spots in conventional LCA models, particularly the inability to recognize unrecovered resources, ecological co-benefits, and regenerative potentials. Drawing from case analyses and conceptual comparisons, the study questions the adequacy of cradle frameworks in addressing spatial, biological, and systemic complexities. In response, it proposes an expanded evaluation approach grounded in spatial-temporal dynamics, ecosystem integration, and syntropic principles. The findings support a necessary shift from impact-reduction metrics toward context-sensitive methodologies capable of supporting circular and regenerative design in nature-based solutions (NBS) architecture and infrastructure.

Keywords: waste value; cradle-to-cradle; regenerative design; resource recovery

1. INTRODUCTION

In the face of mounting climate, environmental, and resource crises, a central question emerges: Can sustainability remain limited to technical optimization? Architecture and civil engineering, disciplines that shape space, hold the potential not only to minimize harm but to generate regenerative outcomes. Within this framework, wastewater, long seen as a burden, is increasingly recognized as a resource: a source of energy, nutrients, and ecological value. Yet, if waste is redefined as a resource, can we still plan and evaluate development through the lens of waste management, rather than resource recovery? Such a shift requires not just new technologies but a revised methodology, one that can measure regenerative gains, not only losses. Life Cycle Assessment (LCA), central to sustainability evaluation, thus warrants critical re-examination. Its limits are not solely technical, but epistemological, shaping how we assign value in architecture and ecology. Current sustainability assessments remain grounded in linear, quantitative frameworks such as ISO 14040/14044. While LCA effectively measures emissions and consumption, it often overlooks spatial, biological, and socio-ecological benefits emerging from interactions between built and natural systems, such as carbon sequestration, nutrient cycling, and microclimate regulation [1]. This gap persists across sectors: in renewable energy, where social and spatial dimensions are underrepresented [2], and in urban water systems, where wastewater supports Cradle-to-Cradle material cycles [3].

This paper thus has a dual objective: to examine the methodological boundaries of LCA in architectural and ecological systems, and to explore extended valuation frameworks that incorporate local context, biological flows, and ecosystem services. Waste is framed as an energetic, material, and ecological resource, not as a residual output. The paper proceeds from theory and critique of LCA, through a comparison of classical and ecological engineering, to a model for regenerative urban infrastructure.

2. THEORETICAL FRAMEWORK

The Life Cycle Assessment (LCA) methodology emerged in the late 1960s within an industrial context, as a method for assessing energy flows and the environmental impact of packaging. Its development was closely linked to classical engineering, operating within the paradigm of control and optimization. Consequently, LCA has been oriented from the beginning toward quantitative measurement, the identification of emissions, resource consumption, and critical pollution. With its standardization through ISO 14040, ISO 14041, and ISO 14042, this approach became a dominant instrument in sustainable planning and production [4].

In the field of building construction, LCA serves as a basis for selecting materials, assessing energy efficiency, and quantifying emissions over a building's life cycle. However, such applications remain confined to the mitigation of damage rather than the creation of benefits. Spatial dimensions, biological interactions, and local ecosystem connections remain beyond its analytical reach. The assumption of spatial neutrality is particularly problematic, as if the place of intervention were irrelevant, even though regenerative effects such as water infiltration, microclimate improvement, or biodiversity enhancement occur precisely through local integration. In standard models, LCA treats the environment as a passive recipient of negative impacts. This reductionist framework overlooks the potential of systems to act as active agents that generate value through natural and social flows. At this point, the distinction between classical engineering and ecological engineering

emerges (Table 1). While the former remains focused on the product and technical performance, the latter incorporates space, time, and relationships as integral components of the system. These distinctions are supported by literature emphasizing the integration of natural systems, local knowledge, and regenerative design principles [5], [6], [7], [8].

Table 1. The author's synthesis compares classical and ecological engineering approaches. Informed by the holistic and site-integrative principles [5], [6], [7], [8].

Aspect	Classical Engineering	Ecological Engineering
Focus	Product, object-oriented	Process, flow-oriented
Methods	Performance optimization (efficiency, cost)	Regenerative integration (effectiveness, cycles)
Time Frame	Linear: design, production, end-of-life	Cyclical: adaptation, renewal, continuity
Location Context	Universal, site-neutral	Context-specific, ecosystem-rooted
Relationship with Nature	Control, impact avoidance	Symbiosis, support of natural processes

This comparison is supported by contemporary research. Schönborn and Junge (2021) emphasizes that Ecological Engineering integrates principles, processes, and organisms into traditional engineering practices as a holistic approach to problem-solving [5]. In architectural systems, Hecht et al. (2024) propose that regenerative design can be measured through exergy and the generation of ecosystem services, whereby buildings become active participants in biological cycles [6]. Furthermore, Toner et al. (2023) highlight the importance of integrating site-specific ecological knowledge into design practice, stressing that architecture cannot be separated from the context of nature [7]. In a broader sense, de Oliveira et al. (2025) point to the evolution of concepts such as ecological engineering and nature-based solutions, underlining the need to transcend terminological divisions in favor of synthetic, integrative, and holistic approaches [8]. From this perspective, a central question arises: can LCA, in its classical form, respond to the challenges of architecture that seeks to design symbiotic relationships between humans, technology, and nature? If evaluation remains limited to emissions and consumption, positive effects are neither targeted nor visible. If, however, the goal is to identify and measure benefits, not only avoided damage, LCA expands both methodologically and epistemologically.

The potential of this transformation lies precisely in re-examining LCA not as a finalized method of environmental accounting, but as a framework capable of evolving beyond its classical roots [9]. This paper interrogates whether ecological engineering truly breaks away from reductionist logic, or if it represents an adaptive layer within the same paradigm, one still focused on optimization and impact minimization. By doing so, it investigates whether ecological engineering constitutes a transitional stage, one still constrained by optimization logics and system neutrality, or whether it signals a paradigm shift toward nature-based, regenerative thinking. In this expanded view, LCA is not limited to quantifying losses but is redefined to recognize benefits, relationships, and spatially embedded potentials. Such an evolution could serve as the basis for a new architectural paradigm and LCA methods aligned with deep ecological engineering and Nature-Based Solutions (NbS).

3. METHODOLOGICAL LIMITS OF CLASSICAL LCA IN THE CONTEXT OF ECOLOGICAL ENGINEERING

The methodological boundaries of classical LCA become most evident when applied to systems that involve dynamic interactions between infrastructure and ecology. While LCA excels in quantifying environmental burdens (emissions, energy use, pollutant loads), it remains limited in assessing opportunities for regeneration and integration with natural processes. Building upon the conceptual distinction outlined in Table 1, this section examines how classical and ecological engineering approaches diverge in interpreting the same infrastructure scenario. Through this lens, LCA's reductionist focus on quantifiable impacts is contrasted with the need to account for hidden losses, such as unutilized energy, nutrient flows, and unrealized ecosystem functions, particularly in wastewater systems. These differences are not merely theoretical: they shape how problems are defined, what is considered valuable, and which solutions are prioritized. In what follows, we contrast the conventional LCA logic with an extended perspective informed by regenerative design and ecological integration.

Classical engineering would approach urban wastewater management through hydraulic and sanitary parameters: the capacity of sewer networks, overflow risks, and concentrations of pollutants such as BOD, COD, nitrogen, and phosphorus in the effluent. In this framework, LCA analysis typically focuses on quantifiable indicators such as energy consumption for treatment, CO₂-equivalent emissions, operational costs, and effluent quality [10], [11]. These metrics, while essential for environmental accounting, are grounded in a damage-mitigation paradigm. However, such assessments often fail to capture the broader ecological context and the system's hidden losses: irreversibly lost resources, dissipated energy flows, and nutrients discharged into receiving waters. Wastewater infrastructure, viewed through this lens, is not just a technical system but also a site of unrealized regenerative potential. It consumes energy to neutralize pollution, yet ignores the value embedded in the waste itself, a value that could be recovered and reintegrated into ecological and urban systems [12].

Consider, for example, centralized combined sewer systems, which dominate most urban regions. These systems mix blackwater and stormwater, resulting in diffuse and diluted pollutant loads that are energetically expensive to treat. More importantly, they disperse key resources, such as nitrogen, phosphorus, and organic matter, across large volumes of water [13], making their recovery technically complex and economically unfeasible.

In contrast, an ecological engineering perspective would prioritize the source separation of wastewater streams, treating blackwater as a concentrated carrier of nutrients and energy. This enables localized strategies such as biogas production, nutrient cycling, and integration with green infrastructure [6]. When viewed through this regenerative logic, the goal of LCA is not only to quantify consumption and emissions but also to identify missed opportunities, the energy that remains unrecovered, the nutrients that are lost, and the ecosystem services that go unrecognized.

Expanding LCA in this way requires a shift in epistemology: from evaluating harm avoidance to recognizing system potential. This includes not only biophysical flows but also spatial configurations and ecological relationships. The methodological challenge lies in developing metrics and indicators that account for benefits, not just costs: for example, how much nutrient recycling is enabled, how much carbon is sequestered, or how much urban heat is mitigated through wastewater-linked vegetation.

3.1. HIDDEN ENERGY LOSSES IN THE C2G PARADIGM

The cradle-to-grave (C2G) paradigm developed within classical LCA models during the second half of the twentieth century, in accordance with the industrial logic of linear flows. Its fundamental premise is that a product has a clearly defined beginning in resource extraction and production, followed by a use phase and an end of life, which marks disposal or destruction of waste. Although this model enabled systematic tracking of environmental impacts and comparability between technologies, it simultaneously introduced a fundamental limitation: the end of life also signifies the end of analysis, without considering the potential of waste as a new resource [9].

In the case of renewable energy sources (RES), particularly solar and wind energy systems, analyses conducted within the cradle-to-grave framework reveal both advantages and shortcomings. Research shows that LCA enables quantitative comparison of technologies and documents the advantages of RES over fossil fuels [2], [14]. However, within such analyses, the end-of-life phase, when systems themselves become waste, is often insufficiently elaborated. For photovoltaic panels, this refers to toxic and non-recyclable components, while for wind turbines it concerns massive composite blades that are technologically difficult to recycle [10], [15]. Materials that once symbolized the energy transition during production eventually become indistinguishable waste streams at the end of their life cycle.

The same logic is evident in analyses of wastewater treatment systems, where LCA is traditionally used to assess safe discharge and minimize impacts on receiving waters [11]. These models successfully quantify emissions, energy consumption, and the amount of generated sludge, but they completely overlook resource potential, the thermal, nutrient, and/or energetic value. In fact, studies on heat recovery from wastewater indicate that a large portion of energy remains unrecovered: only a small percentage of available heat (around 3.65 %) is actually recovered through sewer and treatment plant technologies [16]. Reviews of heat recovery from wastewater highlight both the significant theoretical potential and the magnitude of unrecovered energy flows. LCA analyses quantify the primary and final energy consumed during a system's life cycle but fail to account for the energetic potential contained in waste streams. It is precisely this potential energy, whether thermal, biological, and/or nutrient-based, that represents the actual loss remaining outside the energy balance, making the overall methodological outcome incomplete.

This methodological blind spot becomes particularly evident in analyses of greywater treatment systems. The study by Kobayashi et al. applies the LCA methodology to decentralized systems in cold climate zones and demonstrates that they can achieve lower CO₂ emissions and energy consumption compared to centralized models [17]. However, the analysis remains confined within the technical boundaries of the system; it includes the energy for pumping, filtration, and disinfection, but not the thermal potential of the water itself. Greywater typically leaves the household at temperatures between 25 and 35 °C, representing a significant energy flow that is treated as negligible in conventional LCA approaches. In cold climates, this loss can amount to 10–15 % of the total energy consumed for water heating [18]. If this lost flow were included in the balance, the total system efficiency would be lower than the results suggest. This example clearly shows that LCA accurately measures what a system consumes, but not what it loses, such as the energy unrecovered, the potential unrecognized, and the processes that remain beyond its analytical scope.

The C2G model, while effective in tracking environmental burdens, remains confined by its linear logic. Waste is still treated as the end of a process, not the beginning of a new one. This limitation persists even within “green” systems, where valuable resources embedded in waste remain uncounted and unrecovered. In contrast, the Cradle-to-Cradle (C2C) paradigm offers a shift in perspective, one that sees waste not as a problem to be minimized but as a resource to be reintegrated. The following section explores whether this shift can be meaningfully applied to wastewater systems.

3.2. C2C: IS WASTEWATER A RESOURCE?

Building upon the limitations of the C2G model, the C2C paradigm offers a regenerative perspective on material and energy flows. Within this framework, waste is no longer viewed as an endpoint but as a nutrient for future systems. Applied to wastewater, this shift redefines what has traditionally been treated as pollution, reframing it as a valuable input into closed-loop urban metabolism. In conventional infrastructure engineering, wastewater has long been treated as a problem to be quickly and safely removed from the system, a logic inherited from the industrial era and focused on hygiene and public health. However, climate and ecological challenges demand a new perspective: wastewater contains energy, nutrients, moisture, and biological potential, making it a regenerative resource [3], [19].

This shift reframes wastewater systems as visible, ecologically active structures within architecture and landscape. Research shows that such systems regulate microclimates [20], retain soil moisture, and contribute to carbon sequestration [21]. In addition, green infrastructure enhances nutrient cycles through plant uptake and microbial processes, reducing nitrate and phosphate levels and helping prevent eutrophication [22], [23]. A particularly important component is blackwater, rich in both energy and nutrients. Studies confirm its potential for biogas production and fertilizer recovery [3], [24]. Research by Abdalla et al. shows that separate collection and treatment of grey and blackwater can be economically viable and ecologically effective [25].

In this paradigm, wastewater becomes a carrier of energy and nutrients, not an end-product, but an input to circular systems. This aligns with the C2C model, which reframes architecture as part of ecological metabolism. Rather than separating buildings from environmental flows, new designs integrate them, treating water on-site and transforming infrastructure into landscape.

Crucial in this transition is source separation: greywater and blackwater differ in composition and treatment needs. Separation allows for energy savings, nutrient recovery, and low-tech processing [26]. When these flows are integrated into design, buildings become part of local ecological systems, shaping new typologies that reflect site-specific conditions [7]. Nature-based solutions (NbS) now combine water treatment, biodiversity support, and climate regulation [27]. Wastewater is no longer expelled but treated in place, offering direct ecosystem benefits. Architecture, in this view, becomes a node of exchange, mediating between anthropogenic and natural flows. This demands interdisciplinary thinking: engineering knowledge, design sensitivity, and ecological awareness must converge. In this framework, control enables not just efficiency, but regeneration. Buildings become infrastructures of resilience, enhancing biodiversity, stabilizing microclimates, and supporting local ecosystems [28]. Yet despite these regenerative possibilities, current LCA methodologies rarely capture such benefits. This reveals a deeper methodological blind spot, one that will be critically examined in the following section.

3.3. UNMEASURED AND UNREGISTERED: BLIND SPOTS IN CURRENT LCA PRACTICE

Recent developments in Life Cycle Assessment (LCA) emphasize the need to move beyond classical models that quantify energy use, emissions, and waste. While effective in assessing negative impacts, these frameworks often overlook regenerative, ecological, and socio-spatial contributions vital to sustainability transitions.

In LCA analyses of green roofs, it is necessary to distinguish between effects that are unmeasured and resources that are unregistered [16], [17], [29]. The first group refers to ecological and spatial benefits that are acknowledged yet remain outside the quantitative scope, such as microclimate regulation, biodiversity support, or local water infiltration. The second group, crucial for the material and energy balance, refers to actual resources leaving the system without the possibility of return: water that does not remain within the cycle, thermal energy that is not recovered, or biomass that does not re-enter the city's metabolism. These irreversibly lost resources represent a fundamental methodological omission, since their exclusion significantly alters the results and creates an illusion of efficiency that does not reflect the system's actual balance.

Green roofs are increasingly recognized not only as architectural or energy-saving elements, but as integral components of urban green infrastructure, contributing to biodiversity corridors, microclimate regulation, spatial connectivity across the city, and human well-being, a dimension increasingly acknowledged as an area of protection in emerging LCA frameworks [1], [17], [18]. Extending this perspective, decentralized biological wastewater systems, including constructed wetlands and vegetated biofilters, operate as blue-green infrastructures that link hydrological, ecological, and urban metabolic functions. This includes not only water management and habitat formation, but also carbon sequestration through vegetation and soil systems. Studies have shown that extensive green roofs can sequester up to 375 g CO₂/m² annually [19], while constructed wetlands similarly contribute to long-term carbon storage in biomass and sediments [20]. These capacities can significantly alter the carbon balance of a system, yet remain largely absent from standard LCA inventories.

Yet these contributions are often excluded from conventional LCA analyses, not because they lack measurable value but because they occur beyond the spatial and functional scale at which LCA typically operates. While the method is well-suited for product- or material-level assessment, it becomes increasingly limited as evaluation shifts toward neighborhood, urban, or territorial scales, where ecological co-benefits are distributed, context-dependent, and emergent.

This critique aligns with Jasanoff's observation that dominant frameworks for scientific evidence are shaped by institutional and epistemic cultures, leading to what she terms "technologies of hubris", which conceal uncertainty and complexity in favor of apparent objectivity [30]. In the case of LCA, this results in tools that measure efficiency at the cost of systemic understanding. This limitation reflects what Jasanoff describes as the co-production of knowledge and social order, where evaluative frameworks are not neutral tools but institutionalized ways of knowing. In such regimes, what remains unmeasured is not merely complex or uncertain but structurally incompatible with linear logics of control, closure, and standardization. As a result, regenerative and relational processes are not excluded by accident, but by design.

The common denominator of all these studies becomes evident: the more complex the system, the greater the number of losses that LCA fails to register. This reveals a

methodological paradox: Should analytical tools be adapted to the complexity of systems, or should systems be simplified so that existing tools can measure them?

Classical LCA methodology remains a framework that reliably quantifies consumption and emissions, yet fails to capture the dynamics of lost resources and their spatial and biological dimensions. The system boundaries, set according to the cradle-to-grave logic, prevent insight into processes of circulation and value recovery, the very processes that define circular and syntropic systems. These flows are delayed, regenerative, and spatially extended, and resist enclosure within linear accounting models, revealing the mismatch between ecological functioning and techno-analytical framing.

Thus, a method intended to measure sustainability often becomes an instrument for recording losses. This paradox, that sustainability is calculated within frameworks that do not recognize the return flow of matter and energy, marks the limit of classical LCA. It also opens up the possibility for rethinking assessment itself: not through optimization but through ecological integration. The next chapter explores how Life Cycle Assessment can be expanded through the logic of nature, embracing spatiality, relationships, and regeneration as core metrics of sustainable design.

4. EXPANDING LCA THROUGH NATURE-BASED LOGIC

Nature-Based Solutions (NbS) have emerged as a strategic approach to improving water quality and the ecological performance of infrastructure, particularly in urban and peri-urban contexts. According to the European Commission's analysis of EU-funded projects, NbS such as constructed wetlands, vegetated swales, and green roofs not only deliver technical performance in wastewater treatment, but also enhance biodiversity, improve microclimates, and support carbon sequestration [31]. Recent European policy frameworks increasingly acknowledge ecosystem services, circularity, and Nature-Based Solutions, signalling a shift in sustainability discourse. However, from a co-production perspective [30], these inclusions remain epistemically constrained: they expand the vocabulary of sustainability without altering the linear evaluative architectures through which environmental value is ultimately stabilized and validated.

However, these co-benefits are often not captured by conventional evaluation tools such as Life Cycle Assessment (LCA), which prioritize quantifiable outputs such as energy consumption or emissions. This misalignment between ecological function and analytical framing has become a structural methodological gap, especially as NbS increasingly inform ecological engineering and regenerative urban design strategies.

4.1. REDEFINING VALUE: CONTEXTUAL AND REGENERATIVE LCA TOOLS

To address these limitations, several extended valuation models have emerged. Beyond ecosystem-oriented extensions, the LCA field has also evolved through frameworks such as Life Cycle Sustainability Assessment (LCSA), Consequential LCA, and Territorial LCA, which expand the analytical scope toward systemic, socio-economic, and spatial dimensions [9]. Ecosystem Services LCA (ES-LCA) incorporates benefits such as carbon sequestration, water filtration, biodiversity support, and spatial quality, though it is still constrained by challenges in standardizing context-dependent metrics [23]. Social Life Cycle Assessment (S-LCA) adds social and cultural dimensions, using regionally weighted indicators to reflect diverse vulnerabilities, especially in water and sanitation systems [1]. Regenerative LCA reframes flows such as blackwater as productive systems, enabling nutrient recovery and biogas

generation rather than seeing them solely as waste streams. Source control and recovery-oriented systems have been shown to significantly increase potential biogas production and nutrient reuse compared to conventional treatment, highlighting latent ecological and resource benefits that conventional LCA often overlooks [32], [33].

Across all these models, a clear methodological trend emerges: a shift from universal, decontextualized absolute indicators toward relative valuation based on local priorities, ecological vulnerability, and socio-cultural relevance. Nutrient recovery, for example, may be of marginal value in phosphorus-rich regions but critical in degraded agricultural contexts. Similarly, a square meter of green roof has different ecological weight depending on whether it mitigates urban heat or simply serves as architectural décor. Contextual weighting (or indicator prioritization) thus becomes a necessary extension of system boundaries, aligning assessment criteria with actual socio-ecological function. However, for this transformation to be fully realized, LCA must move beyond universal abstraction. Standardized models still rely on absolute values, such as kilograms of CO₂ or square meters of green infrastructure, treating them as uniform across contexts. This enables global comparability, but at the cost of ecological specificity.

In reality, environmental systems operate relationally. A green roof placed in isolation within a dense urban matrix cannot be equated with one that extends a biodiversity corridor. Similarly, the reuse of wastewater carries drastically different value in arid, karstic, or humid zones. Yet classical LCA fails to distinguish between these cases. Relational value disappears, and with it, local benefits that could inform better design.

This limitation has been recognized in several recent reviews. For example, Scolaro et al. observe that green roof LCA studies commonly use uniform functional units (m²), focusing on materials and energy use while ignoring ecological function, connectivity, and urban microclimate effects [18]. Mehmeti and Canaj show that LCA of wastewater reuse often overlooks local hydrological context, treating irrigation benefits in water-rich and water-scarce regions as equivalent [34]. Similarly, life cycle assessment studies have highlighted that blackwater treatment is often evaluated without fully accounting for site-specific resource recovery potentials, such as the availability of land for digestate reuse or the role of climate in biogas efficiency, which can significantly alter environmental outcomes and resource value [33]. This gap highlights a deeper limitation: LCA does not measure relationships. It measures flows, emissions, and quantities, but not ecological or spatial integration. By reducing complex systems to absolute indicators, it risks ignoring their most impactful dimensions. As a result, architecture and infrastructure are evaluated in isolation, rather than as embedded parts of living systems.

Among emerging contextual tools, geobiological methods offer a diagnostic approach to evaluating a site's regenerative capacity. By analyzing subsurface hydrology, soil structure, biological gradients, and local energy fields, these methods identify both constraints (e.g. impermeable soils, shallow groundwater) and opportunities (e.g. infiltration zones, biotic corridors) for decentralized water treatment [35], [36]. Although rarely included in conventional LCA models, such analysis can support place-based infrastructure design aligned with circular metabolism. Crucially, this approach requires methodological clarity: not as a metaphor or biomimetic analogy, but as a functional, scientifically grounded tool for evaluating ecological performance [30], [31].

Recent approaches attempt to bridge this gap by integrating geospatial data, climatic context, and ecosystem variables into circular design processes. Context-aware LCA models incorporate parameters such as land use, hydrology, biodiversity, and urban morphology

into the assessment framework, enabling a responsive, place-based analysis that reflects actual sustainability potential. In practice, LCA applications are increasingly being used to compare alternative sanitation and resource recovery scenarios; for example, resource-oriented sanitation coupled with LCA has been shown to identify significant environmental gains and appropriate technologies when nutrient, water, and energy recovery are considered in design decisions [37].

Empirical studies demonstrate that when domestic wastewater streams are source-separated, the potential for energy and nutrient recovery becomes clear. Anaerobic digestion of blackwater and associated organic fractions can yield substantial energy and nutrient products, thereby transforming wastewater from a burden to a viable resource stream [38]. Moreover, life cycle assessments that include energy and resource recovery pathways reveal that conventional treatment systems understate the overall environmental performance when not accounting for these beneficial outputs [39].

These findings support the claim that when wastewater pathways are redesigned as resource flows, the system's energy balance and material outputs shift significantly, underscoring our argument that LCA must capture these changes if it is to assess circular transitions meaningfully. The implication is not just methodological, but political: what we measure defines what we value. Whether wastewater is seen as a pollutant or a resource depends not on its chemistry, but on the framework of evaluation. As extended models demonstrate, recognizing potential is not only a matter of technology, but of shifting the logic of valuation itself.

4.2. FROM ENTROPIC TO SYNTROPIC LOGIC: REFRAMING THE EVALUATION PARADIGM

The evolution of Life Cycle Assessment (LCA) reveals more than just methodological shifts; it reflects a deeper transformation in how value, performance, and environmental agency are conceptualized. Historically rooted in industrial engineering, LCA developed as a tool for accounting for loss: emissions, depletion, and degradation [40]. This loss-oriented logic aligns with a linear evaluative structure and an entropic understanding of irreversibility, framing the reduction of harm as the primary goal of sustainability. Within such a paradigm, waste is a terminal state, and evaluation is structured around minimizing negative impact.

However, regenerative approaches, as explored throughout this paper, suggest that many of the outputs labeled as “waste” or “loss” may actually carry unrealized value [41]. Blackwater flows, heat residuals, or vegetated infrastructure can generate energy, support biodiversity, or enhance microclimates. Under a different lens, these systems are not just less harmful, but actively beneficial. What one model sees as entropic may reveal syntropic properties in another.

Syntropy is a term borrowed from systems biology and ecology that points toward integration, regeneration, and circularity [42]. It implies delayed returns, emergent benefits, and context-dependent relationships that resist enclosure within linear, decontextualized metrics. Yet this logic remains largely unrecognized in engineering-based evaluation tools, not because its phenomena are immeasurable, but because current methods lack sensitivity to spatial embeddedness, temporal layering, and ecological reciprocity.

The repeated expansion of sustainability indicators does not signal methodological progress, but reveals the fundamental incompatibility between linear evaluative logics and systems whose value lies in continuity, regeneration, and open-ended ecological processes. This opens a series of critical questions: Can impact be measured not only in terms of what

is consumed, but also in terms of what is returned to the system? How does location shape impact? How should evaluation account for benefits that are delayed, dispersed, or co-produced with other systems?

Beyond questions of measurement, these limitations point to deeper institutional and epistemic conditions under which evaluation operates:

Can evaluation frameworks designed for control and standardization meaningfully engage with systems characterized by growth, care, and open-ended ecological change?

Where are the limits of object-centered design when confronted with architectures that function as living processes rather than finished products?

How does the demand for evaluative certainty shape what kinds of architectural futures can be institutionally recognized?

In this light, syntropy does not reject quantification, but calls for its transformation. The prevailing notion that regenerative processes are too complex to measure may reflect more on the limits of existing tools than on the nature of the processes themselves. Rather than abandoning metrics, syntropic thinking asks how indicators might evolve: to become context-sensitive, relational, and temporally aware.

As Ben-Eli argues, this shift requires moving away from abstraction and control toward systems that respond to place, co-evolve with nature, and redistribute value across scales [42]. In infrastructure and architecture, this means designing not for “less harm,” but for positive contribution: flows that produce energy, support biodiversity, and stabilize microclimates. Whether this shift represents a true paradigm change or remains a marginal extension within LCA remains uncertain. What is clear, however, is that syntropy cannot be recognized through tools built to measure decay. It demands new frameworks that see infrastructure not as a terminal line, but as a cradle of reciprocal exchange.

This section concludes by mapping the transition from classical to extended LCA approaches, as illustrated in Figure 2. The figure captures three zones: (1) classical models rooted in entropic logic; (2) emerging tools that extend boundaries to account for spatial and ecological dynamics; and (3) a syntropic zone aligned with Nature-Based Solutions, where design and evaluation converge to regenerate systems rather than simply optimize them.

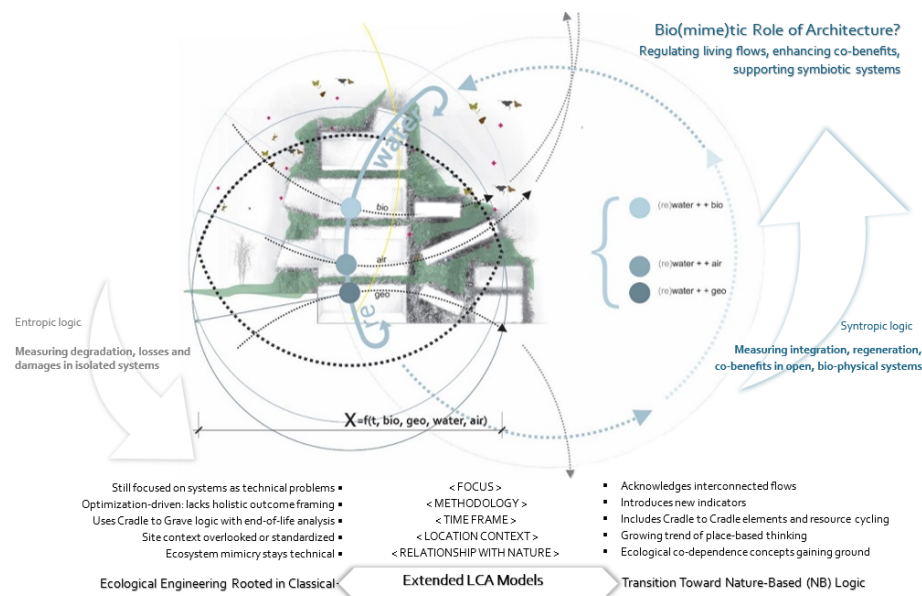


Figure 1. Transition in LCA Evaluation Logic through Architectural Integration (created by author)

5. CONCLUSION

This paper has critically examined the conceptual and methodological limitations of Life Cycle Assessment (LCA) within the context of circular transitions and regenerative design. It has shown that LCA, grounded in classical engineering and entropic logic, operates through a linear understanding of systems and effectively quantifies what is consumed, emitted, or discarded, yet remains limited in its capacity to address regenerative, spatial, and circular dynamics central to nature-based solutions (NbS).

The case of wastewater illustrates this limitation clearly: traditionally treated as a pollutant to be removed, it is increasingly reframed as a regenerative resource rich in energy, nutrients, and ecological potential. Yet conventional LCA rarely incorporates these latent values into its evaluative outcomes.

Rather than offering a ready alternative, NbS expose a growing misalignment between regenerative processes and the evaluative frameworks used to assess them. In this light, regeneration appears not as an added benefit but as a dimension of value that remains structurally under-recognized within linear assessment models. What is at stake, therefore, is not the adoption of new tools, but the adequacy of existing evaluative logics to account for systems characterized by continuity, reciprocity, and co-evolution.

If we begin to assess not only what ends, but what must continue, then we must also ask: Are we still designing buildings, or are we designing flows? Are we building structures or planting systems? This question does not prescribe a direction, but marks a threshold at which evaluation itself becomes a site of transformation.

While this study remains conceptual in scope, it seeks to interrogate the evaluative logic of LCA critically and to outline the foundations of an expanded perspective. The empirical application of such an approach, whether through real-world or hypothetical case studies, represents a necessary direction for future research.

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ПРЕИСПИТИВАЊЕ ОТПАДНЕ ВОДЕ: ВРИЈЕДНОСТ И УЛОГА ОДРЖИВИХ ТЕХНОЛОГИЈА У КРУЖНИМ ТРАНЗИЦИЈАМА ЗАСНОВАНИМ НА РЈЕШЕЊИМА ИЗ ПРИРОДЕ

Сажетак: Овај рад критички разматра методолошка ограничења процјене животног циклуса (Life Cycle Assessment – LCA) у контексту одрживог пројектовања и инфраструктурних система. Упоређујући класичне инжењерске приступе са еколошким и регенеративним концептима, рад указује на аналитичке слијепе тачке конвенционалних LCA модела, посебно њихову ограничену способност да препознају неискоришћене ресурсе, еколошке ко-користи и регенеративне потенцијале. На основу концептуалних поређења и анализе токова ресурса, доводи се у питање адекватност линеарног „cradle“ оквира у сагледавању просторне, биолошке и системске сложености. Као одговор, рад разматра потребу за проширеним евалуацијским приступима утемељеним на просторно-временској динамици, интеграцији екосистема и синтропијским принципима. Резултати указују на нужност помака са метрика заснованих искључиво на смањењу негативних утицаја ка контекстуално осјетљивим методологијама које могу подржати кружне и регенеративне приступе у архитектури и инфраструктури заснованој на рјешењима из природе (Nature-Based Solutions – NbS).

Кључне ријечи: процјена животног циклуса (LCA); вриједност отпада; кружни токови; регенеративни дизајн; рјешења заснована на природи (NbS); опоравак ресурса